48th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics
Sacramento, California
http://www.aps.org/meetings/meeting.cfm?name=DAMOP17
Monday, June 5, 2017 8:30AM - 3:30PM –
Session 1A Graduate Student Symposium on Quantum Information 308 -

8:30AM 1A.00001 Sign In –

8:55AM 1A.00002 Welcome –

9:00AM 1A.00003 Exploring Quantum Physics with Trapped Ions DIETRICH LEIBFRIED, National Institute of Standards and Technology — Trapped ions were among the first systems, where a single quantum particle can be confined and manipulated in almost perfect isolation from its environment. This makes ions prime candidates for high precision experiments and for demonstrating textbook quantum mechanical principles. Several ions in the same trap can couple strongly to each other through their Coulomb interaction. This enables entangling quantum logic gates and as a consequence, many experiments with trapped ions have concentrated on advancing quantum information processing in the last 20 years. While much work still needs to be done before a scalable, fault tolerant universal quantum processor can be realized in any system, the advances with ions have enabled exploration of new avenues, such as quantum simulation, quantum logic spectroscopy for ion clocks, and for molecular ion and highly charged ion spectroscopy. Lately, ion-based sensors and ideas for hybrid quantum systems that aim to couple trapped ions to photons, neutral atoms, superconducting circuits, micro-mechanical oscillators or other quantum coherent entities are gaining momentum.

10:15AM 1A.00004 Morning Coffee Break –

10:45AM 1A.00005 Graduate Student Symposium II, MATTHIAS TROYER, ETH Zurich and Microsoft

12:00PM 1A.00006 Lunch –

12:30PM 1A.00007 Optical studies of current-induced magnetization switching and photonic quantum states, VIRGINIA LORENZ, University of Illinois at Urbana-Champaign — The ever-decreasing size of electronic components is leading to a fundamental change in the way computers operate, as at the few-nanometer scale, resistive heating and quantum mechanics prohibit efficient and stable operation. One of the most promising next-generation computing paradigms is Spintronics, which uses the spin of the electron to manipulate and store information in the form of magnetic thin films. I will present our optical studies of the fundamental mechanisms by which we can efficiently manipulate magnetization using electrical current. Although electron spin is a quantum-mechanical property, Spintronics relies on macroscopic magnetization and thus does not take advantage of quantum mechanics in the algorithms used to encode and transmit information. For the second part of my talk, I will present our work under the umbrella of new computing and communication technologies based on the quantum mechanical properties of photons. Quantum technologies often require the carriers of information, or qubits, to have specific properties. Photonic quantum states are good information carriers because they travel fast and are robust to environmental fluctuations, but characterizing and controlling photonic sources so the photons have just the right properties is still a challenge. I will describe our work towards enabling quantum-physics-based secure long-distance communication using photons.

1:45PM 1A.00008 Afternoon Coffee –

2:15PM 1A.00009 A fermionic simulator with ultracold atoms in engineered optical potentials, JULIO BARREIRO, University of California, San Diego — In this talk I will show how our ultra-cold atom experiment will eventually simulate paradigmatic topological matter (fractional Chern insulators), black holes, and the electronic structure of molecules. Our experiment employs fermionic strontium atoms in engineered optical potentials, specifically optical lattices and tweezers. This system offers single-atom imaging and manipulation, fermionic statistics, as well as the same exquisite control of the internal electronic states of the atoms offered by trapped ions, used as a quantum computing architecture.

Monday, June 5, 2017 6:00PM - 9:00PM –
Session 1B Welcome Reception East Lobby and Terrace -

6:00PM 1B.00001 Welcome Reception –

Monday, June 5, 2017 8:00PM - 10:00PM –
Session 1C DAMOP Business Meeting 309 -

8:00PM 1C.00001 DAMOP Business Meeting –

Tuesday, June 6, 2017 8:00AM - 10:00AM –
Session A1 Prize Session Sheraton Grand Nave Ballroom - Steven Rolston, University of Maryland/JQI
Seeds in the Flowering of Quantum Science, DANIEL KLEPPNER, Massachusetts Institute of Technology — The Rydberg atom, When we excite a single Rydberg electron in a Bose-Einstein Condensate, the orbital size of which becomes comparable to For principal quantum numbers n in the range of 100-200 up to several ten thousand ultracold ground state atoms can be located inside one mechanism and the properties of these exotic molecules. At higher Rydberg states the spatial extent of the Rydberg electron orbit is increasing. a line shift proportional to the scattering length [1]. At ultracold temperatures one can ask the opposite question: What does a Rydberg electron atoms via a 1/rˆ4 potential is purely s-wave and can be described by a Fermi pseudopotential and a scattering length. To study this interaction In Institut and Center for Integrated Quantum Science and Technology, Universitaet Stuttgart, Germany — Modern quantum scattering theory was systems, giving hope for a new level of understanding of strongly interacting fermions. Here, a microscope allows for single-atom, single-site resolved detection of density and spin correlations, revealing the Pauli hole as well as antiferromagnetic and doublon-hole correlations. Novel states of matter are predicted for fermions interacting via long-range dipolar interactions. As an intriguing candidate we created stable fermionic molecules of NaK at ultralow temperatures featuring large dipole moments and second-long spin coherence times. In some of the above examples the experiment outperformed the most advanced computer simulations of many-fermion systems, giving hope for a new level of understanding of strongly interacting fermions.

Herbert P. Broida Prize Talk: A single Rydberg electron in a Bose-Einstein condensate: from two to few to many-body physics, TILMAN PFUER, 5. Physikalisches Institut and Center for Integrated Quantum Science, Universitat Stuttgart, Germany — Modern quantum scattering theory was developed in the context of Rydberg spectroscopy in 1934 by Enrico Fermi. He showed that for slow electrons the scattering from polarizable atoms n=12. The potential is purely s-wave and can be described by a Fermi pseudopotential and a scattering length. To study this interaction Rydberg electrons are well suited as they are slow and trapped by the charged nucleus. In a high pressure discharge Amaldi and Segre, observed a line shift proportional to the scattering length [1]. At ultracold temperatures one can ask the opposite question: What does a Rydberg electron do to the neutral atom sitting in the electronic orbit? We found that one, two or many ground state atoms can be trapped in the mean-field potential created by the Rydberg electron, leading to so called ultra-long range Rydberg molecules [2]. I will explain this novel molecular binding mechanism and the properties of these exotic molecules. At higher Rydberg states the spatial extent of the Rydberg electron orbit is increasing. For principal quantum numbers n in the range of 100-200 up to several ten thousand ultracold ground state atoms can be located inside one Rydberg atom, When we excite a single Rydberg electron in a Bose-Einstein Condensate, the orbital size of which becomes comparable to the size of the BEC we observe the coupling between the electron and phonons in the BEC [3]. [1] E. Amaldi and E. Segre, Nature 133, 141 (1934) [2] C. H. Greene, et al., PRL 85, 2458 (2000); V. Bendkowsky et al., Nature 458, 1005 (2009) [3] J. B. Balewski, et al., Nature 502, 664 (2013)

Faculty Member for Research in an Undergraduate Institution Prize Talk: Research and Teaching through high-precision spectroscopy of heavy atomic and molecular systems for atomic-physics-based tests of standard model physics, through (for example) measurements of atomic parity nonconservation and searches for permanent electric dipole moments. The electric dipole moment of the electron provides a unique opportunity to precisely test the standard model, its fundamental symmetries and many proposed modifications. The SM predicts that the electron has an electric dipole moment (EDM), but that this moment should be much too small to be observed with current methods. In distinct contrast, supersymmetric and other models (proposed as improvements to the standard model!) predict that the electron could well have an EDM that is much, much larger. These disparate predictions have been tested for decades. In recent decades, substantial experimental effort has centered on heavy (high-Z) atomic and molecular systems for atomic-physics-based tests of standard model physics, through (for example) measurements of atomic parity nonconservation and searches for permanent electric dipole moments. In all of this work, a crucial role is played by atomic theorists, whose accurate wave function calculations are essential in connecting experimental observables to tests of relevant fundamental physics parameters. At Williams College, with essential contributions from dozens of undergraduate students, we have pursued a series of precise atomic structure measurements in heavy metal atoms such as thallium, indium, and lead. These include measurements of hyperfine structure, transition amplitudes, and atomic polarizability. This work has been recognized with several awards, including the award of the 2017 APS Medal for Exceptional Achievement in Research attests to the vitality of our field and its appreciation by the broad physics community. Having watched the research evolve over many decades, I will describe how a few of todays frontiers grew from tentative suggestions into flourishing fields of research. This talk is particularly aimed at newcomers who may be bewildered by the range of activities today and wonder how such things get started.

Deep Gupta, University of Washington

Deep Gupta Frontiers in Precision Measurements-Electric Dipole Moments 306-307 -

10:30AM B2.00001 ACME Measurement of the Electron Electric Dipole Moment, GERALD GABRIELSE, Harvard Physics Department — The standard model of particle physics (SM) is the great triumph and the great frustration of modern physics. The SM is able to correctly predict the measured size of the electron’s magnetic dipole moment to a remarkable 12 significant figures. At the same time, the SM predicts that essentially equal amounts of matter and antimatter should have been created in the big bang, and no explanation comes close to predicting the amount of matter that avoided being annihilated in collisions with the antimatter to form a matter universe. The electric dipole moment of the electron provides a unique opportunity to precisely test the standard model, its fundamental symmetries and many proposed modifications. The SM predicts that the electron has an electric dipole moment (EDM), but that this moment should be much too small to be observed with current methods. In distinct contrast, supersymmetric and other models (proposed as improvements to the standard model!) predict that the electron could well have an EDM that is much, much larger. These disparate predictions prompted our ACME collaboration to measure the electron electric dipole moment more than an order of magnitude more precisely than ever before. Despite the greatly increased sensitivity of this ACME generation 1 measurement, a non-zero EDM was not detected. Our order of magnitude lower limit has instead been used in many papers to set many limits — on the masses of postulated new particles, for example. It is worth noting that a measurement done with cold molecules is setting limits whose TeV energy reach is as high and higher than is possible at the largest particle accelerator — CERN’s Large Hadron Collider. New ACME apparatus and methods have recently been demonstrated that we expect to increase our EDM sensitivity by more than an additional order of magnitude. An ACME generation 2 measurement is now underway. An overview of the new methods and aspirations will be provided.

1Supported by the NSF
11:00AM B2.00002 Search for an Electric Dipole Moment (EDM) of $^{199}$Hg$^1$. BLAYNE HECKEL, University of Washington — The observation of a non-zero EDM of an atom or elementary particle, at current levels of experimental sensitivity, would imply CP violation beyond the CKM matrix of the standard model of particle physics. Additional sources of CP violation have been proposed to help explain the excess of matter over anti-matter in our universe and the magnitude of $\theta_{QCD}$, the strength of CP violation in the strong interaction, remains unknown. We have recently completed a set of measurements on the EDM of $^{199}$Hg, sensitive to both new sources of CP violation and $\theta_{QCD}$. The experiment compares the phase accumulated by precessing Hg spins in vapor cells with electric fields parallel and anti-parallel to a common magnetic field. Our new result represents a factor of 5 improvement over previous results. A description of the EDM experiment, data, systematic error considerations will be presented.

$^1$This work was supported by NSF Grant No. 1306743 and by the DOE Office of Nuclear Physics under Award No. DE-FG02-97ER41020.

11:30AM B2.00003 Towards a new generation of EDM experiments using molecules$^1$. DAVID DEMILLE, Yale University — Theories of particle physics that extend the Standard Model frequently predict new phenomena at the TeV scale. These phenomena give rise to electric dipole moments (EDMs) of fundamental particles such as the electron and proton that are within a few orders of magnitude of current limits. The observable effects of EDMs can be enhanced by 3 or more orders of magnitude by using molecules rather than atoms. This talk will describe recent advances in technology for cooling, manipulating, detecting, and trapping molecules that are opening the prospects for significant improvements in sensitivity to EDM-related effects. As an example, the CeNTREX experiment—a new search for the proton EDM and related effects—will be described.

$^1$Supported by Templeton Foundation and Heising-Simons Foundation

12:00PM B2.00004 Electric Dipole Moments: A Look Beyond the Standard Model$^1$. MICHAEL RAMSEY-MUSOLF, Univ of Mass - Amherst — Searches for the permanent electric dipole moments of atoms, nucleons, and nuclei provide one of the most powerful probes of CP-violation beyond the Standard Model. I survey the opportunities for discovering BSM CP-violation with the present and next generation EDM searches; discuss the complementary of searches using different systems; and highlight the implications of these searches for explaining the origin of the cosmic matter-antimatter asymmetry.

$^1$Supported in part by U.S. Department of Energy contract DE-SC0011095

Tuesday, June 6, 2017 10:30AM - 12:30PM

Session B3 Focus Session: Floquet Physics 308 - Trey Porto, Joint Quantum Institute, NIST and UMD

10:30AM B3.00001 Rigidity, Criticality and Prethermalization of Discrete Time Crystals. NORMAN YAO, UC Berkeley — Despite being forbidden in equilibrium, spontaneous breaking of time translation symmetry can occur in periodically driven, Floquet systems with discrete time-translation symmetry. The period of the resulting discrete time crystal (DTC) is quantized to an integer multiple of the drive period, arising from a combination of collective synchronization and many body localization. In this talk, I will describe a simple model for a one dimensional discrete time crystal which explicitly reveals the rigidity of the emergent oscillations as the drive is varied. I will analyze the properties of the dynamical phase transition where the time crystal melts into a trivial Floquet insulator. Effects of long-range interactions and pre-thermalization will be considered in the context of recent DTC realizations in trapped ions and solid-state spins.

11:00AM B3.00002 Probing the quantum limit of a chaotic system. JACKSON ANGONGA, ERIC MEIER, FANGZHAO AN, BRYCE GADWAY, Univ of Illinois - Urbana — The study of quantum chaos presents the opportunity to observe new and interesting phenomena. This work limit of a chaotic system. Our approach involves mapping the dynamics of a $^{87}$Rb condensate in a $(2J+1)$-site momentum-space lattice to those of an effective non-linear spin-J model. By performing spin rotations and squeezing operations we implement the quantum kicked top, a paradigmatic model for studying chaotic dynamics. We present linear entropy measurements as a probe of the quantum-classical crossover in our kicked top lattice. We also highlight, for a squeezing Hamiltonian, the first atomic quantum gas measurements of out-of-time ordered correlators, which serve both as signatures of quantum chaos and as a measure of information scrambling in complex quantum systems.

11:12AM B3.00003 Quantum Lyapunov Exponent of an Atomic Kicked Rotor$^1$. VICTOR GALITSKI, Joint Quantum Institute, University of Maryland — One of the most intriguing phenomena in the studies of classical chaos is the butterfly effect, which manifests itself in that small changes in initial conditions lead to drastically different trajectories. It is characterized by a Lyapunov exponent that measures divergence of the classical trajectories. The question how/if this prototypical effect of classical chaos theory generalizes to quantum systems (where the notion of a trajectory is undefined) has been of interest for decades, but became more popular recently, when it was realized that there exist intriguing connections to string theory and general relativity in some quantum chaotic models. At the center of this activity is the so-called out-of-time-ordered correlator (OTOC) - a quantity that in the classical limit seems to approximate the classical Lyapunov correlator. However, there are very few solvable models where one can actually calculate Lyapunov exponent and/or OTOC. In this talk, I will discuss the standard model of quantum and classical chaos - kicked rotor - calculate the correlator and Lyapunov exponents, and show how classical chaos and Lyapunov divergence develop and cross-over to the quantum regime. We will see that the quantum out-of-time-ordered correlator exhibits a clear singularity at the Ehrenfest time, when quantum interference effects sharply kick in: transitioning from a time-independent value to its monotonous decrease with time. In conclusion, I will discuss possible experimental realizations of the model and predicted phenomena in ultracold quantum kicked rotors.

$^1$NSF-DMR 1613029 and US-ARO
11:42AM B3.00004 Floquet engineering of unconventional Hubbard terms and heating timescales in an interacting fermionic system. FREDERIK GORG, MICHAEL MESSER, GREGOR JOTZU, KILIAN SANDHOLZER, RMI DESBUQUOIS, TILMAN ESSLINGER, Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland — Periodically modulated systems have recently attracted much interest both from a theoretical and experimental perspective, since they can be used to create novel effective Hamiltonians which feature terms that are not accessible in static systems. In this context, we experimentally demonstrate how Floquet engineering can be used to create unconventional Hubbard terms for interacting Fermions in an optical lattice. By modulating the lattice position at a frequency close to the interaction energy of a two-body system, we can tune both the sign and magnitude of the magnetic exchange energy independently of the single particle tunneling. An open question in this context is if experimental heating timescales are favorable enough to study driven interacting many-body systems. To investigate this problem, we measure spin-spin correlations in a shaken three dimensional lattice and directly compare them to an equivalent static configuration. In addition, we perform a detailed heating study by measuring the lifetime of magnetic correlations as a function of the driving parameters.

11:54AM B3.00005 Observation of discrete time-crystalline order in a disordered dipolar many-body system. SOONWON CHOI, JOONHEE CHOI, RENATE LANDIG, GEORG KUCSKO, HENGYUN ZHOU, Harvard Univ, JUNICHI ISOYA, University of Tsukuba, FEDOR JELEZKO, Ulm University, SHINOBU ONODA, Takasaki Advanced Radiation Research Institute, HITOSHI SUMIYA, Sumitomo Electric Industries Ltd., VEDIKA KHEMANI, Harvard Univ, CURT VON KEYSERLINGK, Princeton University, NAM YON, University of California Berkeley, EUGENE DEMLER, MIKAHIL LUKIN, Harvard Univ — The interplay of periodic driving, disorder, and strong interactions has recently been predicted to result in exotic “time crystalline phases, which spontaneously break the discrete time translation symmetry of the underlying drive. Here, we report the experimental observation of such discrete time crystalline order in a driven, disordered ensemble of dipolar spin impurities in diamond at room temperature. We observe long lived temporal correlations at integer multiples of the fundamental driving period, experimentally identify the phase boundary and find that the temporal order is protected by strong interactions; this order is remarkably stable against perturbations, even in the presence of slow thermalization. We provide a theoretical description of approximate Floquet eigenstates of the system based on product state ansatz and predict the phase boundary, which is in qualitative agreement with our observations. Our work opens the door to exploring dynamical phases of matter and controlling interacting, disordered many body systems.

1NSF, CUA, NSSEFF, ARO MURI, Moore Foundation

12:06PM B3.00006 Emergent Floquet states in strongly-driven optical lattices. ZACHARY GEIGER, KURT FUJIIWARA, KEVIN SINGH, RUVAN SENARATNE, SHANKARI RAJAGOPAL, MIKHAIL LIPATOV, DAVID WELD, University of California, Santa Barbara — We report on progress toward experimental observation of an emergent state of matter using ultracold lithium in an amplitude-modulated optical lattice. In the presence of very strong (sign-changing) modulation in a specific frequency range, a dynamically stable state emerges which can be understood as a direct quantum-mechanical analogue of the classical Kapitza pendulum. Realization of such a state provides an experimental context in which the effects of tunneling and tunable interactions on Floquet phases of matter can be controllably explored.

1Army Research Office, National Science Foundation

12:18PM B3.00007 Mott Time Crystal: Models and Realizations in Cold Atoms. BIAO HUANG, Department of Physics and Astronomy, Univ of Pittsburgh, Pittsburgh PA 15260, USA, YING-HAI WU, Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany, W VINCENT LIU, Department of Physics and Astronomy, Univ of Pittsburgh, Pittsburgh PA 15260, USA — Time crystals, a phase showing spontaneously breaking of time-translation symmetry, has been an intriguing subject for systems far away from equilibrium. Recent experiments found such a phase both in the presence and absence of localization, while in theories localization is usually assumed a priori. In this work, we point out that time crystals can generally exist in systems without disorder and is not in a pre-thermal state. A series of driven interacting ladder models are proposed to demonstrate this unexpected result in principle. Robust time crystalline orders are found in the Mott regime due to the emergent integrals of motion in the dynamical system, which can be characterized by the out-of-time-order correlators (OTOC). We propose two cold atom experimental schemes to realize the Mott time crystals, one by making use of dipolar gases and another by synthetic dimensions.

1U.S. ARO (W911NF-11- 1-0230), AFOSR (FA9550-16-1-0006)

Tuesday, June 6, 2017 10:30AM - 12:30PM — Session B4 Photoassociation and Chemical Reaction of Molecules 309 - Paul Lett, JQI/NIST

10:30AM B4.00001 Microwave dressing of ultracold $^{23}$Na$^{40}$K molecules. ZOE YAN, YIQI NI, JEE-WOO PARK, SEBASTIAN WILL, HUANQIAN LOH, Massachusetts Institute of Technology, KANG KUEN NI, Harvard University, MARTIN ZWIERLEIN, Massachusetts Institute of Technology — Ultrasound molecules with tunable dipolar interactions are a promising platform for quantum simulation and the creation of novel states of matter. Previously, we have demonstrated the creation of a spin-polarized ensemble of fermionic $^{23}$Na$^{40}$K molecules in their rovibrionic and hyperfine ground state. One way to induce strong dipole moments is microwave dressing, which has been proposed to allow shielding of inelastic collisions and the realization of topological superfluids. By applying microwave fields near the frequency of the transition to the first rotationally excited state, we can induce an oscillatory dipole moment of up to 1.1 Debye in the molecules. We characterize this microwave dressing via the Autler-Townes splitting it induces in a rotational transition. We will present recent work exploring how microwave dressing affects the collision rate in the molecular gas.

10:42AM B4.00002 Dipolar collisions of ultracold $^{23}$Na$^{87}$Rb molecules. MINGYANG GUO, XIN YE, JUNYU HE, Chinese Univ of Hong Kong, GOULVEN QUMNER, MAYKEL GONZLEZ-MARTNEZ, OLIVIER DULIEU, Laboratoire Aim Cotton,CNRS, DAJUN WANG, Chinese Univ of Hong Kong — Although ultracold polar molecules have long been proposed as a primary candidate for investigating dipolar many body physics, many of their basic properties, like their collisions in external electric fields, are still largely unknown. In fact, despite the successful production of several new ultracold molecular species in the last two years, so far the only available dipolar collision data is still from JILA’s fermionic $^{40}$K$^{87}$Rb experiment in 2010. In this talk, we will describe our investigation on dipolar collisions of ultracold bosonic and chemically stable $^{23}$Na$^{87}$Rb molecules which possess a large permanent electric dipole moment. With a moderate electric field, an effective dipole moment large enough to strongly couple higher partial waves into the collisions can be achieved. We will report the influence of this effect on the molecular collisions observed in our experiment. Our theoretical model for understanding these observations will also be presented.

1This work is supported by the Hong Kong RGC CUHK404712 and the ANR/RGC Joint Research Scheme ACMHK403/13.
10:54AM B4.00003 Collisions of ultracold $^{23}$Na$^{87}$Rb molecules with controlled chemical reactivity$^1$. XIN YE, MINGYANG GUO, JUNYU HE, DAIJUN WANG, Chinese Univ of Hong Kong, GOULVEN QUEMENER, MAYKEL GONZALEZ-MARTINEZ, OLIVER DULIEU, Laboratoire Aime Cotton, CNRS — The recent successful creation of several ultracold absolute ground-state polar molecules without chemical reaction channel has opened a new playground for investigating the so far poorly understood collisions between them. On one hand, these collisions are indispensable for the exploration of dipolar physics, on the other hand, they are direct manifestations of the brand-new field of ultracold chemistry. Here, we report on the study of molecular collisions with ultracold ground-state $^{23}$Na$^{87}$Rb molecules prepared by transferring weakly bound Feshbach molecules with STIRAP. By tuning the Raman laser wavelength to control the internal states, samples with distinctly different chemical reactivity and inelastic channels can be prepared. Surprisingly, we found that the trap loss of the non-reactive case is nearly identical to that of the reactive case. We also developed a model based on the collision complex formation mechanism. The comparison between experiment and theory will also be presented.

$^1$This work was supported by the French ANR/Hong Kong RGC COPOMOL project (grant no. A-CUHK403/13), the RGC General Research Fund (grant no. CUHK14301815)

11:18AM B4.00005 Photoassociation of cold (RbCs)$_2$ tetramers in the ground electronic state$^1$. MARKO GACESA, NASA ARC, ROBIN CÔTÉ, University of Connecticut — We theoretically investigate prospects for photoassociative formation of cold (RbCs)$_2$ tetramers from a pair of ultracold RbCs molecules. The long-range region of the potential energy surface (PES) of the lowest electronic state of (RbCs)$_2$ can be affected by orienting both RbCs molecules by an external electric field. In fact, we find a long-range barrier that supports long-range shelf states for relative angles between the dimers' internuclear axes smaller than about 20°. We show that these shelf states can be populated by spontaneous decay from the first excited electronic state which can be efficiently populated by photoassociation from the scattering continuum at ultracold temperatures. The vibrationally excited ground-state tetramer molecules formed this way have sufficiently long lifetimes to allow experimental detection. Moreover, for the relative angles between the dimers close to 20°, the proposed approach may result in production of deeply bound tetramers.

$^1$Partially supported by the NASA Postdoctoral Program at the NASA Ames Research Center, administered by USRA and the MURI US Army Research Office Grant No.W911NF-14-1-0378 (MG), and by the PIF program of the National Science Foundation Grant No. PHY-141556.

11:30AM B4.00006 Short-range photoassociation of LiRb$^1$. DAVID BLASING, IAN STEVENSON, Purdue University, JESS PREZ-ROS, None, DANIEL ELLIOTT, YONG CHEN, Purdue University — We have observed short-range photoassociation of $^7$Li$^{85}$Rb to the two lowest vibrational states of the $^3$II potential. We have also observed several $^3\Sigma^+$ vibrational levels with generation rates between $\sim 10^2$ and $\sim 10^3$ molecules per second, resulting from the spontaneous decay of these $^3$II molecules. This is the first observation of many of these $^3\Sigma^+$ levels. We observe an alternation of the peak heights in the rotational photoassociation spectrum that depends on the parity of the excited molecular state. Franck-Condon overlap calculations predict that photoassociation to higher vibrational levels of the $^3$II, in particular the sixth vibrational level, should populate the lowest vibrational level of the $^3\Sigma^+$ state with a rate as high as $10^3$ molecules per second. This work also motivates an experimental search for short-range photoassociation to other bound molecules, such as the $^3\Sigma^+$ or $^3$II, as prospects for preparing ground-state molecules.

$^1$The experimental work was funded by the Purdue Office of the Vice President for Research AMO Incentive Grant 206732 and J.P.-R. acknowledges support from NSF Grant No. PHY-130690.

11:42AM B4.00007 Direct photoassociation of halo molecules in ultracold $^{86}$Sr$^{1+}$. J. A. AMAN, JOSHUA HILL, T. C. KILLIAN, Rice Univ — We investigate the creation of $^1$S$_0+^1$S$_0$ halo molecules in stronitum 86 through direct photoassociation in an optical dipole trap. We drive two photon Raman transitions near-resonance with a molecular level of the $^1$S$_0+^3P_1$ interatomic potential as the intermediate state. This provides large Franck-Condon factors and allows us to observe resonances for the creation of halo molecules through higher order Raman processes. The halo molecule is bound by $E_B \approx 85$ kHz at low excitation-laser intensity, but experiments show large AC Stark shifts of the molecular binding energy. These conditions suggest that STIRAP should be very effective for improving molecular conversion efficiency. Further experiments in a 3D lattice will explore molecular lifetimes and collision rates.

$^1$Travel support provided by Shell Corporation

11:54AM B4.00008 Continuous Production of Rovibronic Ground State RbCs Molecules via Short-Range Photoassociation to the $^3\Sigma^+$, $^3\Pi^+$, and $^3\Pi^0$ states. TOSHIHIKO SHIMASAKI, Dept. of Physics, Yale Univ., USA, JIN-TAE KIM, Dept. of Photonics Eng., Chosun Univ., Korea, YUQI ZHU, DAVID DEMILLE, Dept. of Physics, Yale Univ., USA — Electronic states with strong singlet-triplet mixing can be useful for efficient direct molecule production in the rovibronic ground state via short-range photoassociation (PA). We have observed rovibronic levels of the strongly mixed $^3\Pi^0(\Omega = 1)$, $^3\Sigma^+(\Omega = 0^-$ and 1), and $^3\Pi^+(\Omega = 0^-, 0^+, 1^1)$ and 1) states of $^{85}$Rb$^{133}$Cs in the energy range of 13950 - 14200 cm$^{-1}$ using short-range PA. For selected PA states, vibrational branching and rotational branching in the $^3\Sigma^+(v = 0)$ state have been investigated using resonance-enhanced multiphoton ionization and depletion spectroscopy [1], respectively. Efficient production of the rovibronic ground state $^3\Sigma^+(v = 0, J = 0)$ has been observed for some of the PA states in this energy range. Molecule production rate up to $\sim 1\times 10^4$ molecules/s into the rovibronic ground state has been achieved, which is a factor of 5 improvement compared to previously observed PA states [2].

12:06PM B4.00009 Ultracold atom-molecular ion systems: a photo-assisted spin-dependent polyatomic molecular reaction1. JONEL SIMBOTIN, JOHN A. MONTGOMERY, JR., ROBIN CÔTÉ, Department of Physics, University of Connecticut, Storrs — In recent years, rapid progress in cooling and trapping of hybrid atom-ion systems has led to studies of atom-ion processes. These range from charge transfer, recombination, internal state conversion, to the possibility of changing cross sections and corresponding rates with tunable Feshbach resonances. A recent experiment from the group of Eric Hudson at UCLA explored how ultracold Ca atoms interact with a trapped polyatomic molecular ion, namely BaOCH2. We computed stationary points of the potential energy surface (PES) for this complex system, and reaction paths for different spin states, and found that a large barrier prevents the reaction to form BaOCa1 and CH3 in the singlet channel. We also found a barrier corresponding to a transition state for the triplet channel corresponding asymptotically to Ca(P2)++BaOCH2, but low enough to allow reactions. We computed reaction rates based on a Langevin model, taking into account the different J values of the initial 1P(3) state of Ca, and found that this photo-assisted reaction depends not only on the singlet/triplet spin state, but also on the fine structure of the initial reactants.

1This work is partially funded by the MURI US Army Research Office Grant No. W911NF-14-1-0378.

12:18PM B4.00010 Formation of ultracold molecules induced by a high-power single frequency fiber laser1. HENRY FERNÁNDEZ PASSAGEM, RICARDO COLIN-RODRÍGUEZ, PAULO VENTURA DA SILVA, University of Sao Paulo, NADIA BOULOUFA-MAAFA, OLIVIER DULIEU, Université Paris-Sud, LIUS MARCASSA, University of Sao Paulo — Photoassociation of a pair of ultracold atoms is a quite simple and rapid approach for cold molecule formation. The main limitation of PA is that the latter step is incoherent, so that the population of the created molecules is spread over many vibrational levels with weak or moderate binding energies. If the excited electronic molecular state exhibits a peculiar feature at short internuclear distance like a potential barrier or an avoided crossing, the population of deeply-bound ground state levels may be significantly enhanced. In this work, the influence of a high-power single frequency fiber laser on the formation of ultracold 85Rb2 molecules is investigated as a function of its frequency (in the 1062-1070 nm range) in a magneto optical trap. We found evidence for the formation of ground state 85Rb2 molecules in low vibrational levels (v ≤ 20) with a maximal rate of 104 s−1, induced by short-range photoassociation by the fiber laser followed by spontaneous emission. When this laser is used to set up a dipole trap, we measure an atomic loss rate at a wavelength far from the PA resonances only 4 times smaller than the one observed at a PA resonance wavelength. This work may have important consequences for atom trapping using lasers around 1060 nm.

1This work is supported by grants 2013/02816-8 and 2014/24479-6, Sao Paulo Research Foundation (FAPESP).

Tuesday, June 6, 2017 10:30AM - 12:30PM – Session B5 Atomic and Molecular Structure

10:30AM B5.00001 Closed-channel fraction of a strongly interacting Fermi Gas. XIANG-PEI LIU, HAO-ZE CHEN, XING-CAN YAO, XIAO-QIONG WANG, YU-XUAN WANG, YU-PING WU, University of Science and Technology of China, QI-JIN CHEN, ZHEJIANG University, YU-AO CHEN, JIAN-WEI PAN, University of Science and Technology of China — Near a Feshbach resonance, the many-body state of paired atoms is the so-called dressed molecule which can be understood as a linear combination of open-channel atom pairs and closed-channel bare molecules. The closed-channel fraction plays a crucial role in the description of the BEC-BCS crossover since it quantifies the mixing between the atom pairs and the bare molecules. In this presentation, I will show the experimental procedure for producing of large degenerate Fermi gas. With advanced laser cooling and sympathetic cooling, we are able to obtain a maximum molecule number of 3101 at Τ/Tc ~ 0.06. The low temperature and large atom number allow us to study the closed-channel fraction over a wide parametric range (scattering length, fermi momentum and temperature). With a molecule probe laser, we are able to extract the closed-channel fraction in the BEC-BCS crossover. Experimental results show a good agreement with the prediction of two-channel model.

10:42AM B5.00002 Weak values of spin and momentum in atomic systems.1. ROBERT FLACK, BASIL HILEY, PETER BARKER, VINCENZO MONACHELLO, JOEL MORLEY, University College London — Weak values have a long history and were first considered by Landau and London in connection with superfluids. Hirschfelder called them sub-observables and Dirac anticipated them when discussing non-commutative geometry in quantum mechanics. The idea of a weak value has returned to prominence due to Aharonov, Albert and Vaidman showing how they can be measured. They are not eigenvalues of the system and can not be measured by a collapse of the wave function with the traditional Von Neumann (strong) measurement which is a single stage process. In contrast the weak measurement process has three stages; preselection, weak stage and finally a post selection. Although weak values have been observed using photons and neutrons, we are building two experiments to observe weak values of spin and momentum in atomic systems. For spin we are following the method outlined by Duck et al which is a variant on the original Stern-Gerlach experiment using a metastable, 2+1S1, form of helium. For momentum we are using a method similar to that used by Kocsis with excited argon atoms in the 3P2 state, passing through a 2-slit interferometer. The design, simulation and re

1. John Fetzer Memorial Trust

10:54AM B5.00003 Finding frustrations and topological phases in a quasi-1D zig-zag chain of dipoles. NIRAJ R. GHIMIRE, SUSANNE F. YELIN, Univ of Connecticut - Storrs — The goal is to investigate frustrations that lead to interesting phases in a one-dimensional zig-zag chain of dipoles. This type of system could potentially be modeled by ultracold polaron molecules, and be extended such that topological quantities in triangular or hexagonal lattices can be studied. To do so, we take into account the nearest-neighbor (NN) and next-nearest-neighbor (NNN) hopping and interactions and find the ground state of the spin S = 1/2 model by using the Density Matrix Renormalization Group (DMRG) method.

11:06AM B5.00004 Non-Perturbative Calculation and Measurement of Strong Light Shifts with Floquet Theory. SIMON COOP, SILVANA PALACIOS, PAU GOMEZ, MORGAN W. MITCHELL, ICF-FO.The Institute of Photonic Sciences — We describe a new theory for calculating atomic light shifts (ac Stark shifts) using Floquet’s theorem, and we present spectroscopic data verifying our calculations. The theory remains accurate in the presence of strong level-mixing where the shifts are larger than the hyperfine splitting, and can quantitatively describe shifts due to multiple wavelengths with arbitrary polarization. As the theory can be used to accurately predict large nonlinear shifts, it could be useful for measuring electric-dipole matrix elements. This has implications for optical clocks, tests of atomic structure calculations, and fundamental atomic physics. This theory could also be useful for site-dependent state preparation in quantum simulators, and general experiment design and characterization.
11:18AM B5.00005 Developing Potential Energy Curves of Acidic and Basic Amino Acids Using Quantum Computational Techniques , C.P. DE GUZMAN, M. ANDRIANARIJAONA, Y. YOSHIDA, K. KIM, V.M. ANDRIANARIJAONA, Department of Physics, Pacific Union College, Angwin, CA 94508 — Proteins are made out of long chains of amino acids and are an integral part of many tasks of a cell. Because the function of a protein is caused by its structure, even minute changes in the molecular geometry of the protein can have large effects on how the protein can be used. This study investigated how manipulations in the structure of acidic and basic amino acids affected their potential energy. Acidic and basic amino acids were chosen because prior studies have suggested that these amino acids can be very influential on a molecule’s preferred conformation. Each atom in the molecule was pulled along x, y, and z axis to see how different types of changes affect the potential energy of the whole structure. The results of our calculations, which were done using ORCA, emphasize the vibronic couplings. The aggregated data was used to create a data set of potential energy curves to better understand the quantum dynamic properties of acidic and basic amino acids (preliminary data was presented in http://meetings.aps.org/Meeting/MAR16/Session/M1.273 and http://meetings.aps.org/Meeting/FWS16/Session/F2.6).

11:30AM B5.00006 Topological spin-charge separation in one dimensional optical superlattices , HAIPING HU, CHUANWEI ZHANG, The University of Texas at Dallas — Spin-charge separation is a hallmark phenomenon of 1D strongly interacting systems. However, whether spin and charge excitations in strong interacting region can possess non-trivial topological properties has not been explored. Here we show that topological spin-charge separation can be realized using ultracold fermions in a 1D optical superlattice. We demonstrate the emergence of topological magnetic excitations in a wide interaction regime through numerical density matrix renormalization group (DMRG) study. Such topological states are protected by a finite magnon excitation gap and characterized by gapless magnon edge state excitations. The magnon excitations can be quantized pumped between edges by adiabatically tuning the superlattice phases, realizing topological magnon pumping.

11:42AM B5.00007 Spectroscopic studies of the ground state dissociation energy and isotope shift of NaD1. CHIN-CHUN TSAI, Department of Physics, National Cheng-Kung University, Tainan, Taiwan, CHIA-CHING CHU, YIN-JI LI, RONG-SIN LIN, WEI-FUNG HE, THOU-JEN WHANG, Department of Chemistry, National Cheng-Kung University, Tainan, Taiwan — We report a spectroscopic measurement of the NaD X1Σ+ ground state dissociation energy and its isotope shift. Stimulated emission pumping with fluorescence depletion spectroscopy is applied to measure the rovibrational levels of the near-dissociation region. A total of 230 rovibrational levels in the range of 9 ≤ v′′ ≤ 29 and 1 ≤ J′′ ≤ 11 are observed and the highest vibrational level v′′ = 29 is about 50 cm−1 to the dissociation limit. Analyzing the highest 5 vibrational levels yields the dissociation energy D0 = 15822 ± 5 cm−1 with v0P = 31.2 ± 0.1. With our previous study, we are able to determine the difference in the well depths of this isotopologues, D0 = D0(NaH) − D0(NaD) = −7 cm−1.

1This work is supported by the Ministry of Science and Technology, Taiwan.

11:54AM B5.00008 Proposal of a Robust Quantum Switch with Rydberg excitations1, JING QIAN, Department of Physics, School of Physics and Material Science, East China Normal University, Shanghai 200062, People’s Republic of China, DEPARTMENT OF PHYSICS, SCHOOL OF PHYSICS AND MATERIAL SCIENCE TEAM — Depending on a Y-type level configuration of atoms, we develop a scheme of efficiently switching Rydberg excitations between two Rydberg states via opening or closing the intrastate interaction on the strongly-coupled Rydberg state (the other Rydberg state is weakly-coupled). When such interaction is open, a large number of atoms will be counterintuitively excited to the weakly-coupled state, rather than the strongly-coupled state as in the case of that interaction is closed. By systematically investigating relevant parameters we find the scheme is quite robust and very insensitive to the intrastate interaction on the weakly-coupled state, the spontaneous decay rate of middle excited state, and the duration time of conversion. Moreover, we simulate a switching cycle under realistic experimental parameters and find the single Rydberg excitations can indeed be switched in which the switch efficiency reaches as high as 0.92. This scheme may serve as a new route to the selective excitations with multiple Rydberg states, enabling new applications in developing various quantum devices.

1This work is supported by the NSFC under Grants No. 11474094, No. 11104076, the Specialized Research Fund for the Doctoral Program of Higher Education No. 20110076120004.

12:06PM B5.00009 On the computations of decay widths of Fano resonances1, TSVETA MITEVA, SÉVAN KAZANDJIAN, NICOLAS SISOURAT, Université Pierre et Marie Curie, Paris — We present a novel approach to the calculation of decay widths of Fano resonances in singly-ionized systems. In our approach, the bound part of the resonance is approximated at the zeroth order as a one-hole configuration. The final states of the decay are obtained after diagonalization of the Hamiltonian matrix in the space of all two-hole-one-particle (2h1p) configurations with a fixed virtual orbital. The Fano-CI method can be applied to the computation of both total and partial decay widths. Furthermore, it has fairly low computational costs and can thus be employed for investigating medium-sized atomic and molecular systems. To check the validity of our method, we carried out benchmark calculations of Auger and ICD widths of small rare-gas and hydrogen-bonded clusters. Comparison with available theoretical and experimental data shows that a satisfactory estimate of the atomic and molecular systems. To check the validity of our method, we carried out benchmark calculations of Auger and ICD widths of small rare-gas and hydrogen-bonded clusters. Comparison with available theoretical and experimental data shows that a satisfactory estimate of the decay width can be achieved with a relatively small basis set, which is of importance for the application of the method to larger systems. [1] [1] T. Miteva, S. Kazandjian and N. Sisourat, accepted in Chem. Phys. (2016)

1European Unions Horizon 2020 research and innovation programme Grant agreement No 705515

12:18PM B5.00010 Focusing of Rydberg Ps atoms using an electrostatic mirror with minimal chromatic aberration1, ADRIAN JONES, J. MOXOM, H. J. RUTTENBERG-GOLDMAN, K. A. OSORNO, G. CECCHINI, M. FUENTES-GARCIA, D. J. ADAMS, R. G. GREAVES, H. W. K. TOM, A. P. MILLS, JR., Univ of California - Riverside — We present experimental measurements demonstrating the electrostatic focusing of point source of Rydberg Ps atoms to a 30 mm spot on a position sensitive detector 6 m away, using a novel mirror design that is very nearly free of chromatic aberrations. The mirror is composed of 360 wires, 1 mm in diameter, arranged to form a truncated oblate cylindrical surface. Alternating positive and negative potentials are applied to neighboring wires, producing a radial electric field ≤ 105 V/m which diminishes exponentially. We see an increase in the signal rate of a factor of 7 ± 1, about 2.8 times smaller than the geometric ratio of the mirror collection area to that of the detector. This apparent deviation from the expected efficiency is understood to result from two systematic effects: (1) the angular range of excitation accessible with the UV laser bandwidth on resonance, and (2) the difficulty in producing Rydberg Ps in low-field seeking Stark states (i.e., those of k > 0). Using a mirror of similar design with an optical quality finish, it would be possible to make a measurement of the gravitational deflection of antimatter in Earth’s field to a precision of about 1%.

1Work supported by NSF grants PHY 1404576 & PHY 1505903
10:30AM B6.00001 Interplay of classical and quantum dynamics in an ensemble of hot atoms1, ARIF LASKAR, NIHARIKA SINGH, ARUNABH MUKHERJEE, SAIKAT GHOSH, Indian Inst of Tech-Kanpur — When a transparent window opens up for a probe light, transmitted through a resonant thermal ensemble of atomic system driven by a strong classical field, how much of it is actually due to quantum superposition of states and how it develops in the midst of classical processes like optical pumping and thermal diffusion? Here we address these questions by stroboscopically probing a closed Λ-like atomic system in a Rbodium vapor cell, driven by coherent and incoherent field, with a 100 ns probe pulse. Time evolution of transmitted probe peak shows an overshoot with turn-on of control, indicating signatures of lasing without inversion. Corresponding rise time is controlled by the driven field with a distinct signature of half cycle Rabi flop. Then optical pumping process leads to a steady state over a longer time scale, that sustain the dark state, which usually probed in EIT like spectrum. Potential turning-off of control leads to sudden fall in transmission, which carry a unique signature to quantify close and open system, and in particular, induced coherence in the system. We use detailed numerical simulation and toy models to explain our observations and support our claims. We believe our results can provide a metric for testing competing quantum or classical hypothesis.

1IIT-K(Initiation grant) and DST-SERB(SB/2/LOP-05/2013)

10:42AM B6.00002 Polarization control of spontaneous emission for rapid quantum state initialization1, CHITRA RANGAN, CHRISTOPHER DILORETO, University of Windsor — The practical implementation of quantum computers places two specific requirements on the lifetime of a qubit, namely, long relevant decoherence times, and rapid state initialization times. There is a need for protocols wherein the spontaneous emission rate of a quantum system can be selectively increased so that long state lifetimes can be maintained during operation, and upon demand, selectively decreased so that the cooling time can be drastically reduced. We present an efficient method to selectively enhance the spontaneous emission rate of a quantum system by changing the polarization of an incident control field and exploiting an accidental control field, and changing the polarization dependence of the system’s spontaneous emission rate. This differs from the usual Purcell enhancement of spontaneous emission rates as it can be selectively turned on and off. Using a three-level Λ system in a quantum dot placed in between two silver nanoparticles and a linearly-polarized, monochromatic driving field, we present a protocol for rapid quantum state initialization; while maintaining long coherence times for control operations. This process increases the overall amount of time that a quantum system can be effectively utilized for quantum operations.

1We gratefully acknowledge support from the Discovery Grant program of the Natural Sciences and Engineering Research Council of Canada. Computations were performed on the Sharncnet supercomputing cluster.

10:54AM B6.00003 Preparation of a single highly vibrationally excited quantum state using Stark induced adiabatic Raman passage1, WILLIAM PEREAULT, NANDINI MUKHERJEE, RICHARD ZARE, Stanford Univ — Stark induced adiabatic Raman passage (SARP) allows us to prepare an appreciable concentration of isolated molecules in a specific highly excited vibrational level. As a demonstration, we transfer nearly 100% of the HD (v=0, J=0) in a supersonically expanded molecular beam of HD molecules to HD (v=4, J=0). This is achieved with a sequence of partially overlapping nanosecond pump (355 nm) and Stokes (680 nm) single-mode laser pulses of unequal intensities. The experimental spectral broadening with pump to Stokes delay and saturation against Stokes power suggest that complete population transfer has been achieved from the initial HD (v=0, J=0) to the target (v=4, J=0). By comparing our experimental data with our theoretical calculations we are able to draw two important conclusions: (1) using SARP a large population (>1011 molecules per laser pulse) is prepared in the (v=4, J=0) level of HD, and (2) the polarizability of HD is reduced by a factor of 5 to 10 for the (v=0, J=0) Raman overtone transition is only about five times smaller than for the (v=0, J=0) to (v=1, J=0) fundamental Raman transition. This capability of preparing selected, highly vibrationally excited quantum states of molecules opens new opportunities for fundamental scattering experiments.

1This work has been supported by the Army Research Office under ARO Grant No. W911NF-16-1-1061, and by the Natural Sciences and Engineering Research Council of Canada.

11:06AM B6.00004 Four-Photon Stark Induced Ladder Climbing Prepares Large Ensemble of H2 in Selected High Lying Vibration Levels1, NANDINI MUKHERJEE, WILLIAM PEREAULT, RICHARD ZARE, Stanford Univ — To selectively prepare highly vibrationally excited quantum states of molecules like H2, we present a novel multi-photon ladder-climbing technique where the successive rungs of the ladder are connected by Stark-induced adiabatic Raman passage (SARP). Previously, we have demonstrated that SARP achieves complete population transfer from the v=0 to the v=1 and v=4 levels of H2. We show here that SARP can be generalized into a continuously coupled, multiphoton adiabatic passage which uses one or more intermediate states having strong Raman coupling to access highly vibrationally excited states weakly coupled to the ground state. As an example, we consider the case of four-photon coherent excitation to high vibrational levels of H2 via an intermediate level coupled to both the initial and target levels by two-photon SARP. Using a sequence of commercially available single mode, nanosecond lasers, a pump pulse partially overlapping with two Stokes pulses, we show that the complete population of v=0 can be selectively transferred to the most weakly coupled v=6 and v=9 vibrational levels of H2, without leaving any population stranded in the intermediate level. The present method provides a practical way of generating an entangled pair of fragments without resorting to an ultracold system.

1This work has been supported by US Army Research Office under ARO Grant No. W911NF-16-1-1061

11:30AM B6.00006 Coherent and simultaneous addressing of individual atoms in a 1D Optical Lattice, HYOK SANG HAN, HYUN GYUNG LEE, SEOKCHAN YOON, D. CHO, Korea Univ — Coherent addressing and independent control of individual atoms are key elements for the lattice-based quantum computing. While recent approaches using a focused addressing laser beam enables a fast and high-fidelity addressing of individual atoms, the process is inevitably sequential for independent control of multiple qubits. On the other hand, when individual atoms are addressed by a position-dependent Zeeman shift, a simultaneous addressing is possible because each atom has a distinct identity. In previous experiments, however, use of large B-gradient to overcome an inhomogeneous broadening due to differential ac-Stark shift complicated the noise control and hindered the coherent addressing. Instead of using a large B-gradient, we reduce the linewidth down to the Fourier limit by using “magic polarization” that removes the trap-induced differential shift. In our demonstration, single 7Li atoms in a 1D lattice with 532-nm spacing are resolved in RF domain with the nearest-site resolution preserving long coherence. Moreover, two adjacent atoms are simultaneously addressed and controlled independently, paving the way for a more generalized parallel processing of multiple qubits.
photoionization studies of atoms and molecules with shaped laser pulses [1,2] and XUV [3], metrology schemes using Angle-Resolved RABBIT, interest, for example: (a) dynamical process in time-resolved measurements, such as rotational, vibrational and electronic wavepackets, and understanding of photoionization [1]. At a more complex level, such measurements can also provide a powerful probe for other processes of photoelectron spectra: metrology schemes making use of these interferograms are thus phase-sensitive, and provide a powerful route to detailed Council of Canada — Photoionization is an interferometric process, in which multiple paths can contribute to the final continuum photoelectron traversing a CI to control the shape of the wavepacket.

This work was supported by the National Science Foundation under Grant No. PHY-0649578, the DOE SCGSR fellowship program, and the DOE, Office of Science, BES, Chemical Sciences, Geosciences, and Biosciences Division.

12:06PM B6.00009 Doppler-free spectroscopy of the atomic rubidium fine structure using ultrafast spatial coherent control method1, MINHYUK KIM, KYUNGTAE KIM, WOOJUN LEE, HYOSUB KIM, JAEWOOK AHN, KAIST — Spectral programming solutions for the ultrafast spatial coherent control (USCC) method to resolve the fine-structure energy levels of atomic rubidium are reported. In USCC, a pair of counter-propagating ultrashort laser pulses are programmed to make a two-photon excitation pattern specific to particular transition pathways and atom species, thus allowing the involved transitions resolvable in space simultaneously. With a proper spectral phase and amplitude modulation, USCC has been also demonstrated for the systems with many intermediate energy levels. Pushing the limit of system complexity even further, we show here an experimental demonstration of the rubidium fine-structure excitation pattern resolvable by USCC. The spectral programming solution for the given USCC is achieved by combining a double-V-shape spectral phase function and a set of phase steps, where the former distinguishes the fine structure and the latter prevents resonant transitions. The experimental results will be presented along with its application in conjunction with the Doppler-free frequency-comb spectroscopy for rubidium hyperfine structure measurements.

1Samsung Science and Technology Foundation [SSTFB1301-12]
12:00PM B7.00004 Do nuclei move on an attosecond timescale in strong-field photodissociation?1, B.D. ESRY, J.R. Macdonald Laboratory, Kansas State University — Without the ready availability of single attosecond pulses with sufficient energy to perform pump-probe experiments, the push to measure electronic dynamics on its natural timescale of attoseconds has enlisted less direct measurements. Photoionization “time delays”, in particular, have been measured and calculated to be on the attosecond timescale and thus have attracted considerable attention. The ultimate goal of such attosecond-scale measurements is the molecular movie— i.e., making movies of the electronic motion during chemical reactions. It has been universally assumed, however, that any measured attosecond timescales in observables relate exclusively to electronic dynamics, even during a reaction which necessarily includes nuclear motion. I will explore some of the limits of this assumption and highlight a few specific cases where it fails, emphasizing in the process that phases should be favored over “time delays”.

1Supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy

Tuesday, June 6, 2017 10:30AM - 12:30PM — Session B8 Fundamental Quantum Science 314 - Jacob Taylor, QuICS, University of Maryland, JQI, NIST

10:30AM B8.00001 Retrodiction of a sequence of measurements in a qubit interferometer , MARK HILLERY, DANIEL KOCH, Hunter College of CUNY — Alice gains information about the trajectory of a particle going through a series of interferometers by making measurements to obtain information about the path the particle took through each interferometer. Bob obtains the particle after it has passed through all of the interferometers, and he wants to determine the results of Alice’s measurements. That is, he wants to determine the record of the particle’s trajectory by making a single measurement on the particle. What can he find out? We model this process by a qubit going through a series of Hadamard gates, with Alice measuring the particle between each pair of gates. We examine several kinds of measurements that Bob can make, including one to determine the entire trajectory and one that rules out a trajectory. The first of these can make an error, that is, give the wrong trajectory, while the second will not give a wrong answer. The measurement that excludes a trajectory is useful in that Bob can use it to be sure of getting at least one of the results of Alice’s measurements correct. Reference: M. Hillery and D. Koch, Phys. Rev. A 94, 032118 (2016).

10:42AM B8.00002 Observation of a Discrete Time Crystal1 — A. KYPRIANIDIS, J. ZHANG, P. HESS, P. BECKER, A. LEE, J. SMITH, G. PAGANO, Joint Quantum Institute and U. of Maryland Dept. of Physics, A. POTTER, Dept. of Physics, U. of Texas at Austin, A. VISHWANATH, Dept of Physics, Harvard University, I.-D. POTIRNICHE, N. YAO, Dept of Physics, U. of California-Berkeley, C. MONROE, Joint Quantum Institute and U. of Maryland Dept. of Physics — Spontaneous symmetry breaking is a key concept in the understanding of many physical phenomena, such as the formation of spatial crystals and the phase transition from paramagnetism to magnetic order. While the breaking of translational symmetry is forbidden in equilibrium systems, it is possible for non-equilibrium Floquet driven systems to break a discrete time translation symmetry, and we present clear signatures of the formation of such a discrete time crystal. We apply a time periodic Hamiltonian to a chain of interacting spins under many-body localization conditions and observe the system’s sub-harmonic response at twice that period. This spontaneous doubling of the periodicity is robust to external perturbations. We represent the spins with a linear chain of trapped $^{171}$Yb$^+$ ions in an rf Paul trap, generate spin-spin interactions through spin-dependent optical dipole forces, and measure each spin using state-dependent fluorescence.

1This work is supported by the ARO Atomic Physics Program, the AFSOR MURI on Quantum Measurement and Verification, and the NSF Physics Frontier Center at JQI.

10:54AM B8.00003 Hamiltonian identifiability assisted by single-probe measurement , AKIRA SONE, PAOLA CAPPELLARO, Massachusetts Inst of Tech-MIT, QUANTUM ENGINEERING GROUP TEAM — We study the Hamiltonian identifiability of a many-body spin-1/2 system assisted by the measurement on a single quantum probe based on the eigensystem realization algorithm (ERA) approach employed in [Phys. Rev. Lett. 113, 080401 (2014)]. We demonstrate a potential application of Gröbner basis to the identifiability test of the Hamiltonian, and provide the necessary experimental resources, such as the lower bound in the number of required sampling points, the upper bound in total required evolution time, and thus the total measurement time. Focusing on the examples of the identifiability in the spin chain model with nearest-neighbor interaction, we classify the spin-chain Hamiltonian based on its identifiability, and provide the control protocols to engineer the non-identifiable Hamiltonian to be an identifiable Hamiltonian.

11:06AM B8.00004 Worldline Method for Electromagnetic Casimir Energies , JONATHAN MACKRORY, University of Oregon, Department of Physics, TAMMOY BHATTACHARYA, Santa Fe Institute, DANIEL STECK, University of Oregon, Department of Physics — We present our work on the worldline method for calculating electromagnetic Casimir energies. The worldline method calculates the energy by generating an ensemble of closed Brownian paths through space, and then summing up the contributions from the potential along each path. We calculate the Casimir’s energy due to dispersionless, dielectric bodies. We decompose the electromagnetic field into transverse electric (TE) and transverse magnetic (TM) polarizations, each of which behave as scalar fields. We will present our analytical and numerical work for both polarizations, and show agreement with prior results for both Casimir-Polder and Casimir energies for planar dielectric bodies. We will also present results showing the numerical convergence of the algorithm.

11:18AM B8.00005 Entanglement dynamics in itinerant fermionic and bosonic systems1, DURGANANIDINI PILLARISHETTY, Department of Physics, S. P. Pune University, Pune 411 007, India — The concept of quantum entanglement of identical particles is fundamental in a wide variety of quantum information contexts involving composite quantum systems. However, the role played by particle indistinguishability in entanglement determination is being still debated. In this work, we study, theoretically, the entanglement dynamics in some itinerant bosonic and fermionic systems. We show that the dynamical behaviour of particle entanglement and spatial or mode entanglement are in general different. We also discuss the effect of fermionic and bosonic statistics on the dynamical behaviour. We suggest that the different dynamical behaviour can be used to distinguish between particle and mode entanglement in identical particle systems and discuss possible experimental realizations for such studies.

1I acknowledge financial support from DST, India through research grant.
Binary gas mixture in a high speed channel. Dr. Sahadev Pradhan, Indian Institute of Science — The viscous, compressible flow in a 2D wall-bounded channel, with bottom wall moving in? the positive x-direction, simulated using the direct simulation Monte Carlo (DSMC) method. It has been used as a test bed for examining different aspects of flow phenomenon and separation performance of a binary gas mixture at Mach number Ma = (Uw / √g()) in the range: 0.1 < Ma < 20, and Knudsen number Kn = 1/(√(2πd2 n e H)) in the range: 0.1 < Kn < 10. The generalized analytical model is formulated which includes the fifth order differential equation for the boundary layer at the channel wall in terms of master potential χ, which is derived from the equations of motion in a 2D rectangular (x-y) coordinate. The starting point of the analytical model is the Navier-Stokes, mass, momentum and energy conservation equations in the (x-y) coordinate, where χ and y are the streamwise and wall-normal directions, respectively. The linearization approximation is used (Pradhan & Kumaras, J. Fluid Mech.-), where the equations of motion are truncated at linear order in the velocity and pressure perturbations to the base flow, which is an isothermal compressible Couette flow. Additional assumptions in the analytical model include high aspect ratio (L >> H), constant temperature in the base state (isothermal condition), and low Reynolds number (laminar flow). The analytical solutions are compared with direct simulation Monte Carlo (DSMC) simulations and found to be in good agreement (with a difference of less than 10%), providing the boundary conditions are accurately incorporated in the analytical solution.
11:06 AM B9.00004 Observation of charge density wave correlations in the attractive Fermi-Hubbard model. DEBAYAN MITRA, PETER BROWN, ELMER GUARDADO-SANCHEZ, PETER SCHAUSS, WASEEM BAKR, Princeton University — The attractive Hubbard model is the simplest condensed matter model that gives rise to conventional superfluidity in a lattice. At half-filling, the ground state of the model has degenerate superfluid and charge density wave orders. Using quantum gas microscopy of fermionic lithium in an optical lattice, we detect charge-density wave correlations in attractive gases prepared either on the upper or lower branch of a Feshbach resonance. Away from half-filling, the correlations get weaker as the system favors superfluid order. These correlations form a low-temperature order parameter and are an indirect way to measure the strength of superfluid correlations in the gas. Our characterization of the entropy of spin-balanced attractive gases in lattices sets the stage for searching for signatures of non-zero momentum superfluids in spin-imbalanced lattice gases.

11:18 AM B9.00005 Detecting correlations in deterministically prepared quantum states with single-atom imaging. ANDREA BERGSCHNEIDER, VINCENT M. KLINKHAMER, JAN HENDRIK BECHER, PHILINE L. BOMMER, JUSTIN F. NIEDERMAYER, GERHARD ZUERN, PHILIPP M. PREISS, SELIM JOCHIM, Physikalisches Institut, Heidelberg University, Germany — We deterministically prepare quantum states consisting of few fermions in single and double-well potentials. Here we report on a new imaging scheme for \(^{6}\)Li in which we detect the correlations of the quantum state on a single-atom level and with spin resolution. The detection method uses fluorescence imaging at high magnetic field where the optical transitions for the used hyperfine states are almost closed. With a high-resolution objective we image about 15 scattered photons per atom on an EMCCD camera. This is sufficient to identify and locate single atoms in our imaging plane. We can perform this scheme in situ or after an expansion in time-of-flight and additionally resolve the spin by addressing the different hyperfine states. By combining this scheme with our deterministic preparation, we measure the two-point momentum correlations to probe the spatial symmetry of the two-particle wavefunction. The high contrast and the scalability of the detection technique allows us to go beyond measuring two-point correlations and characterize many-body quantum states.

11:30 AM B9.00006 Site-Resolved Observation of Charge and Spin Correlations in the 2D Fermi-Hubbard Model. MATTHEW NICHOLS, LAWRENCE CHEUK, KATHERINE LAWRENCE, MEILI OKAN, HAO ZHANG, Massachusetts Institute of Technology, EHSAN KHATAMI, San Jose State University, NANDINI TRIVEDI, The Ohio State University, THEREZA PAIVA, Universidade Federal do Rio de Janeiro, MARCOS RIGOL, The Pennsylvania State University, MARTIN ZWIERLEIN, Massachusetts Institute of Technology — The application of quantum gas microscopy to fermionic systems has allowed for rapid advances in the field of ultracold fermionic atoms in optical lattices, including site-resolved studies of metallic, Mott insulating, and band insulating states of the two-dimensional Fermi-Hubbard model. In this talk, we extend these studies to explore spatial charge and spin correlations using spin sensitive fluorescence imaging of ultracold \(^{40}\)K atoms trapped in a square optical lattice [1]. We observe nearest-neighbor antiferromagnetic spin correlations which are maximal at half-filling, and which weaken monotonically upon doping. Correlations between singly charged sites on the other hand display non-monotonic behavior as a function of doping. At low filling, these correlations are negative, revealing the effects of Pauli blocking and strong repulsive interactions. As the filling is increased beyond a critical value however, the correlations become positive, indicating an effective attraction between holes and doublons in the system. These findings agree well with numerical linked-cluster expansion (NLCE) and determinantal quantum Monte Carlo (DQMC) calculations. [1] Cheuk et al., Science 353, 1260 (2016)

11:42 AM B9.00007 Revealing ”Hidden” Antiferromagnetic Correlations in Doped Hubbard Chains via String Correlators. GUILLAUME SALOMON, TIMON HILKER, MARTIN BOLL, AHMED OMRAH, JAYADEV VIJAYAN, JOANNIS KÖEPSELL, IMMANUEL BLOCH, CHRISTIAN GROSS, Max-Planck Institute for Quantum Optics, 85748 Garching, Germany, FABIAN GRUSDTE, EUGENE DEMLER, Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA — Topological phases, among them the celebrated Haldane phase in spin-1 chains, defy characterization through local order parameters. Instead, non-local string order parameters can be employed to reveal their hidden order. Similar diluted magnetic correlations appear in doped 1d systems due to the remarkable phenomenon of spin-charge separation. Here we report on the direct observation of such hidden magnetic correlations via quantum gas microscopy of hole-doped ultracold Fermi-Hubbard chains. The measurement of non-local spin-density correlation functions reveals a hidden finite-range antiferromagnetic order, a microscopic manifestation of spin-charge separation. Our technique, which can be directly extended to higher dimensions, enables the study of the complex interplay between magnetic order and density fluctuations and show how topological order can be directly measured in experiments.

11:54 AM B9.00008 Few-body interactions in a Fermi degenerate optical lattice clock. G. EDWARD MARTI, AKIHISA GOBAN, ROSS HUTSON, SARA CAMPBELL, JUN YE, JILA, NIST, University of Colorado, Boulder — Alkaline-earth-like atoms trapped in optical lattices are at the forefront of both precision measurements, realizing record accuracy as an optical frequency standard, and quantum simulations. Recent advances have sought to use precision spectroscopy on the millihertz-linewidth optical transition to study many-body physics, including the discovery of an interorbital Feshbach resonance, demonstration of spin-orbit coupling, and the realization of a Fermi-degenerate 3D optical lattice clock. In this talk, I will discuss our recent work on resolving few-body interactions of SU(3) fermionic strontium in deep optical lattices with narrow-line optical spectroscopy. By combining spectroscopy with imaging, we can resolve the spatial structure of interacting atoms in a degenerate Fermi gas.\footnote{This work is supported by NIST, DARPA, and the NSF JILA Physics Frontier Center.}

12:18 PM B9.00010 Energy-resolved atomic scanning probe: Mapping local density of states of many-body systems. CHICHChUN CHIEN, University of California, Merced, DANIEL GRUSS, National Institute of Standards and Technology, MASSIMILIANO DI VENTRA, University of California, San Diego, MICHAEL ZWOLAK, National Institute of Standards and Technology — The density of states (DOS) is an important quantity for determining thermodynamic quantities and transport coefficients of many-body systems. The scanning tunneling microscope (STM) measures the product of DOS and the local weight of wavefunction at the measurement location, which is called the local density of states (LDOS). By connecting a narrow-band, noninteracting lattice as a probe to a lattice loaded with interacting particles, the tunneling current also reveals the LDOS of the interacting system. By tuning the relative energy between the probe and the system, the LDOS can be resolved in the energy domain, a task that would be much more difficult in conventional STM. We propose a heterogeneous lattice structure with confined interactions for realizing the energy-resolved atomic scanning probe (ERASP) using cold-atoms in magnetic or optical potentials. The ERASP is capable of mapping out the LDOS of complex interacting systems such as the Hubbard model and provides local information for inhomogeneous systems. Reference: D. Gruss, C. C. Chien, M. Di Ventra, and M. Zwolak, arXiv: 1610.01903.
2:00PM C2.00001 A programmable five qubit quantum computer using trapped atomic ions, SHANTANU DEBNATH, Joint Quantum Institute, University of Maryland - College Park — In order to harness the power of quantum information processing, several candidate systems have been investigated, and tailored to demonstrate only specific computations. In my thesis work, we construct a general-purpose multi-qubit device using a linear chain of trapped ion qubits, which in principle can be programmed to run any quantum algorithm. To achieve such flexibility, we develop a pulse shaping technique to realize a set of fully connected two-qubit rotations that entangle arbitrary pairs of qubits using multiple motional modes of the chain. Following a computation architecture, such highly entangled or “super” qubits along with arbitrary single-qubit rotations can be used to compile modular universal logic gates that are affected by targeted optical fields and hence can be reconfigured according to any algorithm circuit programmed in the software. As a demonstration, we run the Deutsch-Jozsa and Bernstein-Vazirani algorithm, and a fully coherent quantum Fourier transform, that we use to solve the ‘period finding’ and ‘quantum phase estimation’ problem. Combining these results with recent demonstrations of quantum fault-tolerance, Grover’s search algorithm, and simulation of boson hopping establishes the versatility of such a computation module that can potentially be connected to other modules for future large-scale computations.

2:30PM C2.00002 Control of molecular rotation with an optical centrifuge, ALEKSEY KOROBENKO, University of Ottawa — The main purpose of this work is the experimental study of the applicability of an optical centrifuge — a novel tool, utilizing non-resonant broadband laser radiation to excite molecular rotation — to produce and control molecules in extremely high rotational states, so called molecular “super rotors”, and to study their optical, magnetic, acoustic, hydrodynamic and quantum mechanical properties.

3:00PM C2.00003 High precision optical spectroscopy and quantum state selected photodissociation of ultracold $^{88}$Sr$_2$ molecules in an optical lattice, MICKEY MCDONALD, Columbia University — Over the past several decades, rapid progress has been made toward the accurate characterization and control of atoms, epitomized by the ever-increasing accuracy and precision of optical atomic lattice clocks. Extending this progress to molecules will have exciting implications for chemistry, condensed matter physics, and precision tests of physics beyond the Standard Model. My thesis describes work performed over the past six years to establish the state of the art in manipulation and quantum control of ultracold molecules. We describe a thorough set of measurements characterizing the rovibrational structure of weakly bound $^{88}$Sr$_2$ molecules from several different perspectives, including determinations of binding energies; linear, quadratic, and higher order Zeeman shifts; transition strengths between bound states; and lifetimes of narrow subradiant states. Finally, we discuss measurements of photodissociation angular distributions produced by photodissociation of molecules in single quantum states, leading to an exploration of quantum-state-resolved ultracold chemistry. The images of exploding photofragments produced in these studies exhibit dramatic interference effects and strongly violate semiclassical predictions, instead requiring a fully quantum mechanical description.

3:30PM C2.00004 Quantum measurement with atomic cavity optomechanics, SYDNEY SCHREPPLER, Univ of California - Berkeley — A cloud of ultracold atoms trapped within the confines of a high-finesse optical cavity shakes from the pressure of the light that probes it. This radiation pressure is a form of quantum backaction, a disruptive consequence of quantum measurement that imposes fundamental limits on measurement precision. The existence of these limits has long been an underlying tenet of chemistry, condensed matter physics, and precision tests of physics beyond the Standard Model. However, recent experiments enlisting the collective motion of ultracold atoms as the mechanical degree of freedom in a cavity optomechanical system to reach settings cold and quiet enough to allow the effects of measurement backaction to manifest. Recounting observations of quantum-limited force measurement, ponderomotive squeezing, and a new understanding of complex quantum correlations, I focus my experiments that emphasize the nature of measurement backaction: how it can be detected, tuned, and perhaps, through careful accounting, avoided.

Tuesday, June 6, 2017 2:00PM - 4:00PM
Session C3 Topological States and Synthetic Fields 308 - Jonathan Simon, University of Chicago

2:00PM C3.00001 Autonomous Stabilizer for Photonic Many-Body States, BRENDAN SAXBERG, ALEX MA, CLAI OWENS, AMAN LACHAPELLE, DAVID SCHUSTER, JON SIMON, University of Chicago — Synthetic photonic systems are a promising platform for new physics in the regime of strongly interacting and highly correlated quantum materials. However, controlled population of system Hamiltonians in the absence of particle number conservation remains challenging. Here we present an autonomous thermalizer for incompressible photonic quantum materials at non-zero chemical potential to stabilize these photonic many-body states. The thermalizer is comprised of a pumping and a lossy site, where photons can spontaneously thermalize to the ground state of the lattice when driven on the pumping site and excess energy is dissipated via the lossy site. Using the Circuit QED platform, we connect our autonomous thermalizer to a one-dimensional lattice of coupled superconducting qubits and demonstrate a Mott Insulating phase of light in a strongly interacting Bose-Hubbard chain. This work explores a new approach for preparation of quantum many-body photonic phases, and provides a potential route to topologically protected states, for example in a topological microwave cavity lattice with qubit mediated interactions.

2:12PM C3.00002 Protocols for dynamically probing topological edge states and dimerization with fermionic atoms in optical potentials, MEKENA METCALF, CHEN-YEN LAI, University of California, Merced, KEVIN WRIGHT, Dartmouth College, CHIH-CHUN CHIEN, University of California, Merced — Topological states and phases have been observed in ultra-cold atomic systems. However, imposing a confining harmonic potential distorts the energy spectrum and prevents the detection of topological boundary states. We propose realistic setups for generating one-dimensional topological systems with well-defined boundary and protocols to resolve the detection of edge-states arising in a dimerized lattice using ultra-cold fermions. Atoms confined in a dimerized ring lattice, whose boundary conditions are transformed from periodic to open using an off resonant laser sheet, generate topological boundary states. A particle injected onto the edge site of a dimerized structure in a topological configuration can sustain a finite density in the undimerized evolutions in time. Alternatively, injecting an initially filled lattice away from the boundary relieves prominent occupied edge states. Signatures of dimerization in the presence of onsite interactions can be found using certain correlations as the boundary condition dynamically transforms from periodic to open. These correlations reveal a memory effect of the initial state which can distinguish dimerized structures or different insulating phases.
2:24PM C3.00003 Topological order in finite-temperature Gaussian fermionic systems
LUKAS WAVER, Department of Physics, University of Kaiserslautern, DOMINIK LINZNER, Department of Physics, University of Kaiserslautern, University of Darmstadt, MICHAEL FLEISCHHAUER, Department of Physics, University of Kaiserslautern — Since their discovery, topological states of matter have been praised for their fascinating and potentially useful properties as protected edge states or anyonic excitations. However, these features seem to vanish at finite temperature. Exploiting the equivalence of Zak (or Berry) phase and polarization we can classify topological order in finite-temperature systems by means of the many body polarization [1]. We show that topological order defined in this way survives at any finite temperature \( T \) in Gaussian fermionic systems. We first consider a 1D model for symmetry-protected topological order (Su-Schrieffer-Heeger model) and find that there is a quantized winding of the polarization for closed paths in parameter space for all \( T < \infty \). At \( T = \infty \) a topological phase transition occurs and for \( T < 0 \) the polarization winding reverses its sign. We then study a 2D model (Hofstadter-Hubbard model) with intrinsic topology and show a similar behavior. [1] D. Linzner, L. Waver, F. Grusdt, and M. Fleischhauer, Phys. Rev. B 94, 201105(R) (2016)

1DFG/SFB TRR 185

2:36PM C3.00004 Observation of topological states in an optical Raman lattice with ultracold fermions
BO SONG, CHENGDONG HE, Hong Kong Univ of Sci & Tech, LONG ZHANG, TING FUNG JEFFREY POON, Peking University, ELNUR HAJIYEV, ZEJIAN REN, BOJONG SEO, SHANCHAO ZHANG, Hong Kong Univ of Sci & Tech, KIONG-JUN LIU, Peking University, KYU-BOONG JO, Hong Kong Univ of Sci & Tech — The spin-orbit coupling with cold atoms, especially in optical lattices, provides a versatile platform to investigate the intriguing topological matters. In this talk, we will present the realization of a single-particle dimension-dependent lattice dressed by the periodic Raman field. Ultracold

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Yb fermions loaded into an optical Raman lattice reveal non-trivial spin textures due to the band topology, by which we measured topological invariants and determined a topological phase transition. In addition, we explored the non-equilibrium quench dynamics between the topological and the trivial states by suddenly changing the band topology of the optical Raman lattice. The optical Raman lattice demonstrated here opens a new avenue to study the spin-orbit coupling physics and furthermore to realize novel quantum matters such as symmetry-protected topological states.

1Supported by: Croucher Foundation and Research Grants Council (RGC) of Hong Kong (Project ECS26300014, GRF1630215, GRF16311516, and Croucher Innovation grants); MOST (Grant No. 2016YFA0301604) and NSFC (No. 11574008)

2:48PM C3.00005 Majorana fermions in alkaline-earth-like one-dimensional gases
LEONARDO MAZZA, Ecole Normale Supérieure, Paris, FERNANDO IEMINI, ICTP, Trieste, Italy, LEONARDO FALLANI, LENS, Florence, Italy, PETER ZOLLER, IQOQI, Innsbruck, Austria, ROSARIO FAZIO, MARCELLO DALMONT, ICTP, Trieste, Italy — We show how angular momentum conservation can stabilize a symmetry-protected quasi-topological phase of matter supporting Majorana quasi-particles as edge modes in a one-dimensional cold-atom gas. Different from typical scenarios, where such quasi-particles require the presence of superconductivity, we investigate a number-conserving Hubbard model with spin and orbital degrees of freedom in the presence of spin-orbit coupling. The latter reduces the global spin symmetry to an angular momentum parity symmetry, which provides an extremely robust protection mechanism that does not rely on any coupling to additional modes systems. The emergence of Majorana edge modes is elucidated using field theory techniques, and corroborated with advanced numerical simulations. Our results pave the way towards the observation of Majorana edge modes with alkaline-earth-like (Ytterbium) fermions in optical lattices, where the basic ingredients for our recipe - spin-orbit coupling and strong inter-orbital interactions - have been engineered and observed over the last two years.

3:00PM C3.00006 Interaction-induced chiral trajectories in a ladder governed by the Harper-Hofstadter Model
MATTHEW RISPOLI, M. ERIC TAI, ALEXANDER LUKIN, ROBERT SCHTITKO, TIM MENKE, DAN BORGNA, Harvard University, PHILIPP M. PREISS, University of Heidelberg, FABIAN GRUSDT, ADAM M. KAUFMAN, MARKUS GREINER, Harvard University — The combination of interacting charged particles and magnetic fields can lead to exotic physics that exhibit both spatial entanglement and topological order. Using optical fields, ultracold neutral atoms can simulate the behavior of charged particles in magnetic fields. This capability has been used to study effects such as edge states, topological band structures, and the quantum Hall effect. Thus far, however, these experiments have not yet incorporated inter-particle interactions. I will describe recent experimental results in which we apply microscopy to interacting atoms exposed to a synthetic magnetic field and are confined to a 2xN real-space ladder. We observe the chiral dynamics of both single-particle and two-particle systems with strong, finite interactions. We show the interactions for the two-particle system enable chiral dynamics where they would otherwise be absent. Our observation of a novel form of interaction-induced chirality illustrates the richness of physics that can emerge with these ingredients even in the few particle limit. Realizing this combination of elements is essential to advance into the regime of fractional quantum hall physics, as well as to drive explorations for new phenomena with the microscopic tools of AMO systems.


3:12PM C3.00007 Exploring Fractional Quantum Hall Effect in Ultracold Strontium Atomic Gases
XIBO ZHANG, WEI QI, MINGCHENG LIANG, ICMC, Peking University — Ultracold atomic gases in the fractional quantum Hall (FQH) regime hold promise for providing new paths to exotic anyonic excitations. Realizing such atomic systems, however, has been hindered by difficulties in suppressing heating and loss problems due to spontaneous emission and in preparing and manipulating ultracold samples with very small atomic numbers. Owing to its ultra-narrow clock transition, \(^{87}\)Sr has become a promising candidate to overcome these difficulties. We describe progress in building an apparatus that uses Raman optical lattices with novel configurations to engineer synthetic gauge fields for ultracold Sr and induce non-trivial topological flatbands. High-spatial-resolution microscopy and precision coherent spectroscopy can be combined to prepare and characterize strongly-correlated states and their physical properties.

3:24PM C3.00008 Engineering arbitrary synthetic gauge fields in multiple geometries
FANGZHAO AN, ERIC MEIER, BRYCE GADOW, Univ of Illinois - Urbana — Atoms in a uniform synthetic gauge field mimic the behavior of electrons in a homogeneous magnetic field, yet realizing this simple two-dimensional topological model with tunable flux (and thus field strength) has been a challenge. By implementing multiple “synthetic dimensions” of atomic momentum states, we engineer easily tunable, arbitrary flux patterns to study atomic dynamics in both a two-leg ladder geometry and a zig-zag ladder geometry. Starting with a uniform flux ladder, we observe chiral edge states whose flow changes from clockwise to counter-clockwise as we tune the applied flux across the entire range of values. Starting with a uniform flux ladder, we demonstrate the ability to tune the applied flux across the entire range of values, observing chiral edge states whose handedness changes from clockwise to counter-clockwise with varying flux. By introducing a step-like jump in the flux pattern, we show topological reflection from a magnetic defect. In a separate zig-zag ladder geometry, we again explore flux-dependent atom dynamics over the full range of values. Within this geometry, we further study quantum localization driven by added pseudo-disorder, and observe a flux-dependent transition between metal to insulator.
3:36PM C3.00009 Time-reversal invariant bilayer 2D synthetic lattices, YICHAO ZHANG, XIWANG LIOU, KUEI SUN, CHUANWEI ZHANG, Univ of Texas, Dallas, UNIV OF TEXAS, DALLAS TEAM — Recently it has been theoretically proposed and experimentally demonstrated that a 1D spin-orbit coupled optical lattice can emulate a 2D synthetic lattice with a uniform magnetic field, where atomic spins represent the synthetic dimension. The time-reversal symmetry in this system is broken by the magnetic flux. Here we propose the time-reversal symmetry may be restored by considering a bilayer spin-orbit coupled optical lattice with opposite Raman coupling between layers. We show how such layer-spin coupling modifies chiral edge states, fractal Hofstadter butterfly, and layer-spin correlation.

3:48PM C3.00010 Controlling vortex rings in Bose-Einstein condensates using artificial gauge fields, JAMES SCHLOSS, RASHI SACHDEVA, LEE JAMES O’RIORDAN, THOMAS BUSCH, Okinawa Inst of Sci & Tech — The exponentially decaying evanescent fields near the boundary of dielectric systems can be used to create artificial gauge fields for the generation of vortices in Bose-Einstein condensate (BEC) systems. Here we study the artificial gauge field created by the evanescent field outside of an optical nanoﬁber from the fundamental HE11 mode and its application to generating and controlling vortex rings in a toroidal BEC trapped around the nanoﬁber. This has been done by developing a GPU-based code that solves the Gross-Pitaevskii equation for the BEC system in three dimensions and using it to study ground state vortex ring structures and their time evolution. Since these gauge fields may be controlled in a time-dependent manner, we can use this system to study the dynamics of complex vortex topologies.

Tuesday, June 6, 2017 2:00PM - 4:00PM —
Session C4 Atom-Atom and Atom-Molecule Collisions 309 - Daniel Fisher, Missouri University of Science and Technology

2:00PM C4.00001 Wavepacket dynamics in the scattering of hydrogen anions off vicinally nano-stepped metal surfaces, JOHN SHAW, HIMADRI CHAKRABORTY, Northwest Missouri State University, Maryville, MO, DAVID MONISMITH, Software Maintenance Group, Tinker AFB, Oklahoma, USA — We study the electron dynamics in monocristalline Cu, Au and Pd surfaces [1] with stepped vicinal structures modeled in a Kronig-Penney scheme [2]. The unoccupied bands of the surface are resonantly excited via the charge transfer interaction of the surface with a moving hydrogen anion. The interaction dynamics are simulated in a quantum mechanical wavepacket propagation approach [3] that used parallel computations [4]. The survival probability of the interacting ion is calculated as well as the electron probability density at all times during the interaction. Animated videos are produced of the electron probability density which show that, when the electron is transferred to the metal, the first two image states are the most likely locations of the electron as it evolves through the superlattice. The survival probability shows peaks at those energies that produce standing waves between the steps on the surface when the electron is in the image state subbands. [1] Chulkov et al, Surf. Sc. 437, 330 (1999); [2] Mugarza and Ortega, J. Phys. Cond. Matt. 15, 53281 (2003); [3] Schmitz et al, Phys. Rev. A 81, 042901 (2010); [4] Monismith et al, submitted, High Performance Distributed Computing (HPDC2017).

1The work is supported by the XSEDE allocation grant for high performance computation.

2:12PM C4.00002 Bayesian optimization for constructing potential energy surfaces of polyatomic molecules with the smallest number of ab initio calculations, RODRIGO A VARGAS-HERNANDEZ, ROMAN V KREMS, Univ of British Columbia — We examine the application of kernel methods of machine learning for constructing potential energy surfaces (PES) of polyatomic molecules. In particular, we illustrate the application of Bayesian optimization with Gaussian processes as an efficient method for sampling the configuration space of polyatomic molecules. Bayesian optimization relies on two key components: a prior over an objective function and a mechanism for sampling the configuration space. We use Gaussian processes to model the objective function and various acquisition functions commonly used in computer science to quantify the accuracy of sampling. The PES is obtained through an iterative process of adding ab initio points at the locations maximizing the acquisition function and re-training the Gaussian process with new points added. We sample different PESs with one or many acquisition functions and show how the acquisition functions affect the construction of the PESs.

2:24PM C4.00003 Rate Constants for Fine-Structure Excitations in O - H Collisions with Error Bars Obtained by Machine Learning, DANIEL VIEIRA, ROMAN KREMS, University of British Columbia — Fine-structure transitions in collisions of O(3Pj) with atomic hydrogen are an important cooling mechanism in the interstellar medium; knowledge of the rate coefficients for these transitions has a wide range of astrophysical applications. The accuracy of the theoretical calculation is limited by inaccuracy in the ab initio interaction potentials used in the coupled-channel quantum scattering calculations from which the rate coefficients can be obtained. In this work we use the latest ab initio results for the O(3Pj) + H interaction potentials to improve on previous calculations of the rate coefficients. We further present a machine-learning technique based on Gaussian Process regression to determine the sensitivity of the rate coefficients to variations of the underlying adiabatic interaction potentials. To account for the inaccuracy inherent in the ab initio calculations we compute error bars for the rate coefficients corresponding to 20 % variation in each of the interaction potentials. We obtain these error bars by fitting a Gaussian Process model to a data set of potential curves and rate constants. We use the fitted model to do sensitivity analysis, determining the relative importance of individual adiabatic potential curves to a given fine-structure transition.

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2:36PM C4.00004 Multi-band scattering of two atoms in a one-dimensional lattice with on-site interactions, SETH RITTENHOUSE, Department of Physics, US Naval Academy, PANAGIOTIS GIANNAKEAS, Department of Physics and Astronomy, Purdue University, NIRAV MEHTA, Department of Physics and Astronomy, Trinity University — We examine a system of two-particles confined to a one-dimensional lattice described by a multi-band Hubbard model with on-site interactions. Asymptotically the two particles are relegated to remain in bands that are energetically accessible. However, when the particles occupy the same state, they can virtually scatter into bands that are energetically closed. We incorporate this virtual scattering by solving the Lippmann-Schwinger equation for the reactance matrix (K-matrix) using a lattice Green’s operator. The resulting formula for the K-matrix for open band scattering bears a striking similarity to that which arrises from channel closing formulas in standard multi-channel scattering theory. We then apply this formula for two-body scattering in the lowest and first excited bands within a two band approximation. Within this approximation, virtual scattering into closed bands can create scattering resonances in the presence of bound states attached to closed bands in analogy to Feshbach or confinement induced resonances.

1This work was partially funded by grants from the NSF and a the Research Corporation for Science Advancement.
2:48PM C4.00005 Theoretical Investigations in Support of a Cold-Atom Based UHV Pressure Sensor. CONSTANTINOS MAKRIDES, EITE TIESINGA, University of Maryland Department of Physics, Joint Quantum Institute, and National Institute of Standards and Technology, Gaithersburg, MD — Recent efforts are underway in the development of a prototype cold-atom vacuum sensor, which make use of cold atoms to measure pressures in the Ultra-High Vacuum (UHV) and Extreme-High Vacuum (XHV) regimes where modern sensors cannot function or produce accurate measurements. These cold-atom devices would correlate loss of atoms in a cold atomic gas to the pressure of the room-temperature environment in which it is placed. Essential in making this connection is having the best understanding of the various collision processes that can lead to losses from both the background gasses, typically the H$_2$ molecule, as well as the collisions among the cold atoms. Here, we present our investigations into these collisional processes using lithium atoms as the cold constituent. For a complete description, we determine collisional phase shifts and elastic cross sections for collision energies that spans several times room temperature. We compare various semiclassical approximations with full quantum simulations where possible.

3:00PM C4.00006 Experimental Investigations of the Quantum Chemistry of Cold-Atom Based UHV Pressure Sensors. ALEXANDER PETROV, STEVEN SCHOWALTER, MIHAILO VUCKOVIC, JQI and National Institute of Standards and Technology, Gaithersburg, MD 20899

3:12PM C4.00007 Radiative association of a carbon atom and a proton via triplet molecular states$^1$. J. F. BABB, ITAMP, Harvard-Smithsonian CFA, B. M. MCLAUGHLIN, Queen’s U. Belfast — Collisions between a ground state C atom and H$^+$ along triplet molecular states with photon emission leading to a bound CH+ molecular ion (radiative association process) are studied theoretically. Cross sections and rate coefficients are calculated. The present results are compared to those for collisions of C and H$^+$ leading to C$^+$ and H with photon emission (radiative charge transfer process) along triplet molecular states and to those for radiative association of a carbon ion and a hydrogen atom along the singlet molecular state. We investigate the photon emission spectra and discuss possible astrophysical applications.

$^1$Supported in part by the NSF

3:24PM C4.00008 Spin and electronic-excitation exchange in ultracold ion-atom collisions. RUTI BEN SHLOMI, TOMAS SIKORSKY, ZIV MEIR, NITZAN AKERMAN, YEHONATAN DALLAL, MEIRAV PINKAS, ROEE OZERI, weizmann institute of science — We experimentally study the dynamics of single and many inelastic collisions between ultracold $^{87}$Rb atoms and a single $^{88}\text{Sr}^+$ ion. A single ion is trapped in a linear Paul trap, laser cooled to 1 mK, and initially optically pumped to the higher excited metastable D-state. Then the ion is immersed in an ultracold $^{87}\text{Rb}$ cloud. We investigated relaxation rates of the ion from the D-state due to collisions with atoms. We measured relaxation to the S-state after two Langevin collisions on average, followed by an energy release of 1500 K. This can be explained by a non-adiabatic excitation-exchange process: $\text{Sr}^+(D) + \text{Rb}(S) \rightarrow \text{Sr}^+(S) + \text{Rb}(P)$. We further studied the dependence of this process on the mutual spin orientation of the ion and atoms and on initializing the ion in the different spin-orbit split D$_{3/2}$ and D$_{5/2}$ levels. We also initially spin polarized the ion and atoms in their electronic ground state and investigated the spin dynamics of the ion after one to several collisions. We observed that after 7 Langevin collisions on average, the spin of the ion aligned with the spin direction of the cloud, indicating the dominant interaction between the ion and atoms spins during a collision is that of spin-exchange. Since the steady-state spin population of the ion reached only 90%, we conclude that a spin-relaxation mechanism is involved as well.

3:36PM C4.00009 Quantum Chemistry and Non-equilibrium Thermodynamics in an Atom-Ion Hybrid Trap. PRATEEK PURI, MICHAEL MILLS, STEVEN SCHOWALTER, ALEX DUNNING, CHRISTIAN SCHNIEDER, KUANG CHEN, ERIC HUDSON, Univ of California - Los Angeles — Hybrid atom-ion traps allow for the precise control and investigation of atom-ion collisions in the ultracold regime. Recently our group has utilized these platforms for the study of quantum chemistry and non-equilibrium thermodynamics. With the long interrogation times associated with the ion trap environment and precisely tunable entrance channels of both the atom and ion via laser excitation, LQT-MOT hybrid traps are a convenient platform for the study of quantum state resolveable cold chemistry. We describe a recent study of excited state chemistry between cold Ca atoms and the BaOCH$_3^+$ molecular ion, which has resulted in the product BaOCA$^+$, the first observed mixed hypermetallic alkaline earth oxide molecule. Further, due to the complexity of ion-ion heating within an LQT and micromotion interruption collisions, there remain many open questions about the thermodynamics of ions in a hybrid trap environment. We describe an analytical model that explains the thermodynamics of these systems as well as an experimental effort confirming one of the more interesting hallmarks of this model, the bifurcation in steady state energy of ions immersed in an ultracold gas, as parameterized by total ion number.

3:48PM C4.00010 Quantum-State-Resolved Ion-Molecule Chemistry$^1$. GARY CHEN, TIAN-GANG YANG, WESLEY CAMPBELL, ERIC HUDSON, Univ of California - Los Angeles — We are working towards a new platform for quantum-state-resolved ion-molecule chemistry by utilizing a combination of cryogenic buffer gas cooling, laser-cooled ion sympathetic cooling, and integrated mass spectrometry in an RF Paul trap. Cold molecular species produced in a cryogenic buffer gas beam collide with target atomic carbon ions in a linear quadrupole trap. Ion imaging and time of flight mass spectrometry are then used to observe the resulting reaction rates and products. We can utilize the precision control over quantum states allowed by this neutral-plus-ion chemistry environment (N+ICE) to resolve state-resolved quantum chemical reactions without high-density molecular sample production; proposed extensions suggest true state-to-state chemistry is possible in this system. We report progress towards cold carbon and water chemistry, including co-trapping and sympathetic cooling of carbon ions with laser-cooled beryllium ions.

$^1$US Air Force Office of Scientific Research BRI program
2:00PM C5.00001 Effects of electron correlation on the time-delay in photoionization of atomic beryllium, LARS BOJER MADSEN, JUAN OMISTE, WENLIANG LI, Department of Physics and Astronomy, Aarhus University — We report on the effects of electron correlation on the relative time-delay in photoionization of atomic beryllium in the channels $\text{Be}((1s^22s^2)\;^1S^+)^+\rightarrow\text{Be}^+(1s^22s\;^2S^1)+e^- (p\text{-electron})$, and $\text{Be}((1s^22s^2)\;^1S^+)\rightarrow\text{Be}^+(1s^22p\;^2P^0)+e^- (s\text{ or } d\text{ electron})$. We use our recent three-dimensional implementation of the time-dependent restricted-active-space self-consistent-field method and study the changes in the value obtained for the time-delay when including more and more correlation. We find that the mean-field, time-dependent Hartree-Fock theory does not account accurately for the time-delay. A larger active orbital space is needed. We find that the relative time-delay between ionization into $\text{Be}^+(1s^22s\;^2S^1)$ and $\text{Be}^+(1s^22p\;^2P^0)$ is around 7-8 attoseconds.

2:12PM C5.00002 Spatio-Temporal Control of XUV FID (xFID) Emission in Helium, E. R. SIMPSON, S. BENGTSSON, N. IBRAKOVIC, Lund University, S. CAMP, K. J. SCHAFFER, M. B. GAARDE, Louisiana State University, L. RIPPE, J. MAURITSSON, Lund University — Precise spatio-temporal control of extreme ultra-violet (XUV) light resulting from free induction decay (FID) has recently been demonstrated through opto-optical modulation in argon [1]. Here we present an extension of this technique, exploring precision control over XUV induced FID (xFID) in helium. By tuning the frequency content of the coherent XUV excitation pulse, we probe the resonant excitation of a number of bound excited states. The directionality of the xFID signal is controlled by a Stark shift-induced phase gradient applied using a non-coaxial, variable delay, IR control pulse. In this way both the spatial and temporal properties of the xFID signal can be controlled through the intensity and delay of the applied control pulse. We observe the direction of the xFID signal from the 2p state to be opposite to that for the higher np manifold, as expected from the direction of the applied Stark shift. In addition the 2p state splits, emitting FID in both directions. This forms an effective beam splitter, opening the door for ’which way’ interference. By shaping, or increasing the number of control pulses, possibilities for xFID control could include opto-optical switching and focussing of the xFID emission. [1] S. Bengtsson et al. arXiv:1611.04836v1

2:24PM C5.00003 Attosecond time-resolved photoemission from Cu(100) and Cu(111) surfaces, MARCELO AMBROSIO, UWE THUMM, Kansas State University — Motivated by the striking dependence of the valence electronic structure of transition metal surfaces on their crystallographic orientation, and by very recent experiments [1,2] on laser-assisted extended ultraviolet (XUV) photoemission from solid surfaces, we calculated photoemission spectra from Cu(100) and Cu(111) surfaces as a function of the photoelectron final kinetic energy and the delay between an ionizing attosecond XUV pulse train and assisting infrared (IR) laser pulse [3]. Our numerical simulations predict distinct differences in delay-dependent photoelectron energy distributions and photoemission time delays for Cu(100) and Cu(111) surfaces that can be scrutinized experimentally in a suggested in situ comparative RABBITT configuration, by placing the two surfaces on a sliding platform while keeping all optical components and pathlengths fixed. In addition, our numerical results also show that the inclusion of the Fresnel-reflected incident IR pulse at the metal-vacuum interface modifies photoelectron spectra and photoemission time delays in a characteristic way that reveals the degree of spatial location of the initial electronic states. [1] R. Locher et al., Optica 2, 405 (2015). [2] Z. Tao et al., Science 335, 62 (2016). [3] M. J. Ambrosio and U. Thumm, A 94, 063424 (2016).

2:36PM C5.00004 Coupling electronic couplings with tunable long wavelength pulses: Study of Autler-Townes splitting and XUV emission spectra, NATHAN HARKEMA, CHEN-TING LIAO, ARVINDER SANDHU, University of Arizona — Attosecond transient absorption spectroscopy (ATAS) enables the study of excited electronic dynamics with unprecedented temporal and energy resolution. Many ATAS experiments use an extreme ultraviolet (XUV) pump pulse and a near-infrared (NIR) probe fixed at the fundamental laser frequency (∼ 800 nm) to study the light induced effects on electronic structure of atoms and molecules. We extend the technique by using an optical parametric amplifier in one arm of our setup, which allows us to independently tune the frequency of the probe pulse from 1200 to 1800 nm. These long-wavelength pulses allow us to explore a new regime, where we can control the couplings between nearby electronic states to alter the transient absorption line-shapes in atoms. We use this technique to investigate the 4p-3s detuning dependent Autler-Townes splitting of the 4p state in Helium. Light induced Floquet structures extending into the vacuum continuum are observed in our study. We demonstrate new tunable XUV emission channels from four-wave mixing processes, and the efficiency of these emissions can be strongly enhanced through resonant couplings. The tunable IR induced electronic couplings are also used to influence the autoionization dynamics in Argon.

2:48PM C5.00005 Pulse-parameter dependence of nuclear “attosecond time delays”, GREG ARMSTRONG, D. URSREY, J. V. HERNANDEZ, F. ANIS, T. SEVERT, M. ZOHRAHI, BEN BERRY, PEYMAN FEIZOLLAH, BETHANY JOCHIM, KANAKA RAJU P., J. MCKENNA, B. GAIRE, K. D. CARNES, I. BEN-ITZHAK, B. D. ESRY, J. R. Macdonald, GREG ARMSTRONG, BERNICE RANSOM, ARVINDER SANDHU, University of Arizona — We report on the effects of electron correlation on the time-delay in photoionization of atomic beryllium in the channels $\text{Be}((1s^22s^2)\;^1S^+)\rightarrow\text{Be}^+(1s^22s\;^2S^1)+e^- (p\text{-electron})$, and $\text{Be}((1s^22s^2)\;^1S^+)\rightarrow\text{Be}^+(1s^22p\;^2P^0)+e^- (s\text{ or } d\text{ electron})$. We use our recent three-dimensional implementation of the time-dependent restricted-active-space self-consistent-field method and study the changes in the value obtained for the time-delay when including more and more correlation. We find that the mean-field, time-dependent Hartree-Fock theory does not account accurately for the time-delay. A larger active orbital space is needed. We find that the relative time-delay between ionization into $\text{Be}^+(1s^22s\;^2S^1)$ and $\text{Be}^+(1s^22p\;^2P^0)$ is around 7-8 attoseconds.

This work is supported by NSF Grant No. PHY-1505556 and ARO Grant No. W911NF-14-1-0383.

310 - Session C5 Time-Resolved Electron Dynamics and Attosecond Spectroscopy —
Johan Mauritzson, Lund University

Tuesday, June 6, 2017 2:00PM - 4:00PM —
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3:00PM C5.00006 An Attosecond Transient Absorption Spectroscopy Setup with a Water Window Attosecond source\(^1\), ANDREW CHEW, YANCHUN YIN, JIE LI, XIAOMING REN, YANG WANG, YI WU, ZENCHU CHANG, Univ of Central Florida — Attosecond transient absorption, or time-resolved pump-probe spectroscopy, are excellent tools that can be used to investigate fast electron dynamics for a given atomic or molecular system. Recent push for high energy long wavelength few cycle laser sources has resulted in the production of x-ray spectra that would allow the probing of electron dynamics at the carbon k-edge in molecules such as CH\(_4\) and CO\(_2\). The motion of charges can be caused by photo-dissociation and charge migration. We present here the first results from our experimental setup where we produce a broadband attosecond pulse with spectra that stretches into the water window.

\(^1\)National Science Foundation (1068604), Army Research Oce (W911NF-14-1-0383), Air Force Oce of Scientific Research (FA9550-15-1-0037, FA9550-16-1-0013) and the DARPA PULSE program by a grant from AMRDEC (W31P4Q1410017)

3:12PM C5.00007 A comparative study of attosecond photoelectron streaking spectroscopy of metallic nanospheres\(^1\), JIANKIONG LI, ERFAN SAYDANZAD, UWE THUMM, Kansas State University — We present new numerical results for streaked photoemission from Au, Ag, and Cu nanospheres by an extreme ultraviolet (XUV) and an infrared (IR) or visible streaking pulse, based on a quantum-mechanical model \([1]\). We discuss significant plasmonic streaking oscillation-amplitude enhancements and phase shifts for all three metals, relative to the results excluding the induced plasmonic field near the nanoparticle surface. Based on our streaked spectra, we demonstrate the reconstruction of the plasmonic-field enhancement and phase shift for each material, suggesting the use of attosecond streaking spectroscopy to reveal the dielectric plasmonic response of nanoparticles in the IR and visible spectral range. \([1]\) J. Li, E. Saydanzad, and Uwe Thumm, Phys. Rev. A 94, 051401(R) (2016).

\(^1\)Supported by the US NSF-EPSCoR program, US NSF, and US DoE.

3:24PM C5.00008 Control of photoemission delay in resonant two-photon transitions\(^1\), L. ARGENTI, Univ. Central Florida, FL, USA; Univ. Autonoma de Madrid, ES, EU (UAM), A. JIMENEZ GALAN, Max Born Inst. Berlin, D, EU; UAM, R. TAIEB, J. CAILLAT, A. MAQUET, Sorbonne Univ.; UPMC Univ. Paris 6, FR, EU, F. MARTIN, UAM; IMDEA-Nanociencia, IFIMAC, Madrid, ES, EU — The emission time delay \(\tau\) in one-photon absorption, which coincides with half the Wigner scattering delay \(\tau_W\), is a fundamental descriptor of the photoelectric effect. While it is hard to access \(\tau\) in a direct way, it is possible to extrapolate it from the delay in two-photon transitions, \(\tau(2)\), measured with attosecond pump-probe schemes, provided that the contribution of the probe stage can be factored out. In absence of resonances, \(\tau\) can be expressed as the energy derivative of the dipole ionization amplitude, \(\tau = (2Eg \arg D_{Eg})\), and \(\tau \simeq \tau(2) - \tau_{cc}\) where \(\tau_{cc}\) is associated to the dipole transition in the continuum. Here we show that in the presence of a resonance the correspondence between \(\tau\) and \(\tau(2)\) is lost. Furthermore, while \(\tau(2)\) still coincides with \(\tau_{cc}\), it does not have any scattering counterpart. Indeed, \(\tau(2)\) can be much larger than the lifetime of an intermediate resonance in the two-photon process, or more negative than the lower bound imposed on scattering delays by causality. Finally, \(\tau(2)\) is controlled by the probe frequency. By varying \(\omega_{IR}\), therefore, it is possible to radically alter a photoelectron group delay.

\(^1\)NSF Grant No. 1607588, ERC Grant No. 290853 XCHEM, MINECO FIS2013-42002-R/FIS2016-77889-R, e-COST Action XLIC CM1204.

3:36PM C5.00009 Electron Matter-Wave Vortices in Double Photoionization of Helium by Attosecond Pulses\(^1\), JEAN MARCEL NGOKO DJIJKAP, The University of Nebraska - Lincoln, ALEXEI V. MEREMI-ANIN, NIKOLAI L. MANAKOV, Voronezh State University, SUXING HU, University of Rochester, LARS B. MADSEN, Aarhus University, ANTHONY F. STARACE, The University of Nebraska - Lincoln — Double photoionization of helium by a pair of time-delayed circularly-polarized attosecond pulses is shown to produce two-electron momentum distributions that exhibit two-start spiral vortex structures. These structures originate from Ramsey interference of the created pair of two-electron wavepackets, each carrying a total angular momentum of unity. The predicted vortex-shaped patterns occur for any energy partitioning between electrons, and are experimentally sensitive to the time delay between the two pulses, their relative phase, their ellipticity and handedness. Moreover, these kinds of vortices occur for both in-plane and out-of-plane detection geometries; however, they only take place when the angular separation \(\varphi_1 - \varphi_2\) between the electron momenta is held fixed. Our results are obtained by solving \(ab\) \textit{ab initio} the seven-dimensional two-electron time-dependent Schrödinger equation and are analyzed using a perturbation theory. Such vortices are thus general phenomena, as similar patterns have been reported following single-electron ionization in both atomic and molecular processes.

\(^1\)Research supported in part by DOE, BES, Chem. Sciences, Geosciences and Biosciences Div., Grant No. DE-FG03-96ER14646.

3:48PM C5.00010 Spectral Signatures of Resonantly Enhanced High Harmonic Generation and the Influence of Quantum\(^1\), SETH CAMP, Louisiana State University, SAMUEL BEAULIEU, Université de Bordeaux, INSTITUT NATIONAL DE LA RECHERCHE SCIENTIFIQUE; YANN MAIRESE, Université de Bordeaux, KENNETH SCHAFER, METTE C.M.1204.

\(^1\)Supported by the US NSF-EPSCoR program, US NSF, and US DoE.

Tuesday, June 6, 2017 2:00PM - 4:00PM –
Session C6 Sensing and Quantum Interferometry 311-312 - Ron Walsworth, Harvard University
2:00PM C6.00001 Environment-assisted quantum sensing with entangled states of electronic spins in diamond , ALEXANDRE COOPER, California Institute of Technology, WON KYU CALVIN SUN, JEAN-CHRISTOPHE JASKULA, PAOLA CAPPELLARO, Massachusetts Institute of Technology — Entangled states of spins in solid-state materials have been proposed to enhance the performance of quantum sensors, but their physical realization has been hindered by the difficulty of accessing ensembles of electronic spins that can be initialized, manipulated, and readout with high fidelity. Here we present experimental measurements of time-varying magnetic fields with entangled states of electronic spins associated with a single nitrogen-vacancy center and two paramagnetic centers in diamond. These measurements rely on a series of coherent control techniques to identify unknown quantum systems in the environment of a single quantum probe and convert them into quantum resources available for scaling up quantum systems and achieving improvements in sensitivity.

2:12PM C6.00002 Understanding coherence of Nitrogen nuclear spin in NV centers , MO CHEN, WON KYU CALVIN SUN, JEAN-CHRISTOPHE JASKULA, KASTURI SAHA, PAOLA CAPPELLARO, Massachusetts Inst of Tech-MIT — The native nitrogen nuclear spin in nitrogen-vacancy (NV) center proves a useful resource for quantum information storage and coherent feedback control. However, its T2 coherence time falls much shorter than the T1 relaxation time, due to interactions with the NV electronic spin. NV electronic spin flips due to T1 process, which acts as a random telegraph noise (RTN), dephasing the nitrogen nuclear spin. Here we study this decoherence process, comparing experiments with the RTN model, and show the efficiency of harnessing dynamical decoupling to fight against such noise.

2:24PM C6.00003 Characterization and initialization of molecular defects in diamond as a testbed for single-molecule NMR1 , EMMA ROSENFELD, Harvard Univ, DOMINIK BUCHER, Harvard-Smithsonian Center for Astrophysics, LINH PHAM, Lincoln Laboratory, JUNGHYUN LEE, ERIK BAUCH, CONNOR HART, FRANCESCO CASOLA, Harvard University, RONALD WALSWORTH, Harvard University, Harvard-Smithsonian Center for Astrophysics — Nitrogen vacancy (NV) centers in diamond enable promising applications in nanoscale magnetic resonance and manipulation of spins. In particular, single-molecule NMR as well as coherent control of individual electronic and nuclear spins on the diamond surface remain long-standing goals in the NV community. Surface physics challenges, such as background spins and strain, are currently prohibitive of such protocols. In this talk, I will discuss progress towards using molecular defects inside the diamond as a testbed for various NMR pulse sequences and quantum information protocols, ultimately as a step towards single molecule NMR and coherent manipulation of spin networks on the diamond surface.

2:36PM C6.00004 Nanoscale Spin Radar with Nitrogen Vacancy centers in Diamond , YIXIANG LIU, Research Lab of Electronics, MIT Cambridge MA, ASHOK AJOY, University of California Berkeley, CA, PAOLA CAPPELLARO, Research Lab of Electronics, MIT Cambridge MA — Nitrogen Vacancy (NV) centers in diamond have emerged as the preeminent platform for nanoscale magnetic resonance imaging. The NV center acts a single point dipole that can image the presence of spins in its environment by exploiting the anisotropy of the dipole-dipole Hamiltonian that governs the interactions between the spins. Indeed, the NV center can be pictured to be an antenna with that senses spins with a specific angular sensing “lobe”. In this work, we show this anisotropic interaction can be effectively manipulated by the application of strong pulsed DC magnetic fields. This allows the calibrated rotation of the NV angular sensing lobe, allowing one to tuneably scan the space around an NV center, and through it reconstruct the real-space spin density with high spatial resolution.

2:48PM C6.00005 Sensing rotationally-induced magnetic fields with nitrogen-vacancy centers in diamond , ALEXANDER WOOD, EMMANUEL LILETTE, YAAKOV FEIN, School of Physics, University of Melbourne, VIKTOR PERUNICIC, DAVID SIMPSON, ALASTAIR STACEY, LLOYD HOLLENBERG, School of Physics, University of Melbourne and CQC2T, University of Queensland, ROBERT SCHOLTEN, ANDY MARTIN, School of Physics, University of Melbourne — The Larmor theorem states that the effects of a uniform magnetic field on a classical magnetic moment are equivalent to rotation of the system about the axis of the field. We use nitrogen-vacancy (NV) centers in a diamond to detect the effective magnetic field generated by physically rotating the host diamond crystal. Rotationally-induced magnetic fields depend on the rotation axis and the magnetic field orientation, and perturb the precession frequency of carbon-13 nuclear spins in the diamond lattice much more strongly than the NV electron spin. We detect the precessing nuclear magnetic dipole field with an ensemble of NV sensors to infer the rotationally-induced field. These results elucidate the profound connection between magnetism and physical rotation, and establish a unique, non-magnetic means of controlling the nuclear spin bath surrounding the NV center.

3:00PM C6.00006 Coherent control of single electron spins in levitated optomechanics experiments1 , ROBERT M. PETTIT, Univ of Rochester, LEVI P. NEUKIRCH, Los Alamos National Laboratory, YI ZHANG, A. NICK VAMIVAKAS, Univ of Rochester — We report progress on the coherent manipulation of single electron spins contained within optically levitated nanodiamond in a free-space optical dipole trap. Nitrogen-vacancy (NV) centers in diamond provide an ideal platform for room temperature spin manipulation, and are thus well suited for use in optical trapping schemes. Here, we demonstrate coherent control of a single NV center spin at both atmospheric pressure and low vacuum, and show that while the trapping beam reduces the fluorescence emitted by the center, it has no observable effect on the transverse spin coherence time. Furthermore, after an initial exposure to low vacuum, the nanodiamond remains at near room temperatures at all pressures and trapping powers considered in these experiments.

3:12PM C6.00007 Path integral treatment of the Hanbury Brown-Twiss effect for pulsed electron matter wave1 , SAM KERAMATI, ERIC JONES, HERMAN BATELAAN, University of Nebraska - Lincoln — Hanbury Brown-Twiss (HBT) anticorrelations for a continuous beam of free electrons were claimed to be observed in 2002 [1]. The recent advent of femtosecond electron pulses has motivated us to pursue the HBT effect for pulsed electron beams with unprecedentedly higher phase space degeneracies. To provide a rigorous theoretical description of this problem, the quantum decoherence of a two-electron pulsed beam upon entanglement with a two-state emitter will be considered first. The two-particle state will then be propagated in space and time toward a detector using Feynman’s path integral formalism. Effects of the partial temporal coherence in this system will also be taken into account which is an improvement built on an earlier work published in our group [2]. The method can ultimately be extended to include the Coulomb repulsion along with the Pauli exclusion principle. [1] H. Kiesel, A. Renz, and F. Hasselbach, Nature 418, 392 (2002). [2] P. Lougovski, and H. Batelaan, Phys. Rev. A 84, 023417 (2011).

1Supported by the Office of Naval Research, award number N00014-14-1-0442.

1We acknowledge support by NSF under the award number 1602755.
A novel variation on the SU(1,1) interferometer for phase sensing beyond the standard quantum limit, B. M. Henson et al., Phys. Rev. Lett. will be compared with recent relativistic CI calculations. The device is designed to measure $h/m$, where $h$ is Planck's constant and $m$ is the mass of a Yb atom, in order to determine the fine structure constant $\alpha$. The use of the non-magnetic Yb atom and the symmetric geometry of the interferometer makes the measurement immune to several error sources. The narrow momentum and position spread of a Bose-Einstein condensate (BEC) contrast interferometer makes the measurement immune to several error sources. The narrow momentum and position spread of a Bose-Einstein condensate (BEC) contrast interferometer makes the measurement immune to several error sources.

Quantum metrology in a multiport linear optical interferometer, WENCHAO GE, MICHAEL FOSS-FEIG, KURT JACOBS, US Army Research Lab — Quantum metrology explores the benefits of quantum coherence and entanglement for making precision measurements. Here we study the ability of a network of beam-splitters and phase shifters (a “multiport linear optical interferometer”) to perform phase metrology using separable input states. Even though such linear networks are able to generate complex entangled states, we show that when each input is an arbitrary Fock state they are not able to achieve Heisenberg scaling in the number of input modes. This result suggests that there is a sense in which linear networks, and more generally linear dynamics, cannot produce metrologically useful entanglement from separable inputs. This result also raises further questions about the nature of the entanglement that can be generated by linear dynamics, and the types of non-classical input states required to generate metrologically useful entanglement.

Initial Phase Dependence of the Sagnac Effect for Matter Waves, MARTIN KANDES, University of California, San Diego, MICHAEL BROMLEY, The University of Queensland, RICARDO CARRETERO, San Diego State University — We simulate the interference between two counterpropagating matter wave packets confined to a uniformly rotating, circular ring potential in order to study the dynamics of a simple matter wave Sagnac interferometer. Here, we show that the initial phase of the wave packets themselves determines how the Sagnac phase shift accumulates as a function of time. Most interestingly, we find that the phase shift occurs in discrete phase jumps when the wave packets start at rest with respect to the rotating reference frame of the system.

Measuring the fine structure constant with Bragg diffraction and Bloch oscillations, RICHARD PARKER, CHENCHU YU, WEICHENG ZHONG, BRIAN ESTEY, HOLGER MILLER, Univ of California - Berkeley — We have demonstrated a new scheme for atom interferometry based on large-momentum-transfer Bragg beam splitters and Bloch oscillations. In this new scheme, we have achieved a resolution of $\approx 0.25$ ppb in the fine structure constant measurement, which gives over 10 million radians of phase difference between freely evolving matter waves. We have suppressed many systematic effects known in most atom interferometers with Raman beam splitters such as light shift, Zeeman effect shift as well as vibration. We have also simulated multi-atom Bragg diffraction to understand sub-ppb systematic effects, and implemented spatial filtering to further suppress systematic effects. We present our recent progress toward a measurement of the fine structure constant, which will provide a stringent test of the standard model of particle physics.

Scaling up precision in an Ytterbium BEC contrast interferometer for photon recoil and $\alpha$, BENJAMIN PLOTKIN-SWING, DANIEL GOCHNAUER, KATHERINE MICALPINE, SUBHADEEP GUPTA, Univ of Washington — Building on our earlier demonstration, we are now operating a second-generation Ytterbium (Yb) Bose-Einstein condensate (BEC) contrast interferometer. The device is designed to measure $h/m$, where $h$ is Planck's constant and $m$ is the mass of a Yb atom, in order to determine the fine structure constant $\alpha$. The use of the non-magnetic Yb atom and the symmetric geometry of the interferometer makes the measurement insensitive to several error sources. The narrow momentum and position spread of a BEC help improve the coherence length and signal strength of our measurement. A key advantage of the contrast interferometer is that the total phase accumulation and therefore the measurement sensitivity scales quadratically with the momentum separation of the interfering states. We have demonstrated the laser pulse atom-optics required to increase the momentum splitting, including using Bloch oscillations to impart 200 recoil recoils with 5% atom loss per recoil. We have implemented the first steps in applying these high momentum transfer techniques to our interferometer, and will report on our progress towards achieving quadratically increased precision.

The tune-out wavelength for the 1s2s$^2$S − 1s3p$^3$P transition of lithium: relativistic effects, GORDON W.F. DRAKE, JACOB MANALO, University of Windsor — The tune-out wavelength is the wavelength at which the frequency dependent polarizability of an atom vanishes. It can be measured to very high precision by means of an interferometric comparison between two beams. This paper is part of a joint theoretical/experimental project with K. Baldwin et al. (Australian National University) and L.-Y. Tang et al. (Wuhan Institute of Physics and Mathematics) to perform a high precision comparison between theory and experiment as a probe of atomic structure, including relativistic and quantum electrodynaminc effects. We will report the results of calculations for the tune-out wavelength that is closest to the 1s2s$^2$S − 1s3p$^3$P transition of $^3$He. Our result for the $M = 0$ magnetic substate, obtained with a fully correlated Hylleraas basis set, is $413.0795851(12)$ nm. This includes a leading relativistic contribution of $-0.059218.5(16)$ nm from the Breit interaction as a perturbation, and a relativistic recoil contribution of $-0.000044.7(17)$ nm. The results will be compared with recent relativistic CI calculations.

Research supported by the Natural Sciences and Engineering Research Council of Canada.

Funding: NSF
Towards Precision Measurement of the $^2S_0-^3D_2$ Two-Photon Transition in Atomic Helium.  

YI-JAN HUANG, YU-CHAN GUAN, Institute of Photonics Technologies, National Tsing Hua University, TE-HWEI SUEN, LI-BANG WANG, Department of Physics, National Tsing Hua University, JOW-TSONG SHY, Institute of Photonics Technologies, National Tsing Hua University — We intend to accurately measure the frequency for $^2S-^3D$ two-photon transition and to deduce the $2S$ ionization energy to an accuracy below 100 kHz from the theoretical calculation of the $3D$ state. In this talk, we present a precision measurement of the $^2S^2S-^3D^2_2$ two-photon transition in atomic helium at 1009 nm. A master oscillator power amplifier (MOPA) is seeded by an external cavity diode laser (ECDL) is constructed to generate more than 700 mW laser power with TEM00 beam profile at 1009 nm. To observe the two-photon transition, a helium cell is placed inside a power enhancement optical cavity and the helium atoms at $^2S$ metastable level are prepared by a pulsed RF discharge and monitor the 668 nm $^3D^2_2-^2P^1$ fluorescence after RF discharge is turned off. The absolute frequency metrology of the ECDL is carried out by an Er-fiber optical frequency comb (OFC). The two-photon spectrum is obtained by tuning the repetition frequency of the OFC. The $^2S^2S-^3D^2_2$ frequency is determined to be 59441491.967 (80) MHz in He-4. More results will be presented at the annual meeting.

Precision spectroscopy of the 2S-4P transition in atomic hydrogen,  
LOTHAR MAISENBACHER, AXEL BEYER, ARTHUR MATVEEVE, ALEXYE GRIGIN, Max Planck Institute of Quantum Optics (MPQ), RANDOLF POHL, MPQ and Johannes Gutenberg University, Mainz, KSENIA KHABAROVA, NIKOLAI KOLACHEVSKY, Lebedev Physical Institute, Moscow, THEODOR W. HANSCH, MPQ and Ludwig Maximilians University, Munich, THOMAS UDEM, MPQ — Precision measurements of atomic hydrogen have long been successfully used to extract fundamental constants and to test bound-state QED. However, both these applications are limited by measurements of hydrogen lines other than the very precisely known 1S-2S transition. Moreover, the proton r.m.s. charge radius $r_p$ extracted from electronic hydrogen measurements currently disagrees by 4σ with the much more precise value extracted from muonic hydrogen spectroscopy. We have measured the 2S-4P transition in atomic hydrogen using a cryogenic beam of hydrogen atoms optically excited to the initial 2S state. The first order Doppler shift of the one-photon 2S-4P transition is suppressed by actively stabilized counter-propagating laser beams and time-of-flight resolved detection. Quantum interference between excitation paths can lead to significant line distortions in our system. We use an experimentally verified, simple line shape model to take these distortions into account. With this, we can extract a new value for $r_p$ and the Rydberg constant $R_h$ with comparable accuracy as the combined previous H data world.

Forbidden M1 and E2 transitions in monovalent atoms and ions,  
W. R. JOHNSON, University of Notre Dame, U. I. SAFRONOVA, University of Nevada, Reno, M. S. SAFRONOVA, University of Delaware and JQI, NIST and the University of Maryland — We carried out a systematic high-precision relativistic study of the forbidden magnetic-dipole and electric-quadrupole transitions in Ca$^{+}$, Cs, Ba$^{2+}$, Fr, Ra$^{2+}$, Ac$^{3+}$ and Th$^{3+}$. This work is motivated by the importance of these transitions for tests of fundamental physics and precision measurements. The relative importance of the relativistic, correlation, Breit correction and contributions of negative-energy states is investigated. Recommended values of reduced matrix elements are presented together with their uncertainties. The matrix elements and resulting lifetimes are compared with other theoretical values and with experiment where available.

Near-degeneracy in Excited Vibrational States of $^{207}$PbF,  
RICHARD MAWHORTER, ALEXANDER NGUYEN, YONGRÁK KIM, ANDREAS BIEKERT, Pomona College, TREVOR SEARS, Stony Brook University and Brookhaven National Laboratory, JENS-UWE GRABOW, Leibniz Universitait Hannover, Â.D. KUDASHOV, L.V. SKRIPNIKOV, A.V. TITOV, A.N. PETROV, NRC Kurchatov Institute PNPI, & St. Petersburg State University — High-resolution Fourier transform microwave (FTMW) spectroscopy studies of $^{207}$PbF [1,2] have demonstrated the near-degeneracy of two levels of opposite parity. These have attracted attention for the study of parity violation effects and the variation of fundamental constants [3] using $^{207}$PbF. Further theoretical work has improved our detailed understanding of both $^{207}$PbF and $^{208}$PbF [4], and furthermore recently indicated that the finely split $^+/-$ parity levels grow monotonically closer for higher vibrational states. Our experimental results for $v = 0-3$ confirm this, and are in excellent agreement with our extended theoretical calculations up to $v = 4$; both will be presented. TJS acknowledges support from Contract No. DE-SC0012704 with the U.S. Department of Energy, Office of Science, supported by its Division of Chemical Sciences, Geosciences and Biosciences within the Office of Basic Energy Sciences., as do RM, AB, YK, & AN from Pomona College & J-UG from the Deutsche Forschungsgemeinschaft (DFG). 1. L.D. Alphie, et al., Phys. Rev. A 83, 040501 (R) (2011), 2. R. Mawhorter, et al., Phys. Rev. A 84, 022508 (2011), 3. V.V. Flambaum, et al., Phys. Rev. A 88, 052124 (2013), 4. A.N. Petrov, et al., Phys. Rev. A 88, 010501 (R) (2013).

Isotope shifts in the 7S → 8S transition of francium: measurements and comparison to ab-initio theory.  
MUKUT KALITA, JOHN BEHR, ALEXANDRE GORELOV, MATTHEW PEARSON, TRIUMF, AUSTIN DEHART, GERALD GWINNER, MICHAEL KOSLIN, U. of Manitoba, SETH AUBIN, C. of William and Mary, EDUARDO GOMEZ, Instituto de Fisica, UASLP, LUIS A. OROZO, JIQI, Physics, U. of Maryland and NIST, VLADIMIR DZUBA, VICTOR FLAMBAUM, School of Physics, U. of New South Wales, MARIANNA SAFRONOVA, U. of Delaware and JQI, U. of Maryland and NIST — The Standard Model can be tested at low energies by probing parity non-conservation (PNC) effects in atomic systems. At the francium trapping facility at TRIUMF, we are developing a Stark interference experiment to probe PNC in neutral francium atoms using the 7S → 8S atomic transition. We have observed this transition in francium using two-photon spectroscopy. This allows the extraction of the isotope shifts of the 8S state. We have measured the shifts on five isotopes $^{206,208,209,210,212}$Fr of cold trapped atoms. Using our previously measured isotope shifts of the 7P$_{3/2}$ level we can extract the ratio of field shift constants and the relation between specific mass shift constants. The experimental results will be compared to recent ab-initio calculations.

Isotope shifts in 7S → 8S transition of francium: measurements and comparison to ab-initio theory

Funded by NSERC, NRC/TRIUMF, DOE, NSF, CONACYT, Australian Research Council and U. of Manitoba.

Abstract Withdrawn
2:00PM C8.00001 Simulating a Quantum Phase Transition with a Surface Electrode Ion Trap, BICHEN ZHANG, OMID KHOSRAVANI, GANG SHU, KENNETH BROWN, Georgia Inst of Tech — The Rabi model describes the interaction of a two-level atom with a quantized electromagnetic field. The model is predicted to have a quantum phase transition (QPT) between a normal and superradiant phase depending on the strength of the interaction. A recent proposal describes how the QPT can be simulated using a trapped ion where the quantized modes of motion simulate the electromagnetic field. The simulation is controlled by an external laser that drives transitions coupling the internal state of the ion to its motion. For this simulation it is critical that the carrier transition, which only changes the internal state, is suppressed. We have demonstrated that the relative coupling strength of ion-motion sidebands to the carrier can be controlled by positioning the ion in a standing wave beam. Here we present our results on optimizing the suppression of the carrier and our progress towards simulating the QPT.


2:12PM C8.00002 Development of a Phonon Toolbox on a Surface Electrode Trap†, K. WRIGHT, K. BECK, D. ZHU, K. COLLINS, C. MONROE, University of Maryland — We report on our current experimental progress towards using a surface electrode trap for quantum simulation with Yb$^{++}$ ions. Currently, we are developing a toolbox for creating, manipulating and reading out phonon occupations in all normal modes of a three ion chain. Using shuttling, composite pulse sequences, and state distillation, we prepare given phonon number-states in these modes and show that these states preserve spin-motion coherence. The prepared state is read out either through a single sideband operation or through a STIRAP process. The sideband operation gives a binary measurement of phonon(s) vs. no phonon occupation; the STIRAP process is sensitive to the number-state occupation. We also engineer coherent couplings between normal modes through optical dipole forces, manipulating the prepared state to sample interacting Bosonic modes.

†This work is supported by ARO with funding from the IARPA LogiQ program.

2:24PM C8.00003 Phonon Effects on Trapped Ion Quantum Simulators, JEFFREY COHN, JAMES FREERICKS, Georgetown University — Trapped ion quantum simulators are beginning to scale in size further than the ability of classical computers to efficiently benchmark results. Nevertheless, if one examines a ferromagnetic coupling between spins, with an all-to-all coupling in a transverse field Ising model, then the system has extra symmetry, which allows simulators with 100s of spins to be described with a classical computer. Here, we examine the laser-driven coupling between a center-of-mass (COM) phonon and the spins, which produces such an all-to-all coupling for the effective spin model, when one is detuned to the blue of the COM mode. We examine the full time dependence for different ramping profiles of the transverse field including a shortcut to adiabaticity called the bang-bang protocol. Our results show that keeping track of real phonon creation and the resultant phonon-spin entanglement actually helps the system to be described by a static Ising model. But, this comes at a price. While the probabilities for the final state to be in the ground state improve over what is seen in a time-dependent spin system, the spin entanglement in the ground state is suppressed, when the phonons are not explicitly measured.

2:36PM C8.00004 Engineering effective 2D Hamiltonians from 1D ion chains, ASHOK AJOY, University of California Berkeley, CA, RAJIBUL ISLAM, Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Ontario N2L 3G1, Canada — The lattice geometry in 2D systems affords one the ability to study a rich variety of physical phenomena – from quantum transport and localization, topological insulators and the Haldane model and in topological quantum computation. Ion traps have emerged as the preeminent platform for quantum simulation, where it would be desirable to simulate several of these 2D Hamiltonian models. The long-ranged Coulomb mediated spin-spin interactions in an ion trap make this possible in conventional radio-frequency ion traps where the ions are often arranged in a linear geometry. In this work, we describe a method for the Floquet engineering of 2D nearest neighbor Hamiltonian models from a linear chain of ions. Each cycle of the periodically driven dynamics consists of a calibrated radio-frequency ion traps where the ions are often arranged in a linear geometry. In this work, we describe a method for the Floquet engineering of 2D nearest neighbor Hamiltonian models from a linear chain of ions. Each cycle of the periodically driven dynamics consists of a calibrated radio-frequency ion traps. The normal modes of motion are coupled by a trilinear Hamiltonian $\hbar \omega_c - i \hbar c + h.c.$ and represent “hot”, “work” and “cold” bodies of the refrigerator. We investigate the equilibrium properties of the refrigerator, and demonstrate the absorption refrigeration effect with the modes being prepared in thermal states. We also investigate the coherent dynamics and steady state properties of such a system away from equilibrium operation. We compare the cooling capabilities of thermal versus squeezed thermal states prepared in the work mode as a quantum resource for cooling. Finally, we exploit the coherent dynamics of the system and demonstrate single-shot cooling in the refrigerator. By stopping the evolution in the right moment, we show a significant advance in cooling as compared to both the steady state and equilibrium performance.

3:00PM C8.00005 Quantum Information with 2-D Ion-Trap Arrays, ANDREW WILSON, KATHERINE MCCORMICK, SUSANNA TODARO, DANIEL SLICHTER, JONAS KELLER, DIETRICH LEIBFRIED, DAVID WINELAND, National Institute of Standards & Technology — Laboratory efforts on trapped-ion quantum information are currently focused on two distinct trap architectures – segmented linear traps and 2D trap arrays. In 2D-ion-trap-arrays, each ion is located in its own individually-controllable trapping well, so that interactions between selected ions can be tuned and different array patterns can be fabricated. These features are likely to be useful for a variety of applications in both quantum simulation and computing. Recently we demonstrated quantum entanglement between two ions in separate trapping wells, and now we are standing wave beam. Here we present our results on optimizing the suppression of the carrier and our progress towards simulating the QPT.

1This research is supported by the National Research Foundation, Prime Ministers Office, Singapore and the Ministry of Education, Singapore under the Research Centres of Excellence programme.
transitions, such as molecules. This “sweep cooling” mechanism also shows promise for application to systems lacking closed cycling cycles that are repeatedly swept over the transition frequency. A reduced reliance on spontaneous emission (compared to Doppler cooling) allows for optical transitions. The particles are adiabatically transferred to lower momentum states upon interaction with counter-propagating laser beams.

BARTOLOTTA, MURRAY HOLLAND, MATTHEW NORCIA, JAMES THOMPSON, JULIA CLINE, Department of Physics and JILA, University of Colorado Boulder, Boulder — We study sympathetic cooling with the secondary species of ions, to mediate spin synchronization in the primary species of ions. Our numerical study shows that spin-spin correlations develop, leading to a macroscopic collective spin in steady-state. We propose an experimental method based on Ramsey interferometry to detect signatures of this collective spin; we predict that correlations prolong the visibility of Ramsey fringes, and that population statistics at the end of the Ramsey sequence can be used to directly infer spin-spin correlations.

3:24PM C8.00008 Steady-state spin synchronization through the collective motion of trapped ions. ATHREYA SHANKAR, JOHN COOPER, JILA, NIST, and Department of Physics, University of Colorado Boulder, Boulder, JUSTIN BOHNET, JOHN BOLLINGER, Time and Frequency Division, National Institute of Standards and Technology, Boulder, MURRAY HOLLAND, JILA, NIST, and Department of Physics, University of Colorado Boulder, Boulder — Ultranarrow-linewidth atoms coupled to a lossy optical cavity mode synchronize, i.e. develop correlations, and exhibit steady-state superradiance when continuously repumped. This type of system displays rich collective physics and promises metrological applications. These features inspire us to investigate if a model inspired from cavity superradiance can generate analogous spin synchronization in a different platform that is one of the most robust and controllable experimental testbeds currently available: ion-trap systems. We design a system with a primary and secondary species of ions that share a common set of normal modes of vibration. In analogy to the lossy optical mode, we propose to use a lossy normal mode, obtained by sympathetic cooling with the secondary species of ions, to mediate spin synchronization in the primary species of ions. Our numerical study shows that spin-spin correlations develop, leading to a macroscopic collective spin in steady-state. We propose an experimental method based on Ramsey interferometry to detect signatures of this collective spin; we predict that correlations prolong the visibility of Ramsey fringes, and that population statistics at the end of the Ramsey sequence can be used to directly infer spin-spin correlations.

3:36PM C8.00009 Experimental measurement of correlation functions in trapped ions1, SHUJIANING ZHANG, YANGCHAO SHEN, YAO LU, KUAN ZHANG, JING-NING ZHANG, KIHWAN KIM, Center for Quantum Information, IIIS, Tsinghua University, Beijing, P. R. China, J. S. PEDERNALES, LUCAS LAMATA, ENRIQUE SOLANO, Department of Physical Chemistry, University of the Basque Country UPV/EHU, Bilbao, Spain, J. CASANOVA, Institut fr Theoretische Physik, Universitut Ulm, Ulm, Germany — We measure the time-correlation functions of spins and phonons of a system that evolves under a Hamiltonian of Jaynes-Cumming model or Dirac equation with trapped 171Yb+ ions. The algorithm proposed in Ref. [1] requires only one ancilla qubit to obtain the time correlations of the observables in the system. In the experiment, conditional gates depending on the state of the ancilla, spin-dependent force and spin-independent force have been performed. We measure the spin-spin time-correlations in spin system and the spin-phonon time-correlations in bosonic field. According to the linear response theory, the time-correlations can be characterized to relevant physical magnitude such as magnetic susceptibility. This scheme can be extended to a system including n-time spins and phonons correlations. [1] J. S. Pedernales, et al., Phys. Rev. Lett. 113, 020505 (2014).

3:48PM C8.00010 Performance Characterization of a Scalable Trapped Ion Based Quantum Computer. STEPHEN CRAIN, CHAO FANG, GEERT VRUJSEN, JAMES JOSEPH, JUNGSANG KIM, Duke University — The rapid progress towards a scalable platform for atomic ion based quantum computing has resulted in a need for a careful characterization of the initial performance of basic qubit functions. This work characterizes the error rate for state readout, measurement crosstalk, and single qubit gates for a 171Yb+ qubit in a surface trap. Photons scattered from the qubit are coupled into a multimode fiber using a high numerical aperture lens (0.6 NA) and directed towards a superconducting nanowire single photon detector (SNSPD). State dependent fluorescence is used to determine the state of the qubit, with an average state detection time of 12.3 µs and 6.9(5) × 10−4 detection error. To characterize measurement crosstalk between two qubits, a measurement is performed on one qubit using a focused detection beam, and the coherence of a second qubit is measured as a function of the distance between the two. Gate set tomography is used for the characterization of global single qubit gates driven by a microwave field (5.6) × 10−4 Rπ (±1) error). Individual single qubit gates and two qubit gates driven by Raman transitions will be performed and characterized with temporarily focused beams steered across the qubits by tilting MEMS mirrors.

Tuesday, June 6, 2017 2:00PM - 4:00PM – Session C9 Laser Cooling
2:00PM C9.00001 ABSTRACT WITHDRAWN –

2:12PM C9.00002 Novel Cooling Of Ultracold Atoms Using Spatially Selective Optical Pumping. JONATHAN GILBERT, JACOB ROBERTS, Colorado State University — A novel cooling technique for ultracold gases will be presented. This technique has relatively few requirements for particular properties of the ultracold gas and thus should be widely applicable. A detailed description of how the cooling technique works will be presented, along with specific predictions for the cooling of an ultracold gas of 87Rb confined in an optical trap. Recent experimental efforts have focused on optimizing the cooling technique over multiple cycles of cooling. We have observed cooling of the gas by more than 20%. Possibilities for improvement in the technique will be discussed.

2:24PM C9.00003 Narrow Linewidth Laser Cooling via Adiabatic Transfer. JOHN BARTOLOTTA, MURRAY HOLLAND, MATTHEW NORCIA, JAMES THOMPSON, JULIA CLINE, Department of Physics and JILA, University of Colorado, Boulder — We simulate and provide a theoretical framework for a new cooling method applicable to particles with narrow-linewidth optical transitions. The particles are adiabatically transferred to lower momentum states upon interaction with counter-propagating laser beams that are repeatedly swept over the transition frequency. A reduced reliance on spontaneous emission (compared to Doppler cooling) allows for larger slowing forces. Cooling via a 7.6 kHz dipole forbidden transition in Strontium-88 is simulated using one-dimensional quantum jump and c-number Langevin equation methods. This “sweep cooling” mechanism also shows promise for application to systems lacking closed cycling transitions, such as molecules.
2:36PM C9.00004 Raman sideband cooling to high phase-space density¹, ALBAN URVOY, JIAZHONG HU, ZACHARY VENDEIRO, WENLAN CHEN, VLADAN VULETIC, Massachusetts Institute of Technology — Raman sideband cooling is a very fast and reliable way of cooling atoms to sub-Doppler temperatures. However, as virtually all methods of optical cooling, it has so far only reached a maximum phase-space density two orders of magnitude below that required for Bose-Einstein condensation. Here, we present our results on Raman sideband cooling in a 2D optical lattice. We observe only limited losses as the atoms are cooled, partly as a result of using optical pumping light that is far detuned to the red of atomic transition. By combining this efficient cooling and the compression of the atomic ensemble into individual 1D lattices, we are able to reach phase-space densities on the order of unity in tightly confined tubes, each containing several tens of atoms. We discuss the applicability of this method for a fast and efficient all-optical creation of a degenerate quantum gas.

2:48PM C9.00005 Laser cooling by adiabatic transfer¹, MATTHEW NORCIA, JULIA CLINE, JOHN BARTOLOTTA, MURRAY HOLLAND, JAMES THOMPSON, JILA, University of Colorado Boulder — We have demonstrated a new method of laser cooling applicable to particles with narrow linewidth optical transitions. This simple and robust cooling mechanism uses a frequency-swept laser to adiabatically transfer atoms between internal and motional states. The role of spontaneous emission is reduced (though it is still critical) compared to Doppler cooling. This allows us to achieve greater slowing forces than would be possible with Doppler cooling, and may make this an appealing technique for cooling molecules. In this talk, we will present a demonstration of this technique in a cold strontium system.

¹DARPA QUASAR, NIST, NSF PFC

3:00PM C9.00006 Two Dimensional Grating Magneto Optical Trap in $^{87}$Rb¹, ERIC IMHOF, Utah State Univ, BETHANY KROESE, MATT M SQUIRES, U.S. Air Force — We demonstrate an enhanced two dimensional grating magneto optical trap with a single input beam and a planar diffraction grating. This configuration allows for an increase in experimental access when compared with a traditional two beam 2D MOT. We find a flux $>4\times10^9$ rubidium atoms/s at a mean velocity of 18 m/s. The velocity distribution has 3 m/s standard deviation. We use the atomic beam to load a three dimensional grating MOT with $2\times10^8$ atoms. Methods to improve flux output will be discussed.

¹The authors would like to acknowledge the support of the Air Force Office of Scientific Research and the Department of Energy’s Center for Integrated Nanotechnologies.

3:12PM C9.00007 Dual-species MOT for fermionic dysprosium and potassium atoms, VINCENT CORRE, CORNELIS RAVENBERGEN, SLAVA TZANOVA, ELISA SOAVE, MARIAN KREYER, ALEXANDER WERLBERGER, EMIL KIRILOV, RUDOLF GRIMM, Institute for Quantum Optics and Quantum Information, Austrian Academy of Science, and Institute for Experimental Physics, University of Innsbruck — We report on the first realization of a dual-species magneto-optical trap that combines strongly magnetic lanthanide atoms (dysprosium) with alkali atoms (potassium). Advanced cooling techniques (gray molasses and narrow-line cooling) give us favorable starting conditions for evaporative cooling in an optical dipole trap which, by combining universal dipolar scattering and sympathetic cooling, should allow us to bring polarized samples of both species into the degenerate regime. With naturally abundant fermionic and bosonic isotopes of both dysprosium and potassium, this system provides a versatile platform to study degenerate mixtures. We are particularly interested in Fermi-Fermi mixtures, in which the mass imbalance is expected to give rise to novel pairing mechanisms and exotic quantum phases.

3:24PM C9.00008 Using a directional analog to the Hanle effect to Characterize fields in a magneto-optical trap¹, JAROM JACKSON, DALLIN DURFEE, Brigham Young University — The Hanle effect describes a depolarization of scattered light due to the rotation of atoms in a magnetic field. We will discuss a directional analog to the Hanle effect, in which field-induced rotation changes the spatial emission pattern of the scattered light. We use this effect to measure the spatially dependent magnetic field of a magneto-optical trap (MOT) in situ. The method is well suited for this task, because little to no setup or additional equipment is needed beyond what is typically present in an experiment using a MOT, and the magnitude of the fields in a MOT are naturally in the most sensitive range of this method.

¹This work was supported by NSF grant No. PHY1205736.

3:36PM C9.00009 High Fidelity Preparation of a Single Atom in Its 2D Center of Mass Ground State, PIMONPAN SOMPET, YIN HSIEH FUNG, EYAL SCHWARTZ, MATTHEW D. J. HUNTER, JINDARAT-SAMEE PHROMPAO, MIKKEL F. ANDERSEN, The Dodd-Walls Centre for Photonic and Quantum Technologies, Department of Physics, University of Otago, Dunedin, New Zealand — Complete control over quantum states of individual atoms is important for the study of the microscopic world. Here, we present a push button method for high fidelity preparation of a single $^{87}$Rb atom in the vibrational ground state of a tightly focused optical tweezers. The method combines near-deterministic preparation of a single atom with magnetically-insensitive Raman sideband cooling. We achieve 2D cooling in the radial plane with a ground state population of 0.85, which provides a fidelity of ~0.7 for the entire procedure (loading and cooling). The Raman beams couple two sublevels $|F=3, m=0\rangle$ and $|F=2, m=0\rangle$ that are indifferent to magnetic noise to first order. This leads to long magnetic coherence times, and allows us to implement the cooling in an environment where magnetic field fluctuations prohibit previously demonstrated variations. Additionally, we implement the trapping and manipulation of two atoms confined in separate dynamically reconfigurable optical tweezers, to study few-body dynamics.

3:48PM C9.00010 Shot-noise dominant regime of a nanoparticle in a laser beam, CHANGCHUN ZHONG, FRANCIS ROBICHEAUX, Purdue — The technique of laser levitation of nanoparticles has become increasingly promising in the study of cooling and controlling mesoscopic quantum systems. Unlike a mechanical system, the levitated nanoparticle is less exposed to thermalization and decoherence due to the absence of direct contact with a thermal environment. In ultrahigh vacuum, the dominant source of decoherence comes from the unavoidable photon recoil from the optical trap which sets an ultimate bound for the control of levitated systems. In this paper, we study the shot noise heating and the parametric feedback cooling of an optically trapped anisotropic nanoparticle in the laser shot noise dominant regime. The rotational trapping frequency and shot noise heating rate have a dependence on the shape of the trapped particle. For an ellipsoidal particle, the ratio of the axis lengths and the overall size controls the shot noise heating rate relative to the rotational frequency. For a near spherical nanoparticle, the effective heating rate for the rotational degrees of freedom is smaller than that for translation suggesting that the librational ground state may be easier to achieve than the vibrational ground state.
Vibrational as Well As Linear Kinetic Energies

Egrad student — All masses will have no motion, linear, rotational and or vibrational kinetic energy. In an earlier paper it was found that the total energy at low speeds must therefore be $K = (m - m_0)c^2$, the total kinetic energy of a mass at low speeds therefore must be $K = (m - m_0)c^2$.

D1.00003 Ongoing Work to Improve Precision Laser Spectroscopy of Helium Fine Structure. Garnet Cameron, Ronnie Currey, Khadijah Alnasser, Corey Nook, Ali Khademian, David Shiner, Univ of North Texas — Spectroscopy of the 2P triplet levels of helium provides a nice proving ground for various precision experimental techniques. It also provides a sensitive test of atomic theory, quantum electrodynamics and, with the isotope shift determination of the nuclear size, a test of nuclear few-body theory. It can also provide, with improvements, an important input to the value of the fine structure constant, $\alpha$. Several improvements to our previous experiments are ongoing, including making the study of potential systematic errors more convenient by increasing the count rate. A straightforward increase results from reducing the source-detector separation. This is accomplished by replacing the static high voltage E-field quench plates used for the elimination of the 2S singlet background, with a more reliable and convenient laser to induce the 2S to 2P singlet resonant quenching transition at 2059 nm. We discuss the theory and performance of the 2059 nm cladding-pumped Tm fiber laser we use. The in-house fabricated Tm fiber laser has required several design iterations. Additional 1083 nm fiber lasers are being implemented to improve signal via pumping to a single m level (+1 or -1). As emphasized by Hessels and co-workers [1] for these laser transitions, non-resonant transition amplitudes often make contributions that must be included in the data analysis at current and future levels of precision. We discuss this and experimental tests of its proper inclusion. 1. A. Marsman, M. Horbatsch, and E.A. Hessels, Phys. Rev. A 86, 040501 (2012).

1This work is supported by NSF award #1404498

D1.00004 Preliminary results for a measurement of the n=2 Lamb shift in atomic hydrogen. N. Bezginov, T. Valdez, York University, A. C. Vutha, University of Toronto, K. Kato, T. D. G. Skinner, E. A. Hessels, York University — We perform a measurement of the Lamb shift in atomic hydrogen (n=2 $S_{1/2}$, F=0 to $P_{1/2}$, F=1). A beam of protons moving at 0.01 c undergoes charge exchange with hydrogen gas to produce atomic hydrogen in the metastable 2S state. The atoms travel through two microwave regions where we utilize the novel technique of frequency offset separated oscillatory fields (FOSOF) [PRA 92, 052504 (2015)]. The surviving 2S population is observed using a Lyman-alpha detector. The outcome of this experiment will lead to a measurement of the proton radius, contributing to the resolution of the proton radius puzzle. We present preliminary experimental results, along with systematic studies.

1This research is funded by NSERC, CRC, CFI and NIST.

D1.00005 Preliminary results for a higher-precision measurement of the helium n=2 triplet P fine structure. K. Kato, T. D. G. Skinner, M. C. George, D. W. Fitzakerley, York University, A. C. Vutha, University of Toronto, C. H. Storry, N. Bezginov, T. Valdez, E. A. Hessels, York University — Preliminary results for a higher-precision measurement of the n=2 triplet P J=1 to J=2 fine-structure interval in atomic helium are presented. A beam of metastable helium atoms is created in a liquid-nitrogen-cooled dc-discharge source, and is intensified using a 2D-MOT. These atoms are excited to the 2 triplet P state, and undergo a frequency-offset separated-oscillatory-field (FOSOF) [PRA 92, 052504 (2015)] microwave experiment. Only atoms which undergo a microwave transition, in the time-separated microwave fields are laser-excited to a Rydberg state and then Stark ionized and counted. Our new experimental design has eliminated the major systematic effects of previous experiments, and has led to a substantial improvement in the signal-to-noise ratio of the collected data. Our final improved measurement (with an expected uncertainty of less than 100 Hz) will allow for a test of 2-electron QED-theory in the helium n=2 triplet P system, and will be an important step towards obtaining a precise determination of the fine-structure constant.

1This research is supported by NSERC, CRC, CFI and NIST.

D1.00006 CAVITY QED WITH ULTRACOLD ATOMS —

D1.00007 Cold Atoms Inside Optical Cavity: Beyond the Semi-classical Treatment. Chuanzhou Zhu, Dong Lin, Han Pu, Rice University — The coupling between the atomic internal pseudo-spin (hyperfine) states and a cavity photon field has been extensively studied in quantum optics. We include the atomic external center-of-mass motion into this quantum optical system and consider the interplay of these three degrees of freedom, with the influences of the cavity pumping and dissipation included. The widely used semi-classical treatment, which neglects the atom-photon entanglement and assumes a coherent photon field, is usually adopted to study this type of atom-photon coupled systems. We examine the validity of the semi-classical treatment by comparing it with a quantum Master equation approach, and show that it is not valid under certain circumstances.

D1.00008 ABSTRACT WITHDRAWN —

D1.00009 Two-Photon Blockade in an Atom-Driven Cavity QED System. Christoph Hamsen, Karl Nicolas Tolazzi, Tatjana Wilk, Gerhard Rempe, Max Planck Institute of Quantum Optics — The n-photon blockade is a dynamical quantum-nonlinear effect in which the absorption of n photons blocks the absorption of the (n + 1)th photon. This effect can occur in driven systems with an anharmonic ladder of energy eigenstates, e.g. a single atom strongly-coupled to a high finesse optical resonator. While single-photon blockade has been demonstrated in such a system before [1], we now report on the first observation of two-photon blockade [2]. As a signature, we show a three-photon antibunching with simultaneous two-photon bunching observed in the light emitted from the cavity. The effect occurs for atom driving, not cavity driving. While the two-level atom can only add photons stepwise one-by-one, the bosonic enhancement for cavity driving increases the transition strengths towards higher manifolds which reduces the inherent nonlinearity of the system. We consider these results as a significant step towards multi-photon quantum nonlinear optics.

D1.00010 Observing Higgs and Goldstone modes in a supersolid quantum gas. PHILIP ZUPANCIC, JULIAN LEONARD, ANDREA MORALES, TILMAN ESSLINGER, TOBIAS DONNER, ETH Zurich — We report on the realization of a supersolid with continuous translational symmetry breaking. This U(1) invariance is engineered via symmetry enhancement by coupling a Bose-Einstein condensate to the modes of two optical cavities with individual $Z_2$ symmetries. Spectroscopic measurements reveal the presence of a Goldstone and a Higgs mode, and our data show their energy across the supersolid phase transition. The finite cavity leakage offers a glimpse into real-time dynamics of the system, while the choice of cavity detunings facilitates control of symmetry-breaking fields that tune the mass of the Goldstone mode.

D1.00011 Millimeter-long fiber Fabry-Perot cavities. TORBEN POPPLAU, KONSTANTIN OTT, SÉBASTIEN GARCIA, FRANCESCO FERRI, Laboratoire Kastler Brossel, ENS/CNRS/UPMC, Paris (France), RALF KOHLHAAS, LNE-SYRTE, Observatoire de Paris/CNRS/UPMC, Paris (France). KLEMENS SCHÜPPERT, Institute for Experimental Physics, University Innsbruck, Austria, ROMAIN LONG, JAKOB REICHEL, Laboratoire Kastler Brossel, ENS/CNRS/UPMC, Paris (France) — We present the realization of fiber Fabry-Perot (FFP) micro-cavities with concave mirrors that can be operated at cavity lengths as large as 1.5 mm without significant deterioration of the finesse. This is achieved by using a laser dot machining technique to shape spherical mirrors with ultralow roughness and employing single-mode fibers with large mode area for good mode matching to the cavity. Additionally, in contrast to previous FFPs, these cavities can be used over an octave-spanning frequency range with adequate coatings. We also show directly that shape deviations caused by the fiber’s index profile lead to a finesse decrease as observed in earlier attempts to build long FFP cavities, and show a way to overcome this problem. Beyond concave mirror structures, the novel multi-pulse laser fabrication technique further allows to enlarge the range of accessible structures, including asymmetric mirror profiles, convex shapes on fiber tips and on macroscopic fused silica substrates.

D1.00012 Quantum Many-Body Physics with Multimode Cavity QED. VARUN VAIDYA, YUDAN GUO, ALICIA KOLLAR, Stanford University, KYLE BALLANTINE, JONATHAN KEEILING, University of St. Andrews, BENJAMIN LEV, Stanford University — Phase transitions, where observable properties of a many-body system change discontinuously, can occur in both open and closed systems. Ultracold atoms have provided an exemplary model system to demonstrate the physics of closed-system phase transitions, confirming many theoretical models and results. Our understanding of dissipative phase transitions in quantum systems is less developed, and experiments that probe this physics even less so. By placing cold atoms in optical cavities, and inducing strong coupling between light and excitations of the atoms, one can experimentally study phase transitions of open quantum systems. We will report our observation of a novel form of nonequilibriumphase transition, the condensation of supermode-density-wave-polaritons. These polaritons are formed from a hybrid “supermode” of cavity photons coupled to atomic density waves of a quantum gas. These results, found in the few-mode-degenerate cavity regime, demonstrate the potential of fully multimode cavities to exhibit physics beyond mean-field theories, possibly in the presence of dynamic synthetic gauge fields. We will also present the results of our first experiments in the fully multimode configuration. Such systems will provide experimental access to nontrivial phase transitions.

D1.00013 Cavity-mediated coherent coupling of atomic motion and spin. EMMA DOWD, JONATHAN KOHLER, JUSTIN GERBER, DAN STAMPER-KURN, Univ of California - Berkeley — The collective motion of atomic ensembles in a cavity is well described by cavity optomechanics, while the total atomic spin precessing around an applied magnetic field exhibits analogous cavity optodynamics. For excitations around its high energy state, the spin oscillator acts as an effective negative mass oscillator, which loses energy as it gains excitations. I will present our recent work, in which we achieve cavity-mediated coupling between the mechanical and spin degrees of freedom of a single ensemble of atoms. For coupling between positive and negative mass oscillators, we observe the onset of a dynamical instability caused by a near-resonant exchange of energy as both modes grow in amplitude. This coherent interaction causes dynamics similar to those of a parametric amplifier, resulting in the growth of correlations and two-mode thermal squeezing.

D1.00014 QUANTUM PHASES AND ATOMS IN OPTICAL LATTICES —

D1.00015 Rapid onset of decoherence in driven-dissipative Rydberg systems1. ERIC MAGNAN, JQI - Institut d’Optique, THOMAS BOULAR, CARLOS BRACAMONTES, JAMES MASLEK, JEREMY YOUNG, ALEXEI GORSHKOV, TREY PORTO, STEVEN ROLSTON, JQI, QJ, QJ - RUBIDIUM ONE TEAM — Rydberg atoms have been strong candidates for the realization of quantum information processing and quantum simulation. Recently, however, there has been concerns about this approach due to the observation of a rapid onset of decoherence in large ensembles [PRA 93, 043425 (2016)]. In [PRL 116,113001 (2016)] we provide experimental support for the hypothesis that this is due to the avalanche-like onset of exchange dipole interactions, fueled by blackbody transitions to nearby Rydberg states of opposite parity. Making a fully microscopic model has proven difficult as it requires beyond mean-field arguments, but the ubiquitousness of Rydberg-Rydberg blackbody transitions at room temperature and the always-resonant nature of dipole exchange interactions make it an interesting challenge, and argues for deeper study into the matter. In this poster, we present complementary measurements and analysis that confirm this mechanism. We also discuss several possibilities to reduce its impact on the system’s coherence.

1This work was partially supported by NSF PIF, AFOSR, ARO, ARL-CDQI, and NSF PFC at JQI.

D1.00016 Quantum simulation of spin polarons with dipolar superlattice gases. LUSHUAI CAO, XING DENG, XUE-TING FANG, QIAN-RU ZHU, ZHONG-KUN HU, MOE Key Laboratory of Fundamental Physical Quantities Measurement, School of physics, Huazhong university of Science and technology — Spin polarons are under hot debate as a possible mechanism for high temperature superconducting, while the direct investigation on spin polarons remains difficult. Quantum simulation manifests itself as a promising approach for the study of spin polarons. We propose a strategy to realize effective spin polarons with the dipolar superlattice quantum gases. In this scheme, the spin degree of freedom is modeled by the site occupation of the supercells, and the defect states are modeled by the non-occupation or double occupation of the supercells, giving rise to hole and doublon states. We demonstrate the simulation ability of this strategy by the dynamics of annihilation of a pair of hole and doublon by emitting spin waves.
D1.00017 Efficient numerical technique for calculating the properties of interacting dimers in the Peierls-Hubbard model, John Sous, Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada; V6T 1Z1, MONODEEP CHAKRABORTY, Department of Physics, Indian Institute of Technology, Khagapur, India, ROMAN KREMS, Department of Chemistry, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1, MONA BERCIU, Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1 — We develop a method to compute the Green’s function for two particles in an infinite chain and coupled to phonons by interactions that modulate their hopping as described by the Peierls/Su-Schrieffer-Heeger (SSH) model. The method is based on a variational approximation to the Bogoliubov-Born-Green-Kirkwood-Yvon (BBGKY) hierarchy and is shown to agree with exact diagonalization calculations. We show that the properties of bipolarons arising in such models is qualitatively different from those of the well-studied Holstein bipolarons. In particular, we show that depending on the particle statistics, strongly bound bipolarons may or may not form. In the case of hard-core bosons, we demonstrate novel effects for dimers such as sharp transitions and self-trapping. In the case of soft-core particles/ spinfull fermions, we show that the mediated interactions lead to overscrewing of the bare Hubbard U repulsion resulting in the formation of strongly bound bipolarons.

This work was supported by NSERC of Canada and the Stewart Blusson Quantum Matter Institute.

D1.00018 Resonant interactions of Ytterbium-173 in mixed confinements, Luis Riegger, Nelson Darkwaah Oppong, Moritz Hoefer, Immanuel Bloch, Simon Foelling, LMU, Munich, Germany; Peter Schauss, Peter Brown, Debayan Mitra, Elmer Baragiola, Department of Chemistry, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1, MONA BERCIU, Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1 — We develop a method to compute the Green’s function for two particles in an infinite chain and coupled to phonons by interactions that modulate their hopping as described by the Peierls/Su-Schrieffer-Heeger (SSH) model. The method is based on a variational approximation to the Bogoliubov-Born-Green-Kirkwood-Yvon (BBGKY) hierarchy and is shown to agree with exact diagonalization calculations. We show that the properties of bipolarons arising in such models is qualitatively different from those of the well-studied Holstein bipolarons. In particular, we show that depending on the particle statistics, strongly bound bipolarons may or may not form. In the case of hard-core bosons, we demonstrate novel effects for dimers such as sharp transitions and self-trapping. In the case of soft-core particles/ spinfull fermions, we show that the mediated interactions lead to overscrewing of the bare Hubbard U repulsion resulting in the formation of strongly bound bipolarons.

This work was supported by NSERC of Canada and the Stewart Blusson Quantum Matter Institute.

D1.00019 Engineering quantum dimer models via large-spin Mott insulating ultra-cold bosons, Bhuvanesh Sundar, Cornell University, Todd Rutkowski, Michael Lawler, Binghamton University, Eric Mueller, Cornell University — We propose an experimental protocol to produce quantum dimer models using ultracold bosonic atoms with a large hyperfine spin confined in a deep optical lattice. We explain how an optical Feshbach resonance can control the strength of interactions in different spin channels, leading to a limit where the low-energy Hilbert space is defined by non-overlapping short-range dimers. Solving this model in different lattice geometries yields the columnar phase on a square lattice and the $\sqrt{12} \times \sqrt{12}$ phase on a triangular lattice. The ground state is unknown on a cubic lattice. We give protocols to measure dimer-dimer correlations in the ground state using photoassociation and quantum gas microscopy. Experimentally implementing our proposal would allow us to explore models that have a long history in condensed matter physics, and experimentally resolve theoretically unknown phase diagrams in three-dimensional lattices.

This work was supported by the NSF and by the Army Research Office with funding from the DARPA OLE program.

D1.00020 Mean-field scaling of the superfluid to Mott insulator transition in a 2D optical superlattice, Masayuki Okano, Claire Thomas, Thomas Barter, Tsz-Him Leung, University of California, Berkeley, Gyu-Boong Jo, Hong Kong University of Science and Technology, Jennie Guzman, California State University, East Bay, Itamar Kimchi, Massachusetts Institute of Technology, Ashvin Vishwanath, Harvard University, Dan Stamper-Kurn, University of California, Berkeley — Quantum gases within optical lattices provide a nearly ideal experimental representation of the Bose-Hubbard model. The mean-field treatment of this model predicts properties of non-zero temperature lattice-trapped gases to be insensitive to the specific lattice geometry once system energies are scaled by the lattice coordination number z. We examine an ultracold Bose gas of rubidium atoms prepared within a two-dimensional lattice whose geometry can be tuned between two configurations, triangular and kagome, for which z varies from six to four, respectively. Measurements of the coherent fraction of the gas thereby provide a quantitative test of the mean-field scaling prediction. We observe the suppression of superfluidity upon decreasing z, and find our results to be consistent with the predicted mean-field scaling.

These optical lattice systems can offer a way to study paradigmatic solid-state phenomena in highly controlled crystal structures.

This work was supported by the NSF and by the Army Research Office with funding from the DARPA OLE program.

D1.00021 Measuring correlations in attractive and repulsive Fermi-Hubbard systems with a lithium quantum gas microscope, Peter Schauss, Peter Brown, Debayan Mitra, Elmer Guardado-Sanchez, Waseem Bakr, Princeton University — Quantum gas microscopes have taken the study of Hubbard physics in optical lattices to a new level, enabling site-resolved detection of strongly correlated states like Mott insulators and antiferromagnets. We present two experiments where we use a lithium-6 quantum gas microscope to study the Hubbard model in new regimes. In a first experiment we investigate the spin correlations of the repulsive Hubbard model in the presence of spin-imbalance. We observe short-range canted antiferromagnetism by measuring the anisotropy of spin correlations in two bases. In addition we find non-monotonic behavior of the spin polarization with doping resembling the behavior of the magnetic susceptibility in the cuprates. In another experiment, we observe charge density wave correlations in the attractive Hubbard model at half filling. These correlations provide a low-temperature thermometer for the attractive Hubbard model and allow indirect measurement of superfluid correlations in this system.
D1.00022 Detection of antiferromagnetic order and characterizing spin-charge separation with ultracold $^6\text{Li}$ in a compensated optical lattice. We explore the physics of fermions in both 1D and 3D using ultracold $^6\text{Li}$ atoms in an optical lattice. We have realized the 3D Fermi-Hubbard model and detected short-range antiferromagnetic (AFM) spin correlations via Bragg scattering. We must cool to 40% lower temperatures to realize the long-range ordered N/ el phase. We are setting up a low noise laser and servo to reduce the rate of heating by lattice intensity fluctuation. In addition, we are studying the 1D system by turning off one of the lattice beams. Luttinger liquid theory predicts that fermions have different speeds of sound for spin and charge excitations, an effect known as spin-charge separation. Evidence of spin-charge separation has been obtained in quantum wire tunneling experiments. However, spin and charge dispersion have not been measured independently. Ultracold atoms provide a highly tunable system for which we may directly observe this phenomenon using Bragg spectroscopy.

D1.00023 Exploring long-range antiferromagnets with single-site resolution. We study on an antiferromagnetic spinor condensate in a bichromatic superlattice constructed by a cubic red-detuned optical lattice and a one-dimensional blue-detuned optical lattice. Our data demonstrate a few advantages of this bichromatic superlattice over a monochromatic lattice.

D1.00024 Progress Towards Spectroscopy of Pairs in the Attractive Fermi-Hubbard Model. We explore the physics of fermions in both 1D and 3D using ultracold $^6\text{Li}$ atoms in an optical lattice. We have realized the 3D Fermi-Hubbard model and detected short-range antiferromagnetic (AFM) spin correlations via Bragg scattering. We must cool to 40% lower temperatures to realize the long-range ordered N/el phase. We are setting up a low noise laser and servo to reduce the rate of heating by lattice intensity fluctuation. In addition, we are studying the 1D system by turning off one of the lattice beams. Luttinger liquid theory predicts that fermions have different speeds of sound for spin and charge excitations, an effect known as spin-charge separation. Evidence of spin-charge separation has been obtained in quantum wire tunneling experiments. However, spin and charge dispersion have not been measured independently. Ultracold atoms provide a highly tunable system for which we may directly observe this phenomenon using Bragg spectroscopy.

D1.00025 Quantum Gas Microscope for Fermionic $^{40}\text{K}$. We show our findings on in-situ studies of metallic, Mott insulating, and band insulating states of the two-dimensional (2D) Fermi-Hubbard model as well as the extension of these studies to explore spatial charge and spin correlations using spin-sensitive fluorescence imaging of ultracold 40 K atoms trapped in a square optical lattice. Subsequently, we report on furthering these studies of spatial correlations to lower temperatures.

D1.00026 Magnetic order by adiabatic demagnetization for fermions in an optical lattice. We explore the physics of fermions in both 1D and 3D using ultracold $^6\text{Li}$ atoms in an optical lattice and exhibits antiferromagnetic long-ranged order below the Neel temperature. However, reaching this temperature in the lab has remained an elusive goal. In other atomic systems, such as trapped ions, low temperatures have been successfully obtained by adiabatic demagnetization, in which a strong effective magnetic field is applied to a spin-polarized system, and the magnetic field is adiabatically reduced to zero. There is a fundamental obstacle to applying this approach to the Fermi-Hubbard model: it possesses an SU(2) symmetry that introduces many level crossings which prevent the system from adiabatically reaching the Fermi-Hubbard ground state, even in principle. However, by breaking the SU(2) symmetry with a spin-dependent tunneling, we point out that adiabatic demagnetization can in principle achieve low temperature states. Such spin dependent tunnelings can be engineered by multiple techniques. Using density matrix renormalization group (DMRG) calculations in one dimension, we numerically find that for sufficiently slow demagnetization rates, such states can in principle be achieved.

D1.00027 Antiferromagnetic spinor condensates in a bichromatic superlattice. A spinor Bose-Einstein condensate in an optical superlattice has been considered as a good quantum simulator for understanding mesoscopic magnetism. We report an experimental study on antiferromagnetic spinor condensates in a bichromatic superlattice constructed by a cubic red-detuned optical lattice and a one-dimensional blue-detuned optical lattice. Our data demonstrate a few advantages of this bichromatic superlattice over a monochromatic lattice. One distinct advantage is that the bichromatic superlattice enables realizing the first-order superfluid to Mott-insulator phase transitions within a much wider range of magnetic fields. In addition, we discuss an apparent discrepancy between our data and the mean-field theory.

1Work supported by an ARO MURI grant, our NSF, and the Welch Foundation.


6We acknowledge support from ARO DARPA, AFOSR, ONR, NSF, HQOC, SNSF, NDSEG, and the Gordon and Betty Moore Foundation.

D1.00028 QUANTUM GASES IN LOW DIMENSIONS —
D1.00029 Transport Properties of Bright Matter-Wave Dipolar Solitons in a Tonks-Girardeau gas. MATTHEW EDMONDS, THOMAS BUSCH. Okinawa Inst of Sci & Tech — The dynamics of many-body systems can often be reduced to a particle analogy, leading to rich insight into their behaviour. In the one-dimensional limit the Tonks-Girardeau gas [1,2] has been realized, where strong repulsive interactions dominate the system dynamics. The creation of condensates with atoms possessing significant dipole-dipole interactions [3] heralds a novel avenue in the Ultracold landscape for the study of nonlinear waves, such as bright solitons whose interactions are intrinsically attractive. We investigate the transport properties of a Tonks-Girardeau gas with a bright soliton, for realistic geometries. We study the dynamics and equilibration of these two systems, which we quantify in terms of the strength of their mutual coupling. The dynamics are found to depend on the initial conditions, and are increasingly anharmonic as the strength of the coupling is increased, leading to the identification of different dynamical regimes. [1] B. Paredes, A. Widera, V. Murg, O. Mandel, S. Fölling, I. Cirac, G. V. Shlyapnikov, T. W. Hänsch, and I. Bloch, Phys. Rev. Lett. 90, 020401 (2003). [2] T. Kinoshita, T. Wegner, D. S. Weiss, Science 305, 1125 (2004). [3] T. Lahaye, C. Menotti, L. Santos, M. Lewenstein, and T. Pfau, Rep. Prog. Phys. 72 126401 (2009).

D1.00030 Progress towards a quantum simulator based on ultracold strontium. WEI QI, MINGCHENG LIANG, XIBO ZHANG, ICQM, Peking University — Realizing ultracold atoms in the fractional quantum Hall regime has been challenging because of difficulties in suppressing heating and loss due to spontaneous emission and in preparing and manipulating ultracold samples with very small atom numbers. Owing to its ultra-narrow clock transition, Sr has become a promising candidate to overcome these difficulties. We report experimental progress towards building a quantum simulator that, on the basis of fermionic strontium 87, uses Raman optical lattices to engineer synthetic gauge fields and induce non-trivial topological flatbands. Microscopy with micrometer resolution and coherent spectroscopy based on an ultrastable clock laser can be integrated into the apparatus for manipulating and measuring novel strongly correlated quantum systems.

D1.00031 Measuring the Speed of Sound in a 1D Fermi Gas1, JACOB FRY, YI JIN, ANNA MARCHANT, RANDALL HULET, Department of Physics and Astronomy and Rice Center for Quantum Materials — We have undertaken measurements of the speed of sound in a two-spin component, 1D gas of fermionic lithium. The 1D system is an array of one-dimensional tubes created by a 2D optical lattice. To measure the speed of sound, we create a localized density perturbation at the center of the atom cloud using a sheet of light. Depending on the laser’s frequency, the atoms feel either a spin-sensitive or insensitive force. Once the lightsheet is turned off, the density perturbation propagates to the edge of the atomic cloud with a velocity that depends on the strength of interatomic interactions, which we control using a magnetically-tuned Feshbach resonance. This method may be used to extract the Luttinger parameter vs. interaction strength. We will report our progress.

1 ARO MURI, NSF, ONR, and The Welch Foundation

D1.00032 Detecting the FFLO Phase in The Dimensional Crossover Of An Imbalanced Fermi Gas1, YI JIN, JACOB FRY, ANNA MARCHANT, MELISSA REVELLE, RANDALL HULET, Department of Physics and Astronomy and Rice Center for Quantum Materials, Rice University, Houston, TX 77005 — The exotic Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) magnetized superconductor occupies a large region of the one-dimensional (1D) phase diagram. However, the FFLO phase is more robust against quantum and thermal fluctuations in higher dimensions. This motivated us to map the dimensional crossover between 1D and 3D as it is predicted to be the optimal regime to search for FFLO. We prepare a spin-imbalanced Fermi gas of 6Li, analogous to creating a magnetized atomic cloud. By using a 2D optical lattice, we confine the atoms to 1D tubes and bring the system to the dimensional crossover regime by tuning the inter-tube tunneling rate and interaction strength. To detect FFLO, we take 1D time of flight measurements using a blue-detuned anti-trapping beam to cancel the axial confinement. This permits the mapping of the linear momentum distribution, from which signatures of FFLO may be observed.

1 Supported by an ARO MURI Grant, NSF, ONR, and The Welch Foundation

D1.00033 Coherence of strongly interacting 2D quantum gases. LENNART SOBIREY, JONAS SIEGL, NICLAS LUICK, KLAUS HUECK, THOMAS LOMPE, HENNING MÖRITZ, Univ Hamburg — The dimensionality of a quantum system has a profound impact on its coherence and superfluid properties. In 2D systems true long-range coherence is precluded by thermal fluctuations, nevertheless they can still become superfluid as predicted by Berezinski, Kosterlitz and Thouless. In this superfluid regime the first order coherence decays algebraically, free of any characteristic length scale. Here, we show coherence measurements in a strongly interacting 2D gas of diatomic 4Li molecules. A self-interference technique allows us to locally extract the algebraic decay exponent, which is directly linked to the superfluid density. Furthermore, we present our realization of a homogeneous ultracold 2D Fermi gas. It should enable the direct measurement of non-local quantities such as the momentum distribution, without the complication of averaging over the different densities present in a harmonic trap.

D1.00034 Ring and ring lattice trapping potentials for quantum manybody experiments with lithium. DANIEL ALLMAN, YANPING CAI, KEVIN WRIGHT, Dartmouth College — Multiply-connected geometries (e.g. rings) provide a natural setting for studying transport properties of unusual quantum phases of matter. Precisely-constructed optical traps can provide such a setting to study novel collective behavior in 1D periodic geometries. We have designed and tested an integrated optical system for creating stable and well-structured ring traps and ring lattices for use at multiple laser wavelengths. The system uses amplitude masks, phase imprinting techniques, and the adjustment of aperture stops to control the shape of the projected optical trapping potentials.

D1.00035 SPINOR GASES AND MAGNETIC PHENOMENA —
D1.00036 Preserving squeezed spin states of a spin-1 Bose-Einstein condensate with rotary echoes\textsuperscript{1}, WENXIAN ZHANG, JUN ZHANG, YINGYING HAN, PENG XU, School of Physics and Technology, Wuhan University, Wuhan, Hubei 430072, China — A challenge in precision measurement with squeezed spin states arises from the spin dephasing due to stray magnetic fields. To suppress such environmental noises, we employ a continuous driving protocol, rotary echo, to enhance the spin coherence of a spin-1 Bose-Einstein condensate in stray magnetic fields. Our analytical and numerical results show that the squeezed spin states are preserved for a significantly long time, compared to the free induction decay time, if the magic condition $\hbar \tau = \hbar \tau$ is met with $\hbar$ the pulse amplitude and $\tau$ the pulse duration. In particular, both the spin average and the spin squeezing, including the direction and the amplitude, are simultaneously fixed for a squeezed spin state. Our results provide a practical way to implement quantum measurements based on a spin-1 condensate utilizing a squeezed spin state.

\textsuperscript{1}J. Zhang, Y. Han, P. Xu, W. Zhang, Phys. Rev. A 94, 053608 (2016). Supported by the National Natural Science Foundation of China under Grant No. 11574239.

D1.00037 Manipulation of heteronuclear spin dynamics with microwave and vector light shift\textsuperscript{1}, LINTAO LI, BO LU\textsuperscript{2}, BING ZHU\textsuperscript{3}, DAJUN WANG, Chinese Univ of Hong Kong — We report the study of heteronuclear spin-exchange dynamics starting from a spin-1 mixture of Rb\textsuperscript{1,0}> and Na\textsuperscript{1,0}> atoms. which depends on the competition between the Zeeman energy and interspecies spin-dependent interaction energy. Within a narrow magnetic field window around 1 G, we have observed a dramatic enhancement of a particular process: Rb\textsuperscript{1,0}> + Na\textsuperscript{1,0}> + Rb\textsuperscript{1,1}> + Na\textsuperscript{1,1}>. We also demonstrated the ability to precisely manipulate this process via a far-detuned microwave or laser field. The microwave method, similar to that in single-species spinor gases, tunes the species-selective quadratic Zeeman energy. As a comparison, the light field shifts the species-dependent linear Zeeman energy. Both methods are shown to be powerful and flexible in our system. Our investigations have revealed the richness of quantum manipulations in heteronuclear spin systems.

\textsuperscript{1}This project is supported by the GRF grants 403813 and 14305214 of RGC Hong Kong.
\textsuperscript{2}Current position is School of Physics and Astronomy, Sun Yat-Sen University
\textsuperscript{3}Current position is Physikalisches Institut of the University of Heidelberg

D1.00038 Improved Apparatus to Study Matter-Wave Quantum Optics in a Sodium Spinor Bose-Einstein Condensate, SHAN ZHONG, ANITA BHAGAT, QIMIN ZHANG, ARNE SCHWETTMANN, University of Oklahoma — We present and characterize our recently improved experimental apparatus for studying matter-wave quantum optics in spinor space in ultracold sodium gases. Improvements include our recent addition of a 3D-printed Helmholtz coil frame for field stabilization and a crossed optical dipole trap. Spin-exchange collisions in the F = 1 spinor Bose-Einstein condensate can be precisely controlled by microwave dressing, and generate pairs of entangled atoms with magnetic quantum numbers $m_F = +1$ and $m_F = -1$ from pairs of $m_F = 0$ atoms. Spin squeezing generated by the collisions can reduce the noise of population measurements below the shot noise limit. Versatile microwave pulse sequences will be used to implement an interferometer, a phase-sensitive amplifier and other devices with sub-shot noise performance. With an added ion detector to detect Rydberg atoms via pulse-field ionization, we later plan to study the effect of Rydberg excitations on the spin evolution of the ultracold gas.

D1.00039 Spinor Dynamics Of A Freely Expanding F=1 Bose-Einstein Condensate, ZACHARY GLASSMAN, DONALD FAHEY, Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, ARNE SCHWETTMANN, University of Oklahoma, JONATHAN WRUBEL, Creighton University, PAUL LETT, Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland — Spin-exchange collisions drive coherent population oscillations between $m_F$ ground states in an optically trapped $F = 1$ Bose-Einstein condensate that depend on the density and quadratic Zeeman shift. Due to the slow expansion of the condensate, spinor dynamics persist after release from the trap when time-of-flight detection is used, and the changing density during free expansion must be factored into the analysis, particularly if the effective magnetic field is changed during this time. The recent adoption of microwave dressings in spinor BEC experiments has improved the control over the quadratic Zeeman shift, and allowed for negative shifts and fast switching times for quantum experiments. By switching the parameter $q$ at a variable time during the free expansion of a sodium $F = 1$ Bose-Einstein condensate, the effects of a changing density and magnetic field on the spinor evolution were investigated. Our measurements agree well with a mean-field simulation under the single-mode approximation, and both experimental and simulation data are presented.

D1.00040 COLD AND ULTRACOLD MOLECULES —

D1.00041 Internal state control of a dense sample of ultracold $^{23}$Na$^{87}$Rb molecules\textsuperscript{1}, XIN YE, MINGYANG GUO, JUNYU HE, DAJUN WANG, Chinese Univ of Hong Kong, GOULVEN QUEMENER, MAYKEL GONZALEZ-MARTINEZ, OLIVIER DULIEU, Laboratoire Aime Cotton, CNRS — We report the optimized production of ultracold $^{23}$Na$^{87}$Rb molecules with completely controlled population distribution among internal states. Starting from a sample of $10^7$ weakly bound Feshbach molecules, we achieved a hyperfine-structure-resolved STIRAP transfer to the ground state with an efficiency up to 95%. By tuning the frequency difference between the Raman lasers and applying an additional microwave signal, we realized the preparation of NaRb samples in different vibrational, rotational, and hyperfine levels. Based on this achievement, some results on molecular collisions with a range of possible loss channels will also be reported.

\textsuperscript{1}This work was supported by the French ANR/Hong Kong RGC COPOMOL project (grant no. A-CUHK403/13), the RGC General Research Fund (grant no. CUHK14301815)

D1.00042 Low-energy excitations of a Bose-Einstein condensate of rigid rotor molecules\textsuperscript{1}, JOSEPH SMITH, Western Washington University, EVAN JONES, SETH RITTENHOUSE, RYAN WILSON, US Naval Academy, BRANDON PEDEN, Western Washington University — We investigate the properties of the ground state and low-lying excitations of an oblate Bose-Einstein condensate composed of rigid rotor molecules in the presence of an external polarizing electric field. We build in a quantum model of molecular polarizability by including the full manifold of rotational states. The interplay between spatial and microscopic degrees of freedom via feedback between the molecular polarizability and inter-molecular dipole-dipole interactions leads to a rich quasi-particle spectrum. Under large applied fields, we reproduce the well-understood density-wave rotonization that appears in a fully polarized dipolar BEC, but under smaller applied fields, we predict the emergence of a spin wave instability and possible new stable ground state phases.

\textsuperscript{1}We gratefully acknowledge support from the National Science Foundation under grant No. PHYS-1516421
D1.00043 Towards laser cooling and trapping of barium monohydride. REES MCNALLY, GEOFFREY IWATA, Columbia University, MARCO TARALLO, Istituto Nazionale di Ricerca Metrologica, TANYA ZELEVINSKY, Columbia University — We report progress towards the laser cooling of diatomic BaH, demonstrating operation of a cryogenic buffer gas beam source with a brightness of $10^6 - 10^7$ molecules in the trapping region per ablation pulse, the brightest hydride beam to our knowledge. This source has enabled studies of the transitions and properties of BaH relevant to laser cooling, and we show preliminary results towards optical manipulation. Looking forward, plans for chirped molecular slowing on the $A'\Sigma^+\text{I}$ excited state, followed by magneto-optical trapping on the $B'\Sigma^+$ excited state will be presented. Finally, we discuss the feasibility of photo-dissociation of ultracold BaH as a source of dilute ultracold hydrogen suitable for precision spectroscopy, a unique application for the monohydride.

D1.00044 Bose-Einstein condensate of rigid rotor molecules\(^1\). EVAN JONES, US Naval Academy, JOSEPH SMITH, Western Washington University, SETH RITTENHOUSE, US Naval Academy, BRANDON PEDEN, Western Washington University, RYAN WILSON, US Naval Academy — We study the ground state phases of a quasi-two-dimensional Bose-Einstein condensate (BEC) of dipolar rigid rotor molecules subject to a DC electric field. In the high-field limit, this system acquires the properties of the fully polarized dipolar BEC, which exhibits a roton-maxon excitation spectrum, and has been thoroughly studied in the theoretical literature. In the weak-field limit, we investigate the competition between the (weak) applied field and internal electric fields, which are produced by the molecules themselves. We characterize the ground states of this system, and study its unique dielectric properties.\(^1\)

D1.00045 Cold K-Ca\(^+\) interaction studies in an ion-atom hybrid trap\(^1\). JOYTHI SARALEDAVI, KISRA EGOADITIYA, GANG SHU, Department of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA 30332, BICHEN ZHANG, Department of Physics, Georgia Institute of Technology, Atlanta, GA 30332, JOHN CONDOLUCI, Department of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA 30332, PIERO CHIAPPINA, DI LAO, ZHUBING JIA, Department of Physics, Georgia Institute of Technology, Atlanta, SC 39409, KEN BROWN, Department of Chemistry and Biochemistry, Georgia Institute of Technology, Atlanta, GA 30332 — Mixtures of cooled and trapped ions and atoms enable study of cold collisions including elastic collisions, charge exchange interactions and molecular ion formation. To facilitate these studies, we have developed an apparatus comprising a spatially overlapped ion trap (linear Paul trap) and an atom trap (magneto optical trap) \[1\]. The apparatus is integrated with a high resolution time of flight mass spectrometer for identifying the reaction products. Initial studies on interactions between cold calcium (Ca\(^{+}\)) ions and Potassium (K) atoms will be presented. The prospects for rotational cooling of molecular ions by interaction with ultracold Potassium atoms will be discussed. \[1\] Wade G. Rellergert, Scott T. Sullivan, Steven J. Schowalter, Svetlana Kotochigova, Kuang Chen & Eric R. Hudson, Nature 4 9 5, 490 (2013).

D1.00046 Weakly bound molecular ions with giant electric dipole moment and polarizability. MICHAL TOMZA, Univ of Warsaw, KRZYSZTOF JACHYMSKI, Univ of Stuttgart — We investigate molecular ions in weakly bound rovibrationally excited states and show that they have a giant permanent electric dipole moment with a value up to $10^{15}$ esu. We also find a giant electric dipole polarizability with a value up to $10^{15}$ esu. Using quantum defect theory we derive analytic expressions for these properties as functions of binding energy. We show that the electric properties and radiative lifetimes of weakly bound molecular ions can be controlled with a magnetic field via magnetically tunable Feshbach resonances, whereas the magnetic properties can be controlled with a laser-induced Stark effect. Thus, these systems constitute an interesting example with a controllable interplay between electric and magnetic interactions. We analyze practical implications of our findings and propose new ultracold precision measurement experiments to access the unusual properties of the investigated systems.

D1.00047 A two-species quantum gas experiment for the preparation of ultracold polar NaK molecules. TORBEN SCHULZE, TORSTEN HARTMANN, KAI VOGES, ALESSANDRO ZENESINI, SILKE OSPELKAUS, Institute of Quantum Optics, University of Hannover — Ultracold mixtures of atomic quantum gases provide the starting point for the preparation of polar ground state molecules, which are excellent candidates for the study of quantum chemistry and exotic dipolar quantum phases. Here, we present an experimental apparatus for the preparation of ultracold Na and K quantum gas mixtures, which are two favorable candidates for a mixture experiment due to the well-known cooling strategies for the individual atoms. We describe our experimental setup involving a magneto optical trap (MOT) of Na and K atoms, which is produced by the molecules themselves. We characterize the ground states of this system, and study its unique dielectric properties.

D1.00048 Characterisation of a magneto-optical trap for CaF molecules. STEFAN TRUPPE, JACK DEVLIN, HANNAH WILLIAMS, MORITZ HAMBACH, LUKE CALDWELL, NOAH FITCH, BEN SAUER, ED HINDS, MIKE TARBUTT, Imperial College London — We present a detailed characterization of a magneto-optical trap (MOT) of CaF molecules. We capture approximately $2.2\times10^{10}$ molecules in the MOT from a buffer gas molecular beam which is slowed via radiation pressure. At the highest laser intensity, the lifetime of the molecules in the MOT is about 100ms, the trap frequency is 94Hz and the damping coefficient is 300[s]^{-1}. The molecules reach an equilibrium temperature of 12mK which is nearly 50 times higher than the Doppler limit. We explore how the scattering rate, trap frequency, damping coefficient and temperature depend on the intensity. We compare our results to standard Doppler cooling theory and to an advanced model that takes into account the effect of polarization gradients.

D1.00049 Implementation of in-vacuum electrodes for manipulating interactions between ultracold KRb molecules. KYLE MATSUDA, JACOB COVEY, LUIGI DE MARCO, WILLIAM TOBIAS, GIACOMO VALTOLINA, JUN YE, JILA, National Institute of Standards and Technology and University of Colorado — Ultracold molecules represent an ideal platform for studying many-body physics with long-range dipolar interactions. The field of ultracold polar molecules has recently made enormous progress and many different bi-alkali molecules have been produced in their ground state. Recently, dipolar spin-exchange interactions and many-body dynamics have been observed with Fermionic KRb molecules in an optical lattice, and low-entropy samples in a lattice have been realized. However, the ability to apply large electric fields to polarize the molecules has been limited to several kV/cm. Additionally, high resolution in situ has been lacking for polar molecules despite the enormous progress in the quantum gas field. We present a new apparatus for producing Fermionic KRb molecules where stable, homogeneous electric fields in the range of 30 kV/cm are expected, while also accommodating arbitrary gradients in two dimensions. This apparatus is designed for high resolution addressing and detection, and imaging resolutions well below 1 micron are expected. We present details on this apparatus and its construction, and describe the procedure used to produce ultracold gases of atoms and molecules. Further work will lead to high resolution detection of strongly dipolar quantum systems.
D1.00050 Ultra cold $^{23}$Na$^{40}$K molecules in Munich - d/D route to the ground state 

**NaK molecule**, XIN-YU LUO, FRAUKE SEEELEBERG, NIKOLAUS W. BUCHHEIM, ZHENKAI LU, IMMANUEL BLOCH, CHRISTOPH GÖHLE, Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany — Ultracold polar molecule gases are a promising quantum system to investigate strongly interacting many-body models with long-range interactions like the t-J model and explore novel phases of quantum matter such as fractional Mott insulators and supersolids. We report on the ongoing efforts to create an ultracold, polar NaK gas in Munich. Our setup features open optical access, e.g. for high-resolution imaging or optical lattices, and can reliably produce ultra cold mixtures of sodium and potassium. Recently we succeeded to produce ultracold $^{23}$Na$^{40}$K molecules. To that end we transfer weakly bound Feshbach molecules to the electronic and rovibrational molecular ground state using stimulated Raman adiabatic passage. We employ the d$^3\Pi(\nu = 5, J = 1, \Omega = 1)$ as intermediate state which mixes with the D$^3\Pi$ electronic state via spin orbit interaction. The properties of the ground state such as its lifetime and polarization are discussed.

1 Ludwig-Maximilians-Universität, Schellingstrasse 4, 80799 München, Germany

D1.00051 Ultracold 4-center reactions of KRb molecules.

**MING-GUANG HU, YU LIU, ANDREI GHEORGHE, YEN-WEI LIN, KANG-KUEN NI, Harvard University —** Chemical reactions at the fundamental level obey the laws of quantum mechanics. However, reactions are often far from the regime where the quantum motions of the reagents play an important role. Ultracold reactions of KRb is a good candidate, where the unusual 4-center reactions between two KRb molecules is expected to produce K2 and Rb2 molecules with 10 $\text{cm}^{-1} \cdot \text{K}$ (or 14.4 K) excess energy. To directly measure reaction products and to fully map out their quantum states, we are designing and constructing a novel quantum degenerate gas apparatus with the integration of REMPI and ion velocity mapping imaging. Our work aims to open up new directions for physical chemistry studies with AMO techniques.

D1.00052 Genetic based fitting techniques for potential energy curves of diatomic molecules, IAN STEVENSON, JESUS PEREZ-RIOS, DAN ELLIOTT, Purdue University — We present development of a genetic algorithm for fitting potential energy curves of diatomic molecules to experimental data. Our program takes in a ‘guess’ potential, often from the literature, and an algorithm for fitting potential energy curves of diatomic molecules to experimental data.

D1.00053 Hyperfine structures of the $B^3\Pi$, $c^3\Sigma^+$, and $b^3\Pi$ states of ultracold $^{85}$Rb$^{133}$Cs via short range photoassociation, JIN-TAE KIM, Photonic Eng., Chosun Univ., Korea, TOSHIHIKO SHIMASAKI, YUQI ZHU, DAVID DEMILLE, Dept. of Physics, Yale Univ., USA — Short-range photoassociation (PA) has opened up to investigate various hyperfine structures of deeply bound rovibrational levels of the strongly perturbed $B^3\Pi$, $c^3\Sigma^+$, and $b^3\Pi$ states with high resolution of $\sim 10$ MHz. Peculiar potential curves of the electronic states with crossings and inflections obtained from Fourier-transform spectroscopy (FTS) with low resolution of 900 MHz [1] give strong evidences for strong spin-orbit coupling effects between the singlet and triplet states. We have observed new short-range PA lines of the $B^3\Pi(\Omega = 1)$, $b^3\Pi(\Omega = 0^-, 0^+, 1)$, and $c^3\Sigma^+(\Omega = 0^-)$ states of ultracold $^{85}$Rb$^{133}$Cs molecules, starting with $^{85}$Rb and $^{133}$Cs atoms trapped in their ground states. We have observed rich hyperfine structures of the $B^3\Pi$, $c^3\Sigma^+$, and $b^3\Pi$ states with $\Omega = 1$, which were not observed in the FTS [1]. We will discuss the various hyperfine structures in comparisons with the hyperfine structures observed in PA to the $2^3\Pi(\Omega = 1)$, $2^3\Pi(\Omega = 1)$, and $3^3\Sigma^+(\Omega = 1)$ states [2]: [1] I. Birzniece et al., J. Chem. Phys. 138, 154304 (2013). [2] T. Shimasaki et al., ChemPhysChem 17, 3677 (2016).

D1.00054 Triplet ground state NaLi molecules, ARIEL SOMMER, TIMUR M. RVACHOV, Massachusetts Institute of Technology, HYUNGMOK SON, Harvard University and Massachusetts Institute of Technology, JULIANA PARK, Massachusetts Institute of Technology, SEPEHR EBADI, University of Toronto and Massachusetts Institute of Technology, MARTIN W. ZWIERLEIN, WOLFGANG KETTERLE, ALAN O. JAMISON, Massachusetts Institute of Technology — doi:10.1017/S1437444816001039

D1.00055 Toward Nondestructive Single-Molecule Spectroscopy via Photon Recoil Readout, MARK KOKISH, VINCENT CARRAT, BRIAN ODOM, Northwestern Univ — Spectroscopy of rovibrational transitions in molecules can uniquely provide tighter constraints on the time variation of the proton-to-electron mass ratio. However, ultra-high precision spectroscopy requires control over each molecular degree of freedom. Here we present our progress toward developing a complete blueprint for manipulating the external and internal motion of a single aluminum monohydride cation (AlH$^+$). We have previously exploited the molecule’s small vibrational branching ratios to achieve rovibrational ground state preparation via optical pumping. This property can be used again to perform nondestructive state readout. After preparing AlH$^+$ and a co-trapped Ba$^+$ ion in the ion trap’s motional ground state via optical pumping, the Ba$^+$ acts as a sensitive detector to molecular motion. Such motion can be induced via repeated molecular photon recoil events, contingent upon absorption out of the molecule’s ground vibrational state. This photon recoil readout conveniently makes possible nondestructive rovibrational spectroscopy to a metastable vibrational excited state. The initial conditions can then quickly be regenerated using optical methods.

1Work supported by the NSF and ARO-MURI

1This work is supported by AFOSR Grant No. FA9550-13-1-0116, NSF Grant No. PHY-1404455, and NSF GRFP DGE-1324585.
D1.00056 A Geometric Representation of Correlations: Unveiling Hidden Correlation Structures in Ultracold Matter, KENNETH WANG, ANTHONY MIRASOLA, IAN WHITE, RICK MUKHERJEE, KADEN HAZZARD, Rice Univ — We develop a general method to visualize spin correlations and demonstrate its usefulness for ultracold systems, from fermions in lattices to trapped ions and ultracold molecules. We provide a one-to-one map between the spin correlations and certain three-dimensional objects, analogous to the map between single spins and Bloch vectors. Moreover, much as one can reason geometrically about dynamics using a Bloch vector — e.g. a magnetic field causes it to precess and dephasing causes it to shrink — we show that analogous reasoning holds for our visualizations of correlations for real physical spin models. Phenomena that look complicated and mysterious when analyzed by the components of their correlations become simple and intuitive when described geometrically. Finally, we will describe how this geometric representation not only reveals a surprising similarity of behaviors in a wide range of spin models, but also provides insight into the accuracy of various approximations to the dynamics.

D1.00057 Simple model for molecular scattering1. NIRAV MEHTA, Department of Physics and Astronomy, Trinity University, CHRISTOPHER TICKNOR, Theoretical Division, Los Alamos National Laboratory, KADEN HAZZARD, Department of Physics and Astronomy, Rice University — The collisions of ultracold molecules are qualitatively different from the collisions of ultracold atoms due to the high density of bimolecular resonances near the collision energy. We present results from a simple N-channel scattering model with square-well channel potentials and constant channel couplings (inside the well) designed to reproduce essential features of chaotic molecular scattering. The potential depths and channel splittings are tuned to reproduce the appropriate density of states for the short-range bimolecular collision complex (BCC), which affords a direct comparison of the resulting level-spacing distribution to that expected from random matrix theory (RMT), namely the so-called Wigner surmise. The density of states also sets the scale for the rate of dissociation from the BCC to free molecules, as approximated by transition state theory (TST). Our model affords a semi-analytic solution for the scattering amplitude in the open channel, and a determinantal equation for the eigenenergies of the short-ranged BCC. It is likely the simplest finite-range scattering model that can be compared to expectations from the approximations of RMT, and TST. The validity of these approximations has implications for the many-channel Hubbard model recently developed.

1This research was funded in part by the National Science Foundation under Grant No. NSF PHY-1125915

D1.00058 Stability of a frequency-comb-based transfer-lock using a passive Fabry-Perot resonator and its application to spectroscopy of ultracold molecules, SAMBIT BIKAS PAL, MARK LAM, KAI DIECKMANN, Centre for Quantum Technologies and Dept. of Phys., Nal Univ of Singapore — In this poster, we demonstrate a transfer-lock laser frequency stabilization1 that utilizes a frequency comb (FC) and a radio frequency counter referenced to a GPS frequency standard to compensate for the frequency drifts of two lasers, which are locked to a single passive Fabry-Perot resonator (FPR). The method requires only one optical phase lock with the FC and allows transfer locking of lasers at wavelengths beyond the usable range of the FC. To attain a large frequency tuning range for the lasers, we implement optical serrodyning. We further demonstrate an efficient scheme to suppress residual amplitude modulation, thereby improving the stability of the Pound-Drever-Hall lock used in this case. The absolute frequency stability was found to be better than $2 \times 10^{-13}$ on timescales up to 300 s. Hence, together with the frequency stability on short timescales provided by the FPR, this scheme facilitates coherent Raman spectroscopy as needed for an example for the production of ultracold dipolar heteronuclear molecules.


D1.00059 Coherent microwave control of ultracold $^{23}$Na$^{40}$K molecules, ZOE YAN, YIQI NI, JEE WOO PARK, SEBASTIAN WILL, HUANQIAN LOH, Massachusetts Institute of Technology, KANG KUEN NI, Harvard University, MARTIN ZWIERLEIN, Massachusetts Institute of Technology — Ultracold dipolar molecules provide new opportunities to investigate strongly-correlated systems and quantum information science. Previously, we have demonstrated the creation of a spin-polarized ensemble of fermionic $^{23}$Na$^{40}$K molecules in their rovibronic and hyperfine ground state. One way to induce strong dipole moments is microwave dressing, which has also been proposed to allow shielding of inelastic collisions and the realization of topological superfluids. In contrast to static electric fields, microwave dressing allows for precise control over the orientation and strength of the molecular dipoles. We present recent work on microwave dressing of these molecules on the lowest rotational transition. The dressing induces an oscillatory dipole moment on the order of one Debye, which can prove useful in engineering interest molecule-molecule interaction potentials. Further, we study the dependence of the molecule collision rate on the microwave-induced dipole moment, which may have implications on the microwave trapping of molecules.

D1.00060 VORTICES AND EXCITATIONS IN DEGENERATE QUANTUM GASES —

D1.00061 Bent dark soliton dynamics in two spatial dimensions beyond the mean field approximation1, SIMION MISTAKIDIS, GARYFALLIA KATSIMIGA, GEORGIOS KOUTENTAKIS, Center for Optical Quantum Technologies, University of Hamburg, PANAGIOTIS KEVREKIDIS, Department of Mathematics and Statistics, University of Massachusetts Amherst, PETER SCHMELCHER, Center for Optical Quantum Technologies, University of Hamburg, THEORY GROUP OF FUNDAMENTAL PROCESSES IN QUANTUM PHYSICS TEAM — The dynamics of a bended dark soliton embedded in two spatial dimensions beyond the mean-field approximation is explored. We examine the case of a single bented dark soliton comparing the mean-field approximation to a correlated approach that involves multiple orbitals. Fragmentation is generally present and significantly affects the dynamics, especially in the case of stronger interparticle interactions and in that of lower atom numbers. It is shown that the presence of fragmentation allows for the appearance of solitonic and vortex structures in the higher-orbital dynamics. In particular, a variety of excitations including dark solitons in multiple orbitals and vortex-antidark complexes is observed to arise spontaneously within the beyond mean-field dynamics.

1Deutsche Forschungsgemeinschaft (DFG) in the framework of the SFB 925 “Light induced dynamics and control of correlated quantum systems”
D1.00062 Quasiparticle and phase-slip induced excitations in ultracold lithium gases, FRANCESCO SCAZZA, GIACOMO VALTOLINA, INO-CNR and LENS, University of Florence, Italy, PIETRO MASSIGNAN, ICFO-Institut de Ciencies Photoniques, Castelldefels, Spain, ALESSIO RECATI, INO-CNR BEC Center, University of Trento, Italy and Ludwig-Maximilians-Universität München, Germany, ANDREA AMICO, ALESSIA BURCHIANTI, CHIARA FORT, MASSIMO INGUSCIO, MATTEO ZACCANTI, GIACOMO ROATI, INO-CNR and LENS, University of Florence, Italy — The fine control over interactions in ultracold Fermi gases close to a Feshbach resonance, in combination with tailored optical potentials, provide unique opportunities to explore strongly-correlated fermion phenomena. In our ultracold lithium setup, by superimposing a thin optical barrier to a fermionic superfluid, we realize an atomic Josephson junction, where we recently studied the emergence of dissipation across the BEC-BCS crossover. We directly identify the main source of dissipation with the leakage into the bulk of phase-slip-induced vortex excitations nucleated within the barrier region. In another recent study, we employed radio-frequency spectroscopy to investigate highly polarized spin-mixtures on the repulsive side of the Feshbach resonance. We report on the observation of well-defined repulsive quasiparticles up to unitarity-limited interactions. We characterize the essential properties of repulsive Fermi polaron: their energy, effective mass, quasiparticle residue and lifetime.

D1.00063 Dark soliton rings in a Bose–Einstein condensate using Raman imprinting techniques, MAITREYI JAYASEELAN, JOSEPH D. MURPHEREE, JUSTIN T. SCHULTZ, AZURE HANSEN, NICHOLAS P. BIGELOW, Univ of Rochester — Soliton rings in optical beams have been theoretically and experimentally investigated for their interesting dynamics and connections with novel phenomena, including the formation of non-trivial topological states such as vortices. Density and phase engineering techniques have been proposed to create soliton rings in Bose–Einstein condensates. Here, we explore using a coherent two-photon Raman optical imprinting technique to generate dark soliton rings in a Zeeman spin state of a $^{87}$Rb Bose–Einstein condensate (BEC). The relative intensities and phase of the Raman beams determine the relative populations and phase of the atomic spin states, which can then be measured through atom-optic polarimetry. Dark soliton rings correspond to an annular edge dislocation with a phase jump of $\pi$, forcing the density to vanish at the dislocation. We use higher-order Laguerre–Gauss $p$-modes with the requisite singular phase and intensity profiles to create concentric soliton rings in the BEC via the Raman process, creating dark soliton rings in one spin component filled with population from the second component. Resonant depletion allows us to selectively remove one spin state, facilitating evolution studies of both filled and dark soliton rings.

D1.00064 Collective modes of a soliton train in a Fermi superfluid, ERICH MUELLER, Laboratory of Atomic and Solid State Physics, Cornell University — We characterize the collective modes of a soliton train in a quasi-one-dimensional Fermi superfluid, using a mean-field formalism. In addition to the expected Goldstone and Higgs modes, we find novel long-lived gapped modes associated with oscillations of the soliton cores. The soliton train has an instability that depends strongly on the interaction strength and the spacing of solitons. It can be stabilized by filling each soliton with an unpaired fermion, thus forming a configuration similar to the Fulde-Ferrell-Larkin-Ovchinnikov phase. We find such a state is always dynamically stable, which paves the way for realizing them in experiments via phase imprinting.

1 NSF Grant PHY-1508300, ARO-MURI Non-equilibrium Many-body Dynamics Grant W9111NF-14-1-0003
2 The online membership application form is not accepting my APS Journal account username and password. I have emailed the issue to membership@aps.org on Jan 25, without any response so far.

D1.00065 Decay of Josephson Superflow via Vortex-Ring Emission, NICK PROUKAKIS, KLEIDJA XHANI, KEAN LOON LEE, LUCA GALANTUCCI, Joint Quantum Centre (JQC) Durham-Newcastle, Newcastle Univ., UK, ANDREA TROMBETTONI, CNR-ION and SISSA, Italy, GIACOMO VALTOLINA, FRANCESCO SCAZZA, ANDREA AMICO, CHIARA FORT, MATTEO ZACCANTI, ALESSIA BURCHIANTI, GIACOMO ROATI, INO-CNR and LENS, Italy — Josephson oscillations in fermionic superfluids across the BEC-BCS crossover (Valtolina et al., Science 350, 15050 (2015)) have been recently experimentally observed to decay through the emission of vortical excitations at the barrier connecting the two parts of the superfluid in a double-well trap. By performing full 3D numerical simulations in the molecular BEC regime at both zero and finite temperatures, we explicitly demonstrate the generated structures to be excited vortex rings, and study their propagation, dynamical instability and subsequent decay, shedding more light into this nonlinear process, the role of interactions of vortex rings with other rings and background sound, and the effect of gradually removing the barrier (experimental step undertaken before time-of-flight imaging). By self-consistently coupling the Gross-Pitaevskii equation to a quantum Boltzmann equation (ZNG model) we also discuss the role of finite temperature in damping both Josephson oscillations and macroscopic quantum super-trapping.

1 EPSRC; ERC: EU H2020

D1.00066 QUANTUM INFORMATION

D1.00067 Comparing Zeeman qubits to hyperfine qubits in the context of the surface code: $^{171}$Yb$^+$ and $^{174}$Yb$^+$. N.C. BROWN, K.R. BROWN, Georgia Institute of Technology, Atlanta, GA — Many systems used for quantum computing possess additional states beyond those defining the qubit. Leakage out of the qubit subspace must be considered when designing quantum error correction codes (QECC). Here we consider trapped ion qubits manipulated by Raman transitions. Zeeman qubits do not suffer from leakage errors but are sensitive to magnetic fields to first-order. Hyperfine qubits can be chosen to be insensitive to magnetic fields to first-order, clock states, but spontaneous scattering during the Raman transition can lead to leakage. Here we compare a Zeeman qubit ($^{174}$Yb$^+$) to a hyperfine qubit ($^{171}$Yb$^+$) in the context of the surface code. We find that the number of physical qubits required to reach a specific logical qubit error can be reduced by using $^{174}$Yb$^+$ if the magnetic field can be stabilized to $10^{-3}G$.

D1.00068 Multi-Valued Logic, Neutrosophy, and Schrödinger Equation, FLORENTIN SMARANDACHE, University of New Mexico, VICTOR CHRISTIANANTO, SciPrints — Discussing some paradoxes in Quantum Mechanics from the viewpoint of Multi-Valued-logic pioneered by Lukasiewicz, and the recent concept Neutrosophic Logic. Essentially, this new concept offers new insights on the idea of ‘identity’, which too often it has been accepted as given. Neutrosophy itself was developed in attempt to generalize Fuzzy-Logic introduced by L. Zadeh. The discussion is motivated by observation that despite almost eight decades, there is indication that some of those paradoxes known in Quantum Physics are not yet solved. In our knowledge, this is because the solution of those paradoxes requires re-examination of the foundations of logic itself, in particular on the notion of identity and multi-valuedness of entity. The discussion is also intended for young physicist fellows who think that somewhere there should be a ‘complete’ explanation of these paradoxes in Quantum Mechanics. If this it doesn’t answer all of their questions, it is our hope that at least it offers a new alternative viewpoint for these old questions.
D1.00069 Microfabricated Microwave-Integrated Surface Ion Trap1, MELISSA C. REVELLE, MATTHEW G. BLAIN, RAYMOND A. HALTLI, ANDREW E. HOLLOWELL, CHRISTOPHER D. NORQUIST, PETER MAUNZ, Sandia National Laboratories, Albuquerque, NM — Quantum information processing holds the key to solving computational problems that are intractable with classical computers. Trapped ions are a physical realization of a quantum information system in which qubits are encoded in hyperfine energy states. Coupling the qubit states to ion motion, as needed for two-qubit gates, is typically accomplished using Raman laser beams. Alternatively, this coupling can be achieved with strong microwave gradient fields.2 While microwave radiation is easier to control than a laser, it is challenging to precisely engineer the radiated microwave field. Taking advantage of Sandia’s microfabrication techniques, we created a surface ion trap with integrated microwave electrodes with sub-wavelength dimensions. This multi-layered device permits co-location of the microwave antennae and the ion trap electrodes to create localized microwave gradient fields and necessary trapping fields. Here, we characterize the trap design and present simulated microwave performance with progress towards experimental results.

1This research was funded, in part, by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA).

D1.00070 The generalized analytical model and DSMC simulations of high-speed rotating flow in polar (r − θ) coordinate. DR. SAHADEV PRADHAN, Department of Chemical Engineering, Indian Institute of Science, Bangalore- 560 012, India — The generalized analytical model for the radial boundary layer in a high-speed rotating cylinder is formulated for studying the gas flow field due to insertion of mass, momentum and energy into the rotating cylinder in the polar (r − θ) plane. The analytical solution includes the sixth order differential equation for the radial boundary layer at the cylindrical curved surface in terms of master potential (χ), which is derived from the equations of motion in a polar (r − θ) plane. The linearization approximation ((Pradhan & Kumar, J. Fluid Mech -); (Kumar & Pradhan, J. Fluid Mech -)) is used, where the equations of motion are truncated at linear order in the velocity and pressure disturbances to the base flow, which is a solid-body rotation. Additional assumptions in the analytical model include constant temperature in the base state (isothermal condition), and high Reynolds number, but there is no limitation on the stratification parameter. The analytical solutions are compared with direct simulation Monte Carlo (DSMC) simulations and found good agreement (with a difference of less than 10%), provided the boundary conditions are accurately incorporated in the analytical solution. The slow down of the circumferential velocity of the bulk of the rotating fluid due to the presence of stationary intake tube is studied for stratification parameter in the range 0.707–3.535, and found significant slow down (between 8 to 28%), which induces the secondary radial flow towards the axis, and it further excites the secondary axial flow, which could be very important for the centrifugal gas separation processes.

D1.00071 Grover’s unstructured search by using a transverse field. ZHANG JIANG, ELEANOR RIEFFEL, ZHIHUI WANG, NASA Ames Research Center — We design a circuit-based quantum algorithm to search for a needle in a haystack, giving the same quadratic speedup achieved by Grover’s original algorithm. In our circuit-based algorithm, the problem Hamiltonian (oracle) and a transverse field (instead of Grover’s diffusion operator) are applied to the system alternatively. We construct a periodic time sequence such that the resultant unitary drives a closed transition between two states, which have high degrees of overlap with the initial state (even superposition of all the target states) and the target state, respectively. Let N = 2n be the size of the search space. The transition rate in our algorithm is of order Θ(1/√N), and the overlaps are of order Θ(1), yielding a nearly optimal query complexity of T ≈ √N/π. Our algorithm is inspired by a class of algorithms proposed by Farhi et al. [arXiv:1411.4028], namely the Quantum Approximate Optimization Algorithm (QAOA); our method offers a route to optimizing the parameters in QAOA by restricting them to be periodic in time.

D1.00072 Theoretical study of the adsorption energy of some linear saturated hydrocarbons on SWCNT: DFT calculations. HEWA ABDULLAH, HASSAN H. ABDALLAH, Computational Nanoscience Lab, Research Center, Salahaddin University, 44001 Erbil, Iraq — Carbon nanotubes represent one of the building blocks of innovation across most industries. Carbon nanotubes have many applications based on the aspect ratio, mechanical strength, electrical and thermal conductivity of these nano materials. In this study the adsorption of a single molecule of the some linear saturated hydrocarbons inside and on the surface of a tube of single-walled carbon nanotubes (SWCNT) was investigated using Density Function Theory (DFT). The results showed that all guest molecules prefer to be adsorbed into the surface of SWCNT rather than into the CNT tube. Upon adsorption of the guest molecules, the energy gap was considerably reduced, resulting in improved electrical conductivity. DOS and NBO analysis were performed to discover intermolecular interactions. Chemical reactivity was investigated in terms of chemical hardness, softness and absolute electronegativity.

D1.00073 Hidden-variable hypothesis in quantum paradoxes. FLORENTIN SMARANDACHE, University of New Mexico, VICTOR CHRISTIANUTO, SciPrints — It would be incomplete to discuss quantum paradoxes, in particular Schrödinger’s cat paradox, without mentioning the hidden-variable hypothesis. There are various versions of this argument, but it could be summarised as an assertion that there is ‘something else’ which should be included in the Quantum Mechanical equations in order to explain thoroughly all quantum phenomena. Sometimes this assertion can be formulated in question form: “Can quantum mechanics be considered complete?” Interestingly, however, the meaning of ‘complete’ itself remains quite abstract (fuzzy). An interpretation of this cat paradox suggests that the problem arises because we mix up the macroscopic systems (observer’s wavefunction and apparatus’ wavefunction) from microscopic system to be observed. In order to clarify this, it is proposed that the measurement apparatus should be described by a classical model, and the physical system by a quantum model.

D1.00074 Synthesizing complex spin networks with spin-motion coupled neutral atoms in photonic crystals. YING DONG, IQC, University of Waterloo — We develop a toolbox for realizing “fully programmable” d-dimensional pairwise interacting lattice spin systems with spin-motion coupled neutral atoms in the vicinity of 1D photonic crystal waveguides. The enabling platform thereby allows to synthesize a wide range of strongly interacting quantum materials by way of vacuum-engineered interatomic kinetic interactions. We demonstrate the versatility of our assembly language approach towards arbitrary SU(2)-lattice spin models with explicit constructions of familiar Hamiltonians for perfect state transfer in 1D spin chains, lattice gauge theories, and topologicallyquantum spin liquids. We further construct Dzyaloshinskii-Moriya interaction for the realization of spin liquids and long-range random quantum magnets with spin-glass phase.
D1.00075 Applications of the trilinear Hamiltonian with three trapped ions. ROYAL ESTEBAN HABUTZEL MARRERO, SHIQIAN DING, GLEB MASLENNIKOV, JAREN GAN, STEFAN NIMMrichter, ALEXANDRE ROULET, JIBO DAI, Centre for Quantum Technologies, National University of Singapore, VALERIO SCARANI, DZIMTRY MATSUKEVICH, Centre for Quantum Technologies, National University of Singapore; Department of Physics, National University of Singapore — The trilinear Hamiltonian $a^{†}bc + ab^{†}c$, which describes a nonlinear interaction between harmonic oscillators, can be implemented to study different phenomena ranging from simple quantum models to quantum thermodynamics. We engineer this coupling between three modes of motion of three trapped $^{171}$Yb$^{+}$ ions, where the interaction arises naturally from their mutual (anharmonic) Coulomb repulsion. By tuning our trapping parameters we are able to turn on/off resonant exchange of energy between the modes on demand. We present applications of this Hamiltonian for simulations of the parametric down conversion process in the regime of depleted pump, a simple model of Hawking radiation, and the Tavis-Cummings model. We also discuss the implementation of the quantum absorption refrigerator in such system and experimentally study effects of quantum coherence on its performance.

1This research is supported by the National Research Foundation, Prime Ministers Office, Singapore and the Ministry of Education, Singapore under the Research Centres of Excellence programme

D1.00076 Towards quantum many-body physics with Sr in optical lattices. STEPHAN SNIgrev, ANDR HEINZ, ANNIE JIIHYUN PARK, STEPHAN WISENBEERG, Max-Planck-Institut fur Quantenoptik, Hans-Kopfermann-Stree 1, 85784 Garching, Germany, JEAN DALIBARD, Laboratoire Kastler Brossel, College de France, ENS-PSL Research University, CNRS, UPMC-Sorbonne Universites, 11 place Marcelin Berthelot, 75005 Paris, IMMANUEL BLOCH, SEBASTIAN BLATT, Max-Planck-Institut fur Quantenoptik, Hans-Kopfermann-Stree 1, 85784 Garching, Germany — The widespread use of ultracold fermionic strontium atoms in optical lattices for precision measurements has led to the availability of many advanced tools and techniques for these atoms. With the recent realization of degenerate gases of all Sr isotopes and the development of fermionic quantum gas microscopes for alkali atoms, a new frontier has opened for quantum simulations and quantum information processing with fermionic Sr. Many applications in quantum state engineering and quantum simulation require internal-state-dependent control of the atomic motion. In the Sr atom, there exist so-called tuneout wavelengths, where only one of the clock states is trapped and the other state can move freely. Because of the (in principle) exact cancellation of the other states' position at the tuneout wavelengths, it should be possible to realize spin-dependent lattices with high fidelity. Here, we propose a system to realize such internal-state-dependent control of the atomic motion and report on the construction of a new experiment towards quantum simulations with Sr in optical lattices.

D1.00077 Adiabatic ground state preparation in an expanding lattice. SNIR GAZIT, CHRIS OLUND, NORMAN YAO, University of California - Berkeley — We numerically investigate the newly proposed s-source framework for constructing ground state wave functions of gapped Hamiltonians. The key idea is to utilize the adiabatic principle to build a tensor network representation that smoothly interpolates between the ground state of system sizes L and 2L via an interleaved set of ancillary degrees of freedom. Repeatedly applying this procedure reproduces the thermodynamic limit. The scheme should be contrasted with conventional tensor network methods that rely on the variational principle to target the ground state by iteratively improving a variational energy. We introduce a simple yet flexible tensor network structure and an optimization protocol borrowing techniques from quantum control theory. We anticipate that this approach can, in principle, allow access to problems beyond current tensor network technology and even serve as an experimental scheme for ground state preparation in quantum engineered systems.

D1.00078 Quantum simulations of quantum magnetism with hundreds of trapped ions. KEVIN GILMORE, JILA, NIST, and Dept. Phys. U. Colorado, Boulder, CO, JUSTIN BOHNET, ELENA JORDAN, NIST, Boulder, CO, MARTIN GAERTTNER, ARGHAVAN SAFAVI-NAINI, ANA MARIA REY, JILA, NIST, and Dept. Phys. U. Colorado, Boulder, CO, JOHN BOUGGER, NIST, Boulder, CO — Quantum simulators, where one well-controlled physical system mimics another complex system, may enable understanding of quantum many-body physics that cannot be fully studied using conventional techniques on classical computers. We describe quantum simulations of a network of interacting magnetic spins performed with 2-dimensional arrays of hundreds Be$^{+}$ ions crystallized in a Penning trap. We discuss how we engineer a tunable transverse Ising model, and explain how we generate and observe far-from-equilibrium quantum spin states by varying the parameters, including signs of entanglement. We summarize progress exploring optimized adiabatic protocols for preparing low energy states of the transverse Ising Hamiltonian and implementing a sub-Doppler cooling scheme for the drumhead modes of the ion array.

D1.00079 Integrated Technologies for Chip-Scale Trapped-Ion Quantum Control. ROBERT MCCOY, SURAJ BRAMHAVAR, COLIN BRUZEWICZ, DAVE KHARAS, WILLIAM LOH, MIT Lincoln Laboratory, KARAN MEHTA, MIT, JASON PLANT, JONATHAN SEDLACEK, CHERYL SORACE-AGASKAR, MIT Lincoln Laboratory, JULES STUART, MIT, JOHN CHIAVERINI, MIT Lincoln Laboratory, RAJEEV RAM, MIT, JEREMY SAGE, MIT Lincoln Laboratory — Microfabricated ion-trap arrays are attractive platforms for scalable quantum information processing with large numbers of qubits. The robust photolithographic techniques used to define the trapping laser can potentially be integrated with advanced photonic devices and CMOS electronics to build a single system that performs the key functions of a quantum information processor on-chip. Here we describe progress towards the demonstration of the components of an integrated chip-scale platform, focusing on multilayer photonic waveguides to route multiple laser beams throughout a trap array, integrated photodetectors for ion-state readout, and embedded CMOS circuitry for on-chip electronic control.

D1.00080 Fast scrambling in the Sachdev-Ye-Kitaev model: a numerical test. CHRISTOPHER OLUND, NORMAN YAO, JOEL MOORE, Univ of California - Berkeley — Understanding the approach toward thermalization in isolated quantum systems is challenging. This approach is thought to be characterized by the delocalization, or scrambling, of quantum information over all of a system's degrees of freedom. Experimentally, control of black holes, conjectured to be the fastest scramblers in nature, and model spin and fermionic hamiltonians. These models typically live on fully connected graphs, naturally motivating the question: are all-to-all interactions necessary for fast scrambling? Here, we numerically probe the scrambling rate of the Sachdev-Ye-Kitaev model for intermediate system sizes and vary the range of the underlying interactions. By fitting out of time ordered correlation functions to a known analytic expression, we extract the scrambling rate and perform a detailed finite size scaling analysis. Extrapolating to the thermodynamic limit, we find reasonable agreement with a recently conjectured bound for low to intermediate temperatures.

1Supported by the DoD through NDSEG

D1.00081 Quantum simulation of spin-bath dynamics with trapped ions. DYLAN GORMAN, ELI MEGIDISH, BORGHE HEMMERLING, HARTMUT HAEFFNER, Univ of California - Berkeley — Chains of trapped ions are an ideal platform for studying the dynamics of qubits coupled to bosonic environments. This kind of dynamics is of interest in many current problems in physics and biology such as charge transport, photosynthesis, and olfaction. In a chain of N trapped ions, an experimenter has access to an environment of the SN vibrational modes of the chain, allowing for the simulation of very large vibrational environments with tunable spectral properties. In addition, the ions also serve as qubits, and both qubit-qubit and qubit-bath interactions can be engineered via quantum gates. Here, we discuss recent experimental progress investigating spin-bath dynamics in ion strings. We explore what happens as the spin-bath coupling is varied, as well as when the thermal occupation and quantum state of the environment is varied.
D1.00082 Sorting atoms in a 3D optical lattice . AISHWARYA KUMAR, TSUNG-YAO WU. The Pennsylvania State University, YANG WANG, University of Maryland, DAVID WEISS, The Pennsylvania State University — We report on an atom sorting scheme for perfect pattern formation in a 3D 5x5x5 optical lattice of Cesium atoms, originally proposed in Phys. Rev. A 70, 040302(R) (2004). The combination of site selective state flips and with state selective motion steps can quickly and reliably fill site vacancies. We have previously demonstrated high fidelity site selective single qubit gates in this lattice which can be adapted to the state flips in this scheme [Science 352, 1562-1565 (2016)]. Our newer work demonstrates high fidelity state selective atomic motion.

D1.00083 Trapped ion system for sympathetic cooling and non-equilibrium dynamics1, CHARLIE DORET, SIERRA JUBIN, SARAH STEVENSON, Williams College Dept. of Physics — Atomic systems are superbly suited to the study of non-equilibrium dynamics. These systems exquisite isolation from environmental perturbations leads to long relaxation times that enable exploration of far-from-equilibrium phenomena. We present progress towards trapping chains of multiple co-trapped calcium isotopes geared towards measuring thermal equilibration and sympathetic cooling rates. We also discuss plans for future experiments in non-equilibrium statistical mechanics, including exploration of the quantum-to-classical crossover between ballistic transport and diffusive, Fouriers Law conduction.

1This work is supported by Cottrell College Science Award from the Research Corporation for Science Advancement and by Williams College

D1.00084 ATOM AND MATTER OPTICS —

D1.00085 Magnetic-Gradient Cold-Atom Launching , BENEDICT FEINBERG, HARVEY GOULD, RAPHAEL JANIN, CHARLES T. MUNGER JR., HIROSHI NISHIMURA, Lawrence Berkeley National Laboratory — We have extended our simulations (http://meetings.aps.org/Meeting/APR17/Session/F1.39) of beam transport of ultra cold (2 μK) and cold (130 μK) neutral Cs atoms. In addition to falling under gravity, focusing, and reversing direction, ultra cold atoms in our simulations are now longitudinally bunched and accelerated, reaching 0.5 m above their starting point. An experimental apparatus to test the simulations is being constructed. Experimental progress will be described.

D1.00086 Atomic Coherence Effects of Scattered Light in a Λ-Type Atomic System of D1-line of 85Rb Atoms , SEO HONG MIN, HAN SEB MOON, Pusan National University — We report the two-photon coherence effects by scattered light in D1-line of 85Rb atoms, such as electromagnetically induced transparency (EIT), electromagnetically induced absorption (EIA), and electromagnetically induced focusing (EIF), in a paraffin-coated Rb vapor cell. Especially, according to the direction of the scattered light, sub-natural EIA-like and EIT spectra of the scattered light were measured simultaneously. We will illuminate the interesting spectra of the scattered light as two-photon coherence effects.

D1.00087 Correlated Photon-Pair Generation Based on Spontaneous Four-Wave Mixing in Open & Closed Ladder-Type Atomic System , JIHO PARK, HAN SEB MOON, Pusan National University — We obtained a bright photon-pair source via spontaneous four-wave mixing in a Doppler-broadened atomic ensemble of the open (5D1/2 → 5S1/2 → 5D3/2) and closed (5D1/2 → 5P3/2 → 5D3/2) ladder-type atomic systems of 87Rb. We characterize and compare the photon-pairs generated from both atomic configurations according to the vapor cell temperature and the pump and coupling powers. The coincidence counting rate of the open atomic system is smaller than that of the closed system under the same conditions because of different two-photon coherence. Our bright photon pair source will be used for two photon interference and quantum memory experiment. We believe that our source is important as a useful quantum light source.

D1.00088 Photon-Pair Generation in Cold Atomic Ensemble for Long-Distance Quantum Communication , PYEONG WOO KIM, HAN SEB MOON, Pusan National University — One of the common methods for overcoming limitation of long-distance quantum communication is using entangled photon pair sources between 1.5-μm band photon and near infrared photon. We investigate the three-photon electromagnetically induced absorption (TPEIA) and four-wave mixing (FWM) in the 5S1/2-5P3/2-4D5/2 transition of 87Rb atoms. We will report the photon-pairs with 780-nm and 1.5-μm generated by spontaneous four-wave mixing in this transition of 87Rb.

D1.00089 Storage of Heralded Single Photons in Warm Atomic Ensemble., TAEK JEONG, HAN SEB MOON, Pusan National University — We report the correlated photon-pair generation and the storage of heralded single photons in a warm atomic ensemble. We observed the correlated photon-pairs from warm atomic ensemble of 87Rb by using spatially prepared optical pumping process. The process is realized by donut-like optical pumping beam. The photon pairs are generated at the dark region, which is the center of the optical pumping beam, for reducing fluorescent noise. And we performed experiment for storage of heralded single photons by using another warm 87Rb atom via electromagnetically induced transparency (EIT). We will illuminate single photon manipulation process based on warm atomic ensembles.

D1.00090 Single Atoms in Nearly Concentric Cavity1, ADRIAN NUGRAHA UTAMA, CHI HUAN NGUYEN, NICK LEWTY, CHRISTIAN KURTSIEFER, Centre for Quantum Technologies, QUANTUM OPTICS GROUP TEAM2 — Strong interaction between photons and neutral single atoms are usually observed in cavity quantum electrodynamics (CQED) systems with high finesse mirrors and small physical volume. We demonstrate another approach that employs a near concentric cavity with relatively low finesse mirrors (∼ 100) and large physical separation between mirrors (∼ 10 mm). The transmission spectrum of our CQED system with trapped single atoms is observed to exhibit two resolved normal mode peaks, in which the single atom cooperativity is estimated to be around 0.4. The cooperativity of the system can be improved further by increasing the finesse of the mirrors or moving the cavity closer to the concentric point. The successful realization of concentric CQED systems will open opportunities for scaling up with applications in quantum computing.

1This work is supported by the National Research Foundation and Ministry of Education, Singapore.

2http://www.qolah.org/
D1.0091 Compact Surface Plasmon Resonance Biosensor for Fieldwork Environmental Detection. MARGRETHE BOYD, MADISON DRAKE, KRISTIAN STIPE, MONICA SERBAN, IVANA TURNER, AARON THOMAS, DAVID MACALUSO, University of Montana — The ability to accurately and reliably detect biomolecular targets is important in innumerable applications, including the identification of food-borne parasites, viral pathogens in human tissue, and environmental pollutants. When detection methods do exist, they are typically slow, expensive, and restricted to laboratory use. The method of surface plasmon resonance biosensing offers a unique opportunity to characterize molecular targets while avoiding these constraints. By incorporating a plasmon-supporting gold film within a prism/laser optical system, it is possible to reliably detect and quantify the presence of specific biomolecules of interest in real time. This detection is accomplished by observing shifts in plasmon formation energies corresponding to optical absorption due to changes in index of refraction near the gold-prism interface caused by the binding of target molecules. A compact, inexpensive, battery-powered surface plasmon resonance biosensor based on this method is being developed at the University of Montana to detect waterborne pollutants in field-based environmental research.

D1.0092 QUANTUM OPTICS

D1.0093 High-efficiency Coherent Optical Memory based on Electromagnetically Induced Transparency. YING-CHENG CHEN, Inst. of Atomic and Molecular Sci., Academia Sinica, Taiwan, YA-FEN HSIAO, Molecular Science and Technology, Taiwan International Graduate Program, Academia Sinica and National Central University, Taiwan, PIN-JU TSAI, Department of Physics, National Taiwan University, Taiwan, HUNG-SHIUE CHEN, Institute of Atomic and Molecular Sciences, Academia Sinica, Taiwan, SHENG-XIANG LUN, CHIH-CHIAO HUNG, CHIH-HSI LEE, Department of Physics, National Taiwan University, Taiwan, YI-HSIN CHEND, Department of Physics, National Tsing Hua University, Taiwan, YONG-FAN CHEN, Department of Physics, National Cheng Kung University, Taiwan, ITE ALBERT YU, Department of Physics, National Tsing Hua University, Taiwan — Quantum memory is a crucial component in the long-distance quantum communication based on quantum repeaters. To outperform the direct transmission of photons with quantum repeaters, it is crucial to develop quantum memories with high fidelity, high efficiency, and a long storage time. Here, we present our work to achieve a storage efficiency of larger than 90% for a coherent memory based on the electromagnetically induced transparency (EIT) scheme in cold atomic media with an optical depth of ~1000. At a storage efficiency of 50%, we also obtain a fractional delay of 1200. At high optical depths, nonlinear optical effects, such as the photon switching and four-wave mixing due to the off-resonant excitation of the EIT control field, may become significant and introduce complications in quantum memory applications. We discuss and present methods to reduce these complications.

D1.0094 Cooperative spontaneous emissions from resonant long-range dipole-dipole interactions: Super- and subradiance, and superradiant laser. HSANG-HUA JEN, Institute of Physics, Academia Sinica, Taipeh 11529, Taiwan, MING-SHIEN CHANG, YING-CHEING CHEN, Institute of Atomic and Molecular Sciences, Academia Sinica, Taipeh 10617, Taiwan, IOP QUANTUM LIQUID TEAM, IOP AND IAMS COLLABORATION — Resonant long-range dipole-dipole interaction (LRDDI) has played an important role in initiating super- and subradiance in a cold atomic ensemble. This universal effect is induced from the atom-photon interaction in the dissipation process. Here we propose a complete space of singly-excited states which can be the candidates for superradiance and subradiance. Cooperative single- and multi-photon subradiant states can also be prepared in our proposed scheme by imprinting the required phases via pulsed gradient magnetic or electric fields. This effect of LRDDI is also present in a steady-state superradiant laser (SL) in the bad-cavity limit. We demonstrate that cavity photon number oscillates as an inter-particle distance of the atoms varies. Similarly the atom-atom coherence alternates with signs, showing critical transitions alternatively in SL operations. This suggests a complexity of the collective effect emerging in a large ensemble of atoms. The scaling of a finite number of atoms shows that a steady-state SL outperforms the one without LRDDI, which allows for probing narrow atomic transitions and is potentially useful for precision measurements and next-generation optical clocks.

1 MOST of Taiwan and NCTS in Hsinchu

D1.0095 Towards quantum memory with rare-earth-ions in crystals. HAOQUAN FAN, ELIZABETH A. GOLDSCHMIDT, U.S. Army research laboratory, Joint quantum institute, University of Maryland — Quantum memory is essential to the future of quantum information. At cryogenic temperatures, solids containing rare-earth-ions (REI) offer naturally trapped atomic systems for quantum memory implementations. The properties of REI in crystals enable broadband, efficient, and long-lived quantum memory in solid state materials. Progress to-date toward ensemble-based quantum memory with REI solids has been hampered by inhomogeneous broadening. Recent progress on stoichiometric materials narrows down the inhomogeneous broadening by 2 orders of magnitude, opening up new avenues for quantum memory. We report progress toward quantum memory with Eu$^{3+}$ in crystals.

D1.0096 Line shapes in V-type electromagnetically induced transparency for 87Rb atoms: theory and experiment. HYUNJONG KANG, HEUNG-RYOUL NOH, Chonnam National University — We present a theoretical and experimental study of electromagnetically induced transparency (EIT) in V-type systems of 87Rb atoms. The probe beam frequency is locked to the F$_g$ = 2 → F$_e$ = 2 and F$_g$ = 2 → F$_e$ = 1 transitions of D$_1$ line and the coupling beam frequency is scanned around the F$_g$ = 2 → F$_e$ = 1.23 transitions of D$_2$ line. The polarizations of the probe and coupling beams are linear in parallel or perpendicular direction. We calculate accurate line shapes of V-type EIT spectra using density matrix equations by considering all the magnetic sub-levels and compare them with experimental results. To discriminate the contribution of coherence term, we perform similar calculations by ignoring the coherences between the sublevels in the 5P$_{1/2}$ state and those in the 5P$_{3/2}$ state. We find that the coherence effect is significant only for the cycling transition line.

D1.0097 Light-dragging effect in a moving electromagnetically induced transparent medium. CHANG HUANG, PEI-CHEN KUAN, SHAU-YU LAN, Nanyang Technological University — As one of influential experiments on the development of modern physics, the phenomenon of light dragging in a moving medium has been discussed and observed extensively in different types of systems. In order to get a larger dragging effect, a long duration of light traveling in the medium is preferred. We therefore demonstrate a light-dragging experiment in an electromagnetically induced transparent cold atomic ensemble to enhance the dragging effect by at least three orders of magnitude compared with the previous experiments. With a large enhancement of the dragging effect, we realize an atom-based velocimeter that has a sensitivity two orders of magnitude higher than the velocity width of the atomic medium used. The result suggests the possibility of making a motional sensor using the collective state of atoms in a room temperature vapor cell or solid state material in the future.

1 National Research Foundation
D1.00098 Second-order correlation of an optomechanical oscillator\textsuperscript{1}, HYOJUN SEOK, Department of Physics Education, Kongju National University, DONGYEL KANG, School of Basic Sciences, College of Engineering, Hambat National University — We investigate an optomechanical oscillator quadratically coupled to a single-mode cavity field in the regime in which the cavity dissipation is a dominant source of damping. The mechanical oscillator experiences effective cubic nonlinear interaction following the dynamics of the cavity field adiabatically. We show that the mechanical oscillator is coupled to an effective optical reservoir in addition to its own mechanical heat bath. It is shown that the effective optical reservoir leads to nonlinear cooling of the mechanical oscillator in the thermal limit and antibunching of the phonon field in the quantum regime. We find the condition of the transition from bunching to antibunching of the phonon field both numerically and analytically.

\textsuperscript{1}NRF 2015R1C1A1A01053349

D1.00099 Visible Quantum Imaging of Infrared Ghost\textsuperscript{1}, FELIX JAETAEG SEO, QUINTON RICE, DULITHA JAYAKODIGE, TIKARAM NEUPANE, BAGHÈR TABIBI, Hampton University, HAMPTON UNIVERSITY TEAM — Quantum imaging is of great interest due to unique characteristic interaction and measurement with nonlocal correlation that provides higher accuracy, sensitivity, and security. For quantum ghost imaging, two non-linear crystals in a double Mach-Zehnder interferometer produce a signal beam for the measurement and an idler beam for the interaction with an object through spontaneous parametric down conversion (SPDC) with momentum and energy conservations. The idler in the invisible spectrum interacts with the object, and experiences various optical processes including transmission, scattering, reflection, and phase change. Since the signal beam in the visible spectrum does not interact with the object, the object is a ghost to the signal beam. If the signal beam has a spatial entanglement with the idler beam, the information of idler is the measurement of signal. Since two nonlinear crystals are employed in the interferometer, the indistinguishability with no-which-source provides the interference of two signal beams through a half silver beam splitter while the idlers are completely overlapped through optical parametric generation, not amplification. If the homodyne of the signal probabilities of two interferences is unity, the heterodyne of the signal probabilities will be the product of transmittance coefficient and sinusoidal phase shift of idler through the object. Therefore, quantum ghost imaging may be utilized for secure surveillance of potential threats and noninvasive quantum microscopy.

\textsuperscript{1}Acknowledgement: This work is supported by NASA NNX15AQ03A, NSF HRD-1137747, and ARO W911NF-15-1-0535.

D1.00102 Transfer of Orbital and Spin angular momentum from non-paraxial optical vortex to atomic BEC, ANAL BHOWMIK, Department of Physics, Indian Institute of Technology Kharagpur, Kharagpur-721302, India, PRADIP KUMAR MONDAL, Department of Applied Science, Haldia Institute of Technology, Haldia-721657, India, SONJOY MAJUMDER, Department of Physics, Indian Institute of Technology Kharagpur, Kharagpur-721302, India, BIMALENDU DEB, Department of Materials Science, Indian Association for the Cultivation of Science, Jadavpur, Kolkata 700032, India — Allen and co-workers first brought up the realization that optical vortex can carry well defined orbital angular momentum (OAM) associated with its spatial mode. Spin angular momentum (SAM) of the light, associated with the polarization, interacts with the internal electronic motion of the atom. The exchange of orbital angular momentum (OAM) between optical vortex and the center-of-mass (CM) motion of an atom or molecule is well known in paraxial approximation. We show that, how the total angular momentum (TAM) of non-paraxial optical vortex is shared with atom, in terms of OAM and SAM. Both the angular momenta are now possible to be transferred to the internal electronic and external CM motion of atom. Here we have studied how the Rabi frequencies of the excitations of two-photon Raman transitions with respect to focusing angles. Also, we investigate the properties of the vortex superposed state for a Bose-Einstein condensate condensate by a single non-paraxial vortex beam. The density distribution of the vortex-antivortex superposed state has a petal structure which is determined by the quantum circulations and proportion of the vortex and antivortex.

D1.00103 EIT amplitude noise spectroscopy, BENJAMIN WHITENACK, DEVAN TORMEY, SHANNON O’LEARY, Dept. of Physics, Lewis and Clark College, MICHAEL CRESCIMANNO, Dept. of Physics and Astron., Youngstown State University — EIT Noise spectroscopy is usually studied by computing a correlation statistic based on temporal intensity variations of the two (circular polarization) propagation eigenstates. Studying the intensity noise correlations that result from amplitude mixing that we perform before and after the cell allows us to recast it in terms of the underlying amplitude noise. This leads to new tests of the quantum optics theory model and suggests an approach to the use of noise spectroscopy for vector magnetometry.

D1.00104 Long-lived quantum coherences in symmetric V-system strongly driven by incoherent light, SYUHEY KOYU, TIMUR TSCHERBUL, University of Nevada, Reno — The three-level V-system is a prototype model of quantum coherent dynamics in multilevel systems, including photosynthetic light-harvesting complexes and photovoltaic devices. The symmetric V-system weakly irradiated by incoherent light undergoes coherent dynamics under certain conditions\textsuperscript{1}. Here, we explore the coherent dynamics in the limit where incoherent driving is fast compared to the radiative decay rates. The two-photon quantum coherences between the excited levels of the symmetric V-system display an oscillatory behavior in the underdamped regime ($\Delta/\gamma > n$) and a long-lived quasi-stationary state in the overdamped regime ($\Delta/\gamma < n$) for the effective photon occupation numbers $n \gg 1$. The lifetime of the long-lived coherent state scales as $n^{1/2} (\Delta/\gamma)^{-2}$ for $p > p_c$, where $p_c$ is a critical value of the transition dipole alignment factor ($p_c = 1 - \epsilon$ with $\epsilon \rightarrow 0$) over a wide range of excited-level splittings $\Delta$ and radiative decay rates $\gamma$. For $p < p_c$ the coherence lifetime decreases sharply and becomes comparable to that of the excited levels.


D1.00105 Single-photon nonlinearities in the propagation of focused beams through dense atomic clouds\textsuperscript{1}, YIDAN WANG, Joint Quantum Institute, University of Maryland, College Park, ALEXEY GORSHKOV, MICHAEL GULLANS, Joint Quantum Institute; Joint Center for Quantum Information and Computer Science — We theoretically study single-photon nonlinearities realized when a highly focused Gaussian beam passes through a dense atomic cloud. In this system, strong dipole-dipole interactions arise between closely spaced atoms and significantly affect light propagation. We find that the highly focused Gaussian beam can be treated as an effective one-dimensional waveguide, which simplifies the calculation of photon transmission and correlation functions. The formalism we develop is also applicable to the case where additional atom-atom interactions, such as interactions between Rydberg atoms, are involved.

\textsuperscript{1}This work was supported by the ARL, NSF PFC at the JQI, AFOSR, NSF PIF, ARO, and AFOSR MURI.
We study harmonic generation of Li atoms in one- and two-photon Rabi-flopping regimes where the population transfer from the ground state to the excited states is significant. Our theoretical approach is based on the time-dependent density-functional theory taking into account dynamic multielectron response to the external field. We present a fully ab initio and high precision 3D quantum study of the below- and near-threshold harmonic generation of H$^+_{2}$ molecules in an intense 800-nm near-infrared (NIR) laser field. Combining with a synchrosqueezing transform of the quantum time-frequency spectrum and an extended semiclassical analysis, we explore in-depth the roles of various quantum trajectories, including short- and long-trajectories, multiphoton trajectories, resonance-enhanced trajectories, and multiple rescattering trajectories of the below- and near-threshold harmonic generation processes. Our results shed new light on the dynamical origin of the below- and near-threshold harmonic generation and various quantum trajectories for diatomic molecules.

This work was partially supported by DOE.

We study harmonic generation of Li atoms in one- and two-photon Rabi-flopping regimes where the population transfer from the ground 2s state to the excited 2p, 3s, and 3d states is significant. Our theoretical approach is based on the time-dependent density-functional theory taking into account dynamic multielectron response to the external field. In the one-photon Rabi-flopping regime between the 2s and 2p states, the harmonic spectrum exhibits a fine oscillatory structure, with the spacing between the adjacent subpeaks equal to twice the Rabi frequency. The structure originates from the low-frequency modulation of the time-dependent dipole moment due to oscillations of the electronic population between the 2s and 2p states. For higher laser intensities, the pattern in the harmonic spectrum becomes more complex because of the population transfer to other excited states and pulse shape effects. Using the concept of adiabatic Floquet states, we show that interference of the contributions to the harmonic signal from the leading and trailing edges of the laser pulse also results in a fine structure of the harmonic peaks but on a smaller frequency scale. Similar structures in the harmonic spectra are observed in the two-photon Rabi-flopping regimes as well.

This work is partially supported by DOE.

Non-Sequential Double Recombination High Harmonic Generation in Molecular-like Systems

Non-sequential double recombination (NSDR) high harmonic generation (HHG) is a strongly correlated two-electron HHG process where two electrons combine their potential and kinetic energy into emitting a single photon. We have studied this process in a molecular-like system and found that the two-electron nature of the signal results in the emitted HHG spectrum being dependent on the structure of the molecule, i.e., the nuclear configuration at ionization. A clear dependence in the NSDR HHG signal on the internuclear distance is observed in the cutoffs of the HHG spectrum for large internuclear distances where also an indication of the point of emission (the atom within the molecule from which the electrons is kicked out) can be observed in the HHG spectrum. A change in the NSDR process is observed when a change in the electron charge transfer in the molecule shifts the observed cutoffs in a process not seen in normal one-electron HHG.
D1.00113 Few-cycle strong-field ionization of atomic hydrogen with elliptically polarized light. 1, NICOLAS DOUGUET, KLAUS BARTSCHAT, Drake University — We consider strong-field ionization of atomic hydrogen by elliptically polarized light in the long-wavelength regime (800 nm). By solving the time-dependent Schrödinger equation, we analyze the ionization spectra at various peak intensities up to $1 \times 10^{14}$ W/cm$^2$. The calculations are performed with the length and velocity forms of the electric dipole operator. In particular, we compare the extreme cases of circularly and linearly (studied in [1]) polarized light. Starting from an oriented atomic state, we also consider the dynamics responsible for circular dichroism [2], from the multiphoton to the tunneling regime. A model based on the strong-field approximation is employed in an attempt to predict the variation of the dichroism as a function of the laser peak intensity. Finally, we analyze the tunneling time for photo-ionization in the strong-field regime. [1] A. N. Grum-Grzhimailo, B. Abeln, K. Bartschat, D. Wellen, and T. Urness, Phys. Rev. A 81 (2010) 043408. [2] M. Iichen et al., Phys. Rev. Lett. 118 (2017) 013002. 1Work supported by the NSF under PHY-1403245 and XSEDE-090031.

D1.00114 Understanding strong-field coherent control using the Parametric State Expansion 2, JENS SVENSMARK, B. D. ESRY, J. R. Macdonald Laboratory, Kansas State University — The carrier-envelope phase (CEP) of an ultrashort laser pulse is $2\pi$-periodic. We have shown 3 that from this simple, almost trivial, observation the analytic dependence of any observable on the CEP can be found by expanding the wave function in a Fourier series. The Fourier index turns out to be interpretable as the photon number. From this insight, it is possible to predict when CEP effects will be most pronounced, and thus help choose parameters to maximize control via the CEP. But why stop with CEP? The same basic formulation can be applied to any parameter that influences a given observable on the CEP can be found by expanding the wave function in a Fourier series. The Fourier index turns out to be interpretable as the photon number. From this insight, it is possible to predict when CEP effects will be most pronounced, and thus help choose parameters to maximize control via the CEP. But why stop with CEP? The same basic formulation can be applied to any parameter that influences a given observable.

D1.00115 Time-local equation for exact time-dependent optimized effective potential in time-dependent density functional theory 1, SHENG-LUN LIAO, National Taiwan University, TAK-SAN HO, HERSHEY RABITZ, Princeton University, SHI-H Ku CHU, University of Kansas — Solving and analyzing the exact time-dependent optimized effective potential (TDOEP) integral equation has been a longstanding challenge due to its highly nonlinear and nonlocal nature. To meet the challenge, we derive an exact time-local TDOEP equation that admits a unique real-time solution in terms of time-dependent Kohn-Sham orbitals and effective memory orbitals. For illustration, the dipole evolution dynamics of a one-dimension-model chain of hydrogen atoms is numerically evaluated and examined to demonstrate the utility of the proposed time-local formulation. Importantly, it is shown that the zero-force theorem, violated by the time-dependent Krieger-Liafra rate approximation, is fulfilled in the current TDOEP framework.

1This work was partially supported by DOE.

D1.00116 Strong-field ionization and fragmentation of acetylene, ethylene, and ethane 1, E. WELLS, A. VOZNYUK, D.G. SCHMITZ, J.B. MAHOWALD, S.N. TEGEGN, J.L. NAPIERALA, T.G. BURWITZ, Department of Physics, Augustana University, Sioux Falls, SD 57197 USA, BETHANY JOCHIM, M. ZOHRABI, T. SEVERT, N.G. KLING, K.J. BETSCH, BEN BERRY, M.F. KLING 2, K.D. CARNES, I. BEN-ITZHAK, J.R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, Kansas 66506 USA — Velocity-map-imaging is used to examine the momentum distributions of photofragments arising from strong-field ionization of deuterated acetylene, ethylene, and ethane. The kinetic energy release and photofragment angular distributions of several dissociation processes are examined as a function of laser intensity and pulse duration. Notably, we examine elimination of one or two neutral hydrogen atoms following single ionization, the bond-rearrangement processes that lead to $D_2^+$ fragments from ethane and $CD_3^+$ from ethylene, and the transition of the angular distribution of symmetric and near-symmetric dissociation channels from alignment with the laser polarization at high laser intensity to more complex angular distributions at lower laser intensity.

1Augustana University personnel and equipment are supported by NSF Grant No. 1404185. JRML operations and personnel are supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office for Basic Energy Sciences, Office of Science, U.S. Department of Energy.

D1.00117 Retrieving plasmonic field information from metallic nanospheres using attosecond photoelectron streaking spectroscopy 1, JIANXIONG LI, ERFAN SAYDANZAD, UWE THUMM, Kansas State University — Streaked photoemission by attosecond extreme ultraviolet (XUV) pulses into an infrared (IR) or visible streaking pulse, holds promise for imaging with sub-fs time resolution the dielectric plasmonic response of metallic nanoparticles to the IR or visible streaking pulse. We calculated the plasmonic field induced by streaking pulses for 10 to 200 nm metallic Au, Ag, and Cu nanoparticles and obtained streaked photoelectron spectra by employing our quantum-mechanical model [1]. Our simulated spectra show significant oscillation-amplitude enhancements and phase shifts for all three metals (relative to spectra that are calculated without including the induced plasmonic field) and allow the reconstruction of the plasmonic field enhancements and phase shifts for each material. [1] J. Li, E. Saydanazd, and Uwe Thumm, Phys. Rev. A 94, 051401(R) (2016).

1Supported by the US NSD-EPSCoR program, NSF, and DoE.
D1.00118 Efficient and scalable ionization of neutral atoms by an orderly array of gold-doped silicon nanowires. IGAL DUCAY, AHMED HELAL, DAVID DUNSKY, ALEX LEVIYEV, AKHILA MALAVARAPU, S.V. SREENIVASAN, MARK RAIZEN, University of Texas, Austin — Ionization of atoms and molecules is an important process in many applications such as mass spectrometry. Ionization is typically accomplished by electron bombardment, and while it is scalable to large volumes, it is also very inefficient due to the small cross section of electron-atom collisions. Photoionization methods can be highly efficient, but are not scalable due to the small ionization volume. Electric field ionization is accomplished using ultra-sharp conducting tips biased to a few kilovolts, but suffers from a low ionization volume and tip fabrication limitations. We report on our progress towards an efficient, robust, and scalable method of atomic and molecular ionization using orderly arrays of sharp, gold-doped silicon nanowires. As demonstrated in earlier work, the process greatly enhances the ionization probability, which was attributed to an increase in available acceptor surface states. We present here a novel process used to fabricate the nanowire array, results of simulations aimed at optimizing the configuration of the array, and our progress towards demonstrating efficient and scalable ionization.

D1.00119 Suppressed tunneling ionization of vanadium, XI CHU, The University of Montana, GERRIT GROENENBOOM, Radboud University, NL — Using a time dependent density functional theory method, we reproduce the measured ionization suppression for vanadium in 1500 nm lasers of 1.4 to $2.8 \times 10^{14}$ W/cm$^2$. Our calculation shows that for weaker laser intensities a method with more configurations is needed to properly describe the multiphoton, rather than tunneling, ionization of a transition metal atom. We find two effects that suppress the tunneling ionization. One of them is the isomeric component of the induced potential, which increases the binding energy of the electron. The other is the dipole component that elevates the potential barrier of tunneling ionization.

D1.00120 Ionization of alkaline earth atoms in intense femtosecond laser fields. BRADFORD TALBERT, YU HANG LAI, XIAOWEI GONG, JUNLIANG XU, COSMIN BLAGA, PIERRE AGOSTINI, LOUIS DIMAURO, The Ohio State University — Electron correlation effects in the ionization of He in the presence of strong laser fields has been extensively studied. As an alternative to the alkali earth field, the alkali earth species, Mg, Ca, Sr, and Ba, are gaining interest. The electron correlation effects in strong fields depend on ionization potential and atomic structure. We investigate the yields of single and double ionization of Mg and Ca as a function of intensity, and ellipticity at 0.8, 1.3, and 3.6 m. Of particular interest to our research is the failure of PPT to predict the double ionization yield seen in both Mg and Ca, and the apparent enhancement structure in the double ionization yield of Mg under a circularly polarized (CP) field at 0.8 m [1]. Classical trajectory simulations suggest the enhancement under a CP field is due to electron recollision [2, 3]. In our measurements for Mg, we target Ca to investigate how this phenomenon depends on ionization potential and atomic structure. [1] G. D. Gillen, et al., Phys. Rev. A 64, 043413 (1994). [2] F. Mauger, et al., Phys. Rev. Lett. 105, 083002 (2010). [3] L. B. Fu, et al., Phys. Rev. Lett. 108, 103601 (2012).

D1.00121 Wavelength Dependence of the Strong-Field Ionization of Isomeric Molecules. STEFAN ZIGO, J.R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, KS 66506 USA, ALBERTO GONZALEZ CASTRILLO, ROBERT LUCHESE, Department of Chemistry, Texas A&M University College Station, TX 77843, USA, ANH-THU LE, CARLOS TRALLERO-HERRERO, J.R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, KS 66506 USA — The ionization behavior of isomeric molecules has been studied with the aid of time-of-flight mass spectroscopy (TOFMS). We study the influence of structural changes on the singly ionized strong-field ionization yields in randomly oriented C$_8$H$_8$, C$_9$H$_8$, and C$_6$H$_{10}$ isomers as a function of intensity. The experiments were performed with three different light sources with center wavelengths of 800, 1320, and 1940 nm with pulse duration of 30, 50, and 150 fs, respectively. The isomeric pairs range from small to large changes in structure creating differences in the molecular properties, such as, orbital shape and ionization potential. This allows for the investigation of the influence of these property changes on single ionization in a broader range of conditions. In addition, the experimental results serve as a benchmark for current molecular ionization theories. This proposal was supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy (DOE).

D1.00122 Exploration of laser-driven electron-multirescattering dynamics in high-order harmonic generation$^1$. PENG-CHENG LI, Northwest Normal University, SHIH-I CHU, University of Kansas — We investigate the dynamical origin of multiple rescattering processes in high-order harmonic generation (HHG) associated with the odd and even number of returning times of the electron to the parent ion. We perform fully ab initio quantum calculations and extend the empirical mode decomposition method to extract the individual multiple scattering contributions in HHG. We find that the tunneling ionization regime is responsible for the odd number times of rescattering and the corresponding short trajectories are dominant. On the other hand, the multiphoton ionization regime is responsible for the even number times of rescattering and the corresponding long trajectories are dominant. Moreover, we discover that the multiphoton- and tunneling-ionization regimes in multiple rescattering processes occur alternatively. Our results uncover the dynamical origin of multiple rescattering processes in HHG for the first time. It also provides new insight regarding the control of the multiple rescattering processes for the optimal generation of ultrabroad band supercontinuum spectra and the production of single ultrashort attosecond laser pulse.

$^1$This work is partially supported by DOE.

D1.00123 Three-dimensional momentum imaging of dissociation in flight of metastable molecular ions$^1$. BETHANY JOCHIM, REID ERDWIEN, T. SEVERT, BEN BERRY, PEYMAN FEIZOL-LAH, JYOTTI RAJPUT, Y. MALAKAR, B. KAÑERIYA, W. L. PEARSON, K. D. CARNES, A. RUDENKO, I. BEN-ITZHAK, J. R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, KS 66506 — While fragmentation of molecular ions induced by ultrashort laser pulses or fast ions often proceeds on femtosecond timescales, the population of metastable states can lead to decay on much longer timescales, ranging from picoseconds to even seconds [1,2]. We examine in detail the unimolecular dissociation in flight of such long-lived metastable molecular ions, utilizing the cold target recoil ion momentum spectroscopy (COLTRIMS) technique. Via the example of deprotonation of metastable ethylene dications formed in intense femtosecond laser pulses, we demonstrate a method that allows retrieval of the lifetime(s) of the metastable states, as well as the 3-D momentum distributions of the dissociating fragments. Importantly, our approach is general and can be used to study other heteronuclear metastable molecules that undergo dissociation in flight.


$^1$Supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U. S. Department of Energy.
D1.00124 Imaging three-body breakup involving two identical fragments$^1$, PEYMAN FEIZollahT, T. SEVERT, BETHANY JOCHIM, BEN BERRY, KANAKA RAJU P., M. ZOHRAli, JYoti RAIJPUT. U. ABLIKiM, B. KADEXIYA, FArZANEH ZIAEE, A. RUDENKO, D. ROLLES, K. D. CARNES, B. D. ESRY, I. BEN-ITZHAK, J. R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, KS 66506 — We study the strong-field fragmentation of CO$_2$ and CO$_2^+$ into C$^+ +$O$^2$ + O$^+$ as examples of three-body breakup involving two identical fragments. This process can happen through concerted- or sequential-breakup mechanisms. In concerted breakup, the two O$^+$ fragments play indistinguishable roles. In sequential breakup, however, one of the O$^+$ fragments comes from the first fragmentation step of CO$_2^+$, and the other one comes from unimolecular dissociation of CO$_2^+$ in the second step. Therefore, in sequential breakup the two O$^+$ fragments may be distinguished. A method is proposed that allows us to separate the concerted and sequential processes when the lifetime of the intermediate molecule is much longer than its rotational period. As a result, it is possible to experimentally distinguish the two O$^+$ fragments in the sequential process.

$^1$This work was supported by the Chemical Sciences, Geosciences, and BioSciences Division, Office of Basic Energy Sciences, Office of Science, U. S. Department of Energy.

D1.00125 Extracting the wave-packet phase in High-order Harmonic Generation with a homodyne interferometer., GEORGIOs KOLLIOPOULOS, JAN TROSS, CARLOS TRALLERO-HERRERO, James R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, KS 66506 — A novel self-referencing XUV interferometer is used as a tool of extreme sensitivity to below attosecond stability. Using a liquid crystal phase modulator, two spatially distinct high-order harmonic sources are induced with control on their relative brightness. The radiations from these two sources interfere in the far field providing a highly versatile implement for EUV interferometry. With this tool, we investigate the dependence of the phase of high-order harmonics on the driving field intensity. Our results are compared with theoretical and experimental reports in the existing scientific literature. The error estimates are improved and help to draw a clear picture of the intensity dependent atomic dipole phase in the process of high-order harmonic generation, as expected from the three-step model. However, we observe differences from the strong field approximation: low-order harmonics with photon energies below or near the ionization potential show also a phase dependence on the driving field intensity and a study of HHG driven by pulses in intensity regimes, where saturation effects become important, shows a deviation from the model. This behavior is radically different from what was observed for higher order harmonics.

D1.00126 PHOTOIONIZATION, PHOTODETACHMENT AND PHOTODISSOCIATION –

D1.00127 Photoionization of open-shell Cl@C$_{60}$, DAKOTA SHIELDS, RUMA DE, Northwest Missouri State University, Maryville, USA, MOHAMED MADJET, QUEERI, Hamad Bin Khalifa University, Doha, Qatar, STEVEN T. MANSON, Georgia State University, Atlanta, Atlanta, USA, HIMADIRI CHAKRABORTY, Northwest Missouri State University, Maryville, USA — The ground state of the atomically open-shell Cl@C$_{60}$ endofullerene molecule is modeled in a spherical local density approximation (LDA) augmented by the Leeuw and Baerends exchange-correlation functional [1] where the core of sixty C$^+$ ions is jellized [2]. A time-dependent LDA (TDLDA) method is subsequently applied to calculate the dipole photoionization parameters of the endofullerene molecule. Cross sections for the photoionization from atom-fullerene hybrid levels show the effects of both C$_{60}$ plasmon and atomic Coulomb dynamics, as well as the interference between them. At higher energies, the coherence of confinement and cavity oscillations dominates the structures of the spectra. Detailed comparison with the results from Ar@C$_{60}$, which involves the nearby close-shell atom in the periodic table, provides deeper insights into the role of a single shell-closing electron to noticeably influence the ionization dynamics. [1] R. van Leeuwen et al, Phys. Rev. A 49, 2421 (1994); [2] M. E. Madjet et al., Phys. Rev. A 51, 013202 (2010).

$^1$The work is supported by the US National Science foundation and the US Department of Energy.

D1.00128 Impact of nondipole effects on spin-polarization of photoelectrons from fullerene anions, A. EDWARDS, C. LANE, V. DOLMATOV, University of North Alabama — The present work provides the initial insight into the impact of a nondipole part of low-photon-energy photodetachment on the degree of spin-polarization (SP) of photoelectrons from fullerene anions, A. EDWARDS, C. LANE, V. DOLMATOV, University of North Alabama — The present work provides the initial insight into the impact of a nondipole part of low-photon-energy photodetachment on the degree of spin-polarization (SP) of photoelectrons from fullerene anions. All this might increase significantly the impact of nondipole effects on the degree of photoelectron's SP from C$_{60}^{-}$.


D1.00131 Photoionization and scattering amplitudes for polyatomic molecules using the overest grid complex Kohn variational method¹. LOREN GREENMAN, University of California, Davis and Lawrence Berkeley National Laboratory, ROBERT R. LUCCHESI, Texas A&M University and Lawrence Berkeley National Laboratory. C. WILLIAM MCCURDY, University of California, Davis and Lawrence Berkeley National Laboratory. Recent attosecond dynamics experiments [Calegari, et. al., Science 346, 336 (2014)] and coincidence experiments that measure molecular frame photoionization angular distributions [McCurdy, et. al., Phys. Rev. A 95, 011401(R)(2017)] can be explained using photoionization amplitudes calculated by the complex Kohn variational method (along with time-dependent perturbation theory), although such methods with channel coupling and exchange have so far been limited to small molecules. We have recently overcome this limitation, in large part by using overest grids. These are composed of multiple atom-centered subgrids in addition to a central master grid, with switching functions that partition wavefunctions between grids. We present here the extension of the overest grid complex Kohn variational method to photoionization and to multichannel electron scattering, along with results for the photoionization of SF6 and electron scattering in the RNA base uracil.

¹Army Research Office, MURI W911NF-14-1-0383


¹Supported by the US DoE, US NSF, and Alexander von Humboldt Foundation.

D1.00133 Orientation and alignment of excited molecular photoions from the polarization of their fluorescence¹, ALBERTO GONZALEZ-CASTRILLO, ROBERT LUCCHESI, Texas A and M University. We examine the fluorescence of the photoionized nitrogen molecule, with linearly- and circularly-polarized incident light: N(1Σg⁺) + e⁻ → N+(2Σu⁺, J) + e⁻ (σg, σg) → N+(2Σu⁺, J) + e⁻ (σg, σg). First, we compute the rotational specific transition as a function of the molecular orientation and the incident light polarization. Then, we investigate the fluorescence process from the intermediate molecular photoion reached in the first step, focusing on the dependence of the fluorescence intensity with the polarization parameters of both incident and emitted light. The computed fluorescence intensity, as a function of its polarization parameters, is compared to the experimental results obtained by J. E. Furst et al. Both experimental and theoretical results show that the residual molecular photoion, N+(2Σg⁺, J), is oriented and this is generally opposite to the direction reached in the simple excitation of the N2 by the absorption of circularly-polarized light. This clearly indicates that the ejected electron in the ionization process carries away most of the free angular momentum in the collision.

¹US-DOE, OBE, Chemical Sciences, Geosciences, and Biosciences Division and Welch Foundation

D1.00134 Molecular frame and recoil frame photoelectron angular distributions from dissociative photoionization of NO2 including the effects of rotation¹. RICHARD CARRANZA, ROBERT LUCCHESI, Texas A&M University. We report the computed molecular frame photoelectron angular distributions and recoil frame photoelectron angular distributions, taking into account the influence of rotation between ionization and dissociation, for the single-photon ionization of the non-linear NO2 molecule leading to the (1a2)⁻¹→3A2 and (4a1)⁻¹→3A1 states of NO2⁺. Additionally, we report the effects of channel coupling by employing the Complex Kohn variational method and comparing the results to computed single-channel photoionization cross sections. By comparing computed and measured photoionization cross sections we can estimate an upper bound to the lifetime of the initially produced ion state with respect to dissociation.

¹US-DOE, OBE, Chemical Sciences, Geosciences, and Biosciences Division, and Welch Foundation

D1.00135 Classical trajectory studies on the dynamics of one-photon double photoionization of H2O¹. ZACHARY STREETER, University of California, Davis, FRANK YIP, California State University, Maritime Academy, DYLAN P. REEDY, University of Nevada, Reno, ALLEN LANDERS, Auburn University, C. WILLIAM MCCURDY, University of California, Davis and Lawrence Berkeley National Lab. Recent momentum imaging experiments at the Advanced Light Source have opened the possibility of measuring the complete triple differential cross section (TDCS) for one-photon double ionization of H2O in the molecular frame. The measurements depend on the complete breakup process, H2O→hν→2e⁻+H⁺+H⁺+O. At the 57 eV photon energy of the experiment this process could proceed via any of the nine energetically accessible electronic states of H2O⁺. To discover which ionization channels contribute to the observed TDCS for the electrons measured in coincidence with different kinetic energy releases, we have carried out classical trajectory studies for breakup of the water dication on all nine potential surfaces, sampling from a Wigner phase space distribution for the vibrational ground state of H2O. The final momentum distributions of the protons and branching ratios between two- and three-body breakup are then analyzed and the results are compared with experiment to identify which ionization channels contribute to the TDCS observed in coincidence measurements of the ejected electrons.

¹Office of Basic Energy Sciences, U.S. DOE
D1.00136 Dynamic Effects in the Photoionization of the 6s Subshell of Radon and Nobelium, DAVID KEATING, STEVEN MANSON, Georgia State University, PRANAWA DESHMUKH, Indian Institute of Technology-Tirupati and Indian Institute of Science Education and Research — Photoionization of confined atoms in a C60 fullerene have been under intense investigation in the recent years, in particular the confinement induced resonances, termed confinement resonances. The effects of the C60 potential are modeled by a static spherical well, with (in atomic units) inner radius \( r_0 = 5.8 \), width \( \Delta = 1.9 \), and depth \( U_0 = -0.302 \), which is reasonable in the energy region well above the C60 plasmons [1]. At very high Z, relativistic interactions become important contributors to the photoionization cross section, to explore the extent of these dynamic effects a theoretical study of the 6s photoionization cross section of both radon (Z = 86) and nobelium (Z = 102) have been performed using the relativistic random phase approximation (RRPA) methodology [1]. These two cases have been selected because they offer the clearest picture of the effects in question. In order to determine which features in the photoionization cross section are due to relativity, calculations using the (nonrelativistic) random phase approximation with exchange method (RPAE) [2] are performed for comparison. Interchannel coupling can obscure the dynamic effects by “pulling” minima out of the discrete spectrum and into the continuum or by inducing minima. Therefore it is necessary to perform calculations without coupling included. This is possible thanks to the RRPA and RPAE codes being able to calculate cross sections with particular channels omitted. Comparisons are presented between calculations with and without interchannel coupling. Work supported by DOE and NSF. [1] W. R. Johnson and C. D. Lin, Phys. Rev. A 20, 964 (1979); [2] M. Ya. Amusia, Atomic Photoeffect (Plenum, NY, 1990).

D1.00137 Relativistic Confinement Resonances, DAVID KEATING, STEVEN MANSON, Georgia State University, PRANAWA DESHMUKH, Indian Institute of Technology-Tirupati and Indian Institute of Science Education and Research — Photoionization of confined atoms in a C60 fullerene have been under intense investigation in the recent years, in particular the confinement induced resonances, termed confinement resonances. The effects of the C60 potential are modeled by a static spherical well, with (in atomic units) inner radius \( r_0 = 5.8 \), width \( \Delta = 1.9 \), and depth \( U_0 = -0.302 \), which is reasonable in the energy region well above the C60 plasmons [1]. At very high Z, relativistic interactions become important contributors to the photoionization cross section, to explore the extent of these dynamic effects a theoretical study of the 6s photoionization cross section of both radon (Z = 86) and nobelium (Z = 102) have been performed using the relativistic random phase approximation (RRPA) methodology [1]. These two cases have been selected because they offer the clearest picture of the effects in question. In order to determine which features in the photoionization cross section are due to relativity, calculations using the (nonrelativistic) random phase approximation with exchange method (RPAE) [2] are performed for comparison. Interchannel coupling can obscure the dynamic effects by “pulling” minima out of the discrete spectrum and into the continuum or by inducing minima. Therefore it is necessary to perform calculations without coupling included. This is possible thanks to the RRPA and RPAE codes being able to calculate cross sections with particular channels omitted. Comparisons are presented between calculations with and without interchannel coupling. Work supported by DOE and NSF. [1] W. R. Johnson and C. D. Lin, Phys. Rev. A 20, 964 (1979); [2] M. Ya. Amusia, Atomic Photoeffect (Plenum, NY, 1990).

D1.00138 Fingerprints of core-hole localization in the inner shell ionization of carbon tetrachloride, B. Gaire, P. Stammer, A. Gatton, LBNL, B. Berry, T. Severt, KSU, J. Rist, S. Eckart, U-Frankfurt, J. Williams, UN-Reno, I. Ben-Itzhak, KSU, R. Doerner, U-Frankfurt, TH. Weber, LBNL — We present shell photoionization studies of single carbon tetrachloride molecules by ionizing electrons from the chlorine 2p orbital applying our COLTRIMS method, which we recently upgraded to accommodate low vapor pressure samples in the liquid form. Recoil frame photoelectron angular distributions (RFPADs) are generated by transforming the measured coincident electron-ion 3D-momentum vectors to body fixed frames. The RFPADs for the most prominent two ionization channels are presented for three different photoelectron energies and orientations of the polarization direction of the incoming light with respect to the recoil axis. The asymmetric and rich structures of the electron emission patterns suggest the localization of the core hole at the Cl atom from which the 2p electron was released, similar to the case of the F K-shell ionization of carbon tetrafluoride where, in close collaboration with theory, a strong unambiguous core hole localization effect was identified.

This research used the Advanced Light Source at Lawrence Berkeley National Laboratory. Work supported by DOE-BES under Contract No. DE-AC02-05CH11231 and DE-FC02-86ER13491, the ALS Doctoral Fellowship in Residence, and the DFG and DAAD.

D1.00139 Photoionization of atomic chlorine near the K-edge, Z. FELFLI, Clark Atlanta University, S. T. MANSON, Georgia State University, A. Z. Msezane, Clark Atlanta University — The photoionization cross section for atomic Cl in the vicinity of the 1s threshold has been investigated using R-matrix methodology. Specifically, the resonances leading up to the first two 1s ionization thresholds, the 1s2e2s2p3 2P and 1s2e2s2p3 2S and 2p 3P states of Cl, have been examined in detail. In addition to the 1s2e2s2p3 2P and 2S states of atomic chlorine, which is located by a 1s→3p transition that is possible owing to the open shell nature of the Cl atom, there are six resonances series leading up to the two thresholds: \{1s2e2p2s3p5 3P, 3S, 3D\} nS \rightarrow 2P, 2S, 2D. The results show that the 1s→3p resonances is by far the strongest, as might be expected, and the energy and shape are in rather good agreement with experiment [1]. Furthermore, this lowest 2S resonance “robs” oscillator strength from the resonances of the 1s2e2p2s3p5 3P, 3S, 3D series, which are very much weaker than their 2P and 2D counterparts; there is no 1s→3p resonance in the 2P and 2D manifolds. The next strongest resonances are the six 1s→4P excitations. Each pair 2S, 2P and 2D n=4 resonances interact so that their separation is not the splitting of the \( 2P \) and \( 1S \) ionization thresholds, and their quantum defects are very much larger than the asymptotic values and for the n=4, they are about 1.6 for the \( 2P \) and \( 2D \) while for the \( 2S \) they are about 1.8, reflecting the fact that the \( n=4 \) 2S resonances are also strongly affected by the 1s3p6 resonance; the higher resonances in all series exhibit quantum defects of about 0.9. [1] W. C. Stolte, et al, Phys. Rev. A 88, 053245 (2013). Work supported by U.S. DOE.

D1.00140 Isomerization of Ethanol Induced by Synchrotron Radiation, NORA G. KLING, RAZIB OBAID, Univ of Connecticut - Storrs, UIUUQ ABLIKIM, SVEN AUGUSTIN, BALRAAM KADERIYA, STEFAN ZIGO, Kansas State University, ILEANA DUMITRIU, Hobart and William Smith Colleges, KIRSTEN SCHNORR, Max-Planck-Institut fuer Kernphysik, TIMUR OSIPOV, SLAC National Accelerator Laboratory, RENÉ BILODEAU, Univ of Connecticut - Storrs, DANIEL ROLLES, Kansas State University, NORA BERRAH, Univ of Connecticut - Storrs — We have carried out a synchrotron-based X-ray-induced hydrogen-migration experiment in ethanol (\( CH_3CH_2OH \)) using the photon-photoin coincidence (PIPCO) technique at the Advanced Light Source. A photon energy of 312 eV, situated above the K-edge, ensures that predominantly C(1s) electrons are ionized. This inner-shell ionization induces both single and double hydrogen migration from the carbon sites to the oxygen site, evidenced in our coincidence maps that display the observed channels, including \( H_2O^+ \) + \( C_2H_5^+ \) + \( H^{+}/0 \) and \( H_2O^+ \) + \( C_2H_5^+ \) + \( 2H^{+}/0 \) + \( H^+/0 \) + \( H^+/0 \). The presence of the water ion indicates that at least one hydrogen atom has migrated. We will present the 3D momenta of these and other relevant channels.

This work is funded by the Department of Energy, Office of Science, Basic Energy Sciences, Division of Chemical Sciences, Geosciences and Biosciences under grants No. DE-SC0012376 and DE-FG02-86ER13491.
D1.00141 Absolute single photoionization cross section measurements of Rb\(^{2+}\) and Rb\(^{3+}\) ions: experiment and theory. Daniel Rogers, David Macaluso, Allison Mueller, Andrea Johnson, University of Montana, Kyren Bogolub, University of Colorado, Boulder, Alex Aguilar, A.L. David Kilcoyne, The Advanced Light Source, LLNL, Rene Bioloadeu, University of Connecticut, Manuel Bautista, Western Michigan University, Austin K Merlin, Nicholas Sterling, University of West Georgia — Absolute single photoionization cross-section measurements of Rb\(^{2+}\) and Rb\(^{3+}\) ions were performed using synchrotron radiation and the photo-ion, merged-beams technique at the Advanced Light Source at Lawrence Berkeley National Laboratory. Measurements of Rb\(^{2+}\) were made at a photon energy resolution of 13.5 meV from 37.31 to 44.08 eV spanning the \(^2\)P\(_{3/2}\) ground state and \(^2\)P\(_{1/2}\) metastable state ionization thresholds. Measurements of Rb\(^{3+}\) were made at a photon energy resolution of 30.0 meV from 49.50 to 62.49 eV spanning the \(^2\)P\(_{2}\) ground state and \(^1\)P\(_{0}\), \(^1\)D\(_{2}\), and \(^1\)S\(_{0}\) metastable state ionization thresholds. Multiple autoionizing resonance series arising from both parent ions are identified using quantum defect theory. The measurements are compared to Breit-Pauli R-matrix calculations.

D1.00142 Commission of a new 2-color laser-synchrotron COLTRIMS experiment. A. Gatton, K. Larsen, E. Champenois, N. Shivarow, S. Bakhti, W. Iskander, LBL, T. Sievert, Ksu, D. Reddy, UN-Reno, M. Wellers, U-Frankfurt, J.B. Williams, UN-Reno, A. Landers, Auburn, TH. WEBER, LBNL — We present the technical scheme of a new 2-color laser + synchrotron Cold Target Recoil Ion Momentum Spectrometer (COLTRIMS) experiment in which we overlap a pulsed IR laser (1 MHz, 1030 nm, 12 ps, 5 x 10\(^{11}\) W/cm\(^2\)) with XUV light from beamline 10.0.1 (3 MHz, 18.56 eV, 80 ps, 50 meV resolution) at the Advanced Light Source (ALS) at Lawrence Berkeley National Lab. We discuss the experimental methods for overlapping in 3D the co-linear ALS beam (80 um x 100 um) with the laser beam focus (50 um x 50 um) inside the gas jet target with a horizontal length and depth of 1 mm, as well as the timing scheme for achieving sub nanosecond stable synchrolock of the two pulse trains such that they are overlapped in time at the gas jet target every third ALS pulse. We present a definitive 2 color signal observed in Helium excited with 23.74 eV photons from the ALS to the 1s4p 1P state, and then ionized by the laser. We intend to use this scheme to study dissociation dynamics of excited molecules in the presence of a strong laser field.

D1.00143 Strong field studies of F\(^-\)\(_2\) dissociation and photodetachment\(^*\). Ben Berry, Bethany Joehim, T. Severt, Peyman Feizollahi, Kalanka Raju P., K.D. CARNES, B. D. Ersy, I. Ben-Itzhak, J. R. Macdonald Laboratory, Physics Department, Kansas State University, Manhattan, KS 66506 — While molecular anions have long been used as tools to investigate molecular dynamics, very few studies focus on their behavior in a strong field. In this work, we explore the strong field dissociation and photodetachment of F\(^-\)\(_2\) under a variety of laser conditions. The use of a keV beam of F\(^-\)\(_2\) allows us to measure all of the molecular fragments except electrons, and we obtain the full 3D moment of breakup using a coincidence 3D momentum imaging technique. Past measurements of photoelectrons from F\(^-\)\(_2\) resulted in some uncertainty about the photoemission mechanisms due to unknown nuclear dynamics\(^1\). Our measurements of the final nuclear products (both F\(_2\) and F + F) help clarify the underlying physics associated with this previous study. In addition, we identify dissociation pathways and use the measured kinetic energy release (KER) to evaluate the initial rovibrational population of the anion.

D1.00144 The Iron Project & Opacity Project: Photoionization, radiative transitions of iron ions for Opacities and Astrophysical Applications. Lianshui Zhao, Sultana Nahar, Anil Pradhan, Ohio State Univ - Columbus, Werner Eissner, Stuttgart University — We have carried out converged close coupling R-Matrix (CCC-RM) calculations for photoionization of Ne-like Fe XVII and demonstrate orders-of-magnitude enhancements in cross section due to successive core excitations. Convergence criteria are: (i) inclusion of sufficient number of residual ion Fe XVII core states, (ii) high-resolution of myriad autoionizing resonances, and (iii) high-energy cross sections. We discuss verification of the conventional oscillator strength sum-rule in limited energy regions for bound-free plasma opacity. High energy cross sections are also under investigation. In order to obtain solar iron opacity at the boundary of the radiative and convection zones, we have studied the residual ion states that should provide convergence of resonances of other L-shell iron ions, Fe XIV - Fe XX, in the plasma region. Preliminary results from R-matrix calculations of photoionization cross sections will be reported.

D1.00146 Contribution of Autoionization Process on the Double Ionization Fragmentation Channel of Carbon Dioxide Molecule, WAEL ISKANDAR, AVERELL GATTON, BISHWANATH GAIRE, ELIO CHAMPENOIS, KIRK LARSEN, NIRANJAN SHIVARAM, Lawrence Berkeley National Laboratory, TRAVIS SEVERT, Kansas State University, ALI MORADMAND, Auburn University, JOSHUA WILLIAMS, University of Nevada, DANIEL SLAUGHTER, THORSTEN WEBER, Lawrence Berkeley National Laboratory. We have studied the auto-ionization process happened in CO$_2$ molecule using photon energy below and above the double ionization threshold and a COLTRIMS setup. By populating an excited state of CO$_{2}^{++}$, transition may occur at the crossing point with CO$_{2}^{+}$ leading to dissociation into CO$^+$ + O$^+$. By measuring in coincidence the kinetic energy release of the two ionic fragments and the energy of the two electrons detected, we are able to determine the internuclear distance at which the transition point between the intermediate state CO$_2^{-+}$ and the final state CO$_2^{++}$ occurs. Preliminary results show very large internuclear distance at the transition point and that this latter auto-ionization may occur at one order of magnitude larger than the (CO-O) equilibrium distance.

D1.00147 Multiphoton dissociation of Coronene, CARMEN CISNEROS, FRANCISCO BETANCOURT, Instituto de Ciencias Fisicas, UNAM, Mexico, JUAN CARLOS POVEDA, UIS, Colombia, IGNACIO ALVAREZ, ALFONSO GUERRERO, Instituto de Ciencias Fisicas, UNAM, Mexico. The multiphotonization and multiphotodissociation of Coronene (C$_{24}$H$_{12}$) induced by laser interaction were analyzed with a Time of Flight Mass Spectrometer in reflection mode. A beam of molecules was synchronized with laser radiation of 266nm with intensities between 1.7 $\times$ 10$^9$ and 2.7 $\times$ 10$^{10}$ W/cm$^2$. The resolution reached allowed to identify more than 300 ions, produced by the photofragmentation. The analysis of relative currents, by ion groups and by specific ions, allowed the experimental verification of dissociation routes where prevail products C$_n$H$_m$ with $n$ = 16–24 for low intensities, and $n$ = 1.2,3,4 for high intensities. At low intensities, the presence of C$_{16}$H$_{10}$, C$_{16}$H$_{12}$, C$_{17}$H$_6$, C$_{17}$H$_{8}$, C$_{22}$H$_2$, C$_{23}$H$_4$, C$_{23}$H$_8$, C$_{24}$H$_6$, C$_{24}$H$_8$, C$_{24}$H$_{10}$, C$_{24}$H$_{12}$ ions are remarkable. In addition, ions with mass greater than 300 accounts for the presence of Coronene clusters. The present work was supported by grant PAPIIT UNAM grants IN101215 and IN102516.

D1.00148 ATOM-ATOM AND ATOM-MOLECULE COLLISIONS

D1.00149 Controlling the interactions of very-high-$n$ strontium Rydberg atoms, R.G. FIELDS, F.B. DUNNING, Department of Physics and Astronomy and the Rice Quantum Institute, Rice University, Houston, Texas 77005-1892, USA, S. YOSHIDA, J. BURGDORFER, Institute for Theoretical Physics, Vienna University of Technology, A-1040 Vienna, Austria, European Universities. Rydberg states have demonstrated to be high $n$ limit of 300 strontium states can be manipulated with remarkable precision using one, or more, short half-cycle pulsed electric fields (HCPs). In the present work many body dynamics of interacting Rydberg systems is exploited to create an initial train of approximately equispaced high $n$ Rydberg atoms in an atomic beam. Their mutual interactions are then increased using HCPs to excite them to states of much higher $n$, the degree of coupling being tuned by varying the final target state. Interest centers on energy exchange and ionization, and their dependence on the degree of interaction. The effects of interactions are monitored through changes in the atomic field ionization spectra and through the loss of Rydberg atoms from the beam. Understanding the details of Rydberg-Rydberg interactions promises to allow creation of long-lived Rydberg atom ensembles where, due to their correlated motions, the excited electrons remain far apart.

$^1$Research supported by the NSF and Robert A. Welch Foundation

D1.00150 Patterned Complexity in Atomic Scattering, PAUL JULIENNE, BRANDON RUZIC, JQI, Univ of Maryland-College Park, and NIST, JOHN BOHN, JILA, Univ of Colorado-Boulder, and NIST. As the constituents of cold gaseous matter continue to grow in complexity, the necessity to understand their basic collision processes remains. Exotic atomic species like erbium and dysprosium have been cooled to ultracold temperatures, revealing a dense forest of chaotically distributed resonances, a much more complicated landscape than the broad, isolated resonances seen in alkali-atoms systems. Nevertheless, broad resonances emerge from the chaos. These resonances correspond to special long-range eigenstates of the mixed dipolar plus van der Waals potential, which seem to occur in a predictable pattern. In this study, we describe a simple and powerful quantum defect theory for atomic scattering, how this theory can simply describe chaotic collisions, and how this theory helps illuminate the character of these special eigenstates.

$^1$We acknowledge support from the National Institute of Standards and Technology.

D1.00151 Rate constants for the formation of SiO by radiative association, MARK CAIRNIE, ROBERT FORREY, Penn State University at Berks, JAMES BABB, ITAMP, Harvard-Smithsonian Center for Astrophysics, PHILLIP STANCIL, University of Georgia, BRENDAN MCLAUGHLIN, Queen’s University Belfast. High quality molecular data for the low-lying states of SiO are computed and used to calculate rate constants for radiative association of Si and O. Einstein A-coefficients are also calculated for transitions between all of the bound and quasibound levels for each molecular state. The radiative widths are used together with elastic tunneling widths to define effective radiative association rate constants which include both direct and indirect (inverse predissociation) formation processes. The indirect process is evaluated for two kinetic models which represent limiting cases for astrophysical environments. The first case assumes an equilibrium distribution of quasibound states and would be applicable whenever collisional and/or radiative excitation mechanisms are able to maintain the population. The second case assumes that no excitation mechanisms are available which corresponds to the limit of zero radiation temperature and zero atomic density. Rate constants for SiO formation in realistic astrophysical environments would presumably lie between these two limiting cases.

$^1$NSF Grant No. PHY-1503615

D1.00152 Full-dimensional Quantum Calculations of Ryovibrational Transitions in CS induced by H$_2$, BENHUI YANG, University of Georgia, PENG ZHANG, Duke University, PHILLIP STANCIL, University of Georgia, J. BOWMAN, Emory University, N. BALAKRISHNAN, University of Nevada, R. FORREY, Penn State University. Carbon monosulfide (CS), the sulfur analogue of carbon monoxide, has been widely observed in a variety of interstellar regions. An accurate prediction of its abundance requires collisional rate coefficients with ambient gases. However, the collisional rate coefficients are largely unknown and primarily rely on theoretical scattering calculations. In interstellar clouds, the dominant collision partner is H$_2$. Rate coefficient data on CS-H$_2$ collisions are limited to pure rotational transitions and no data exist for rovibrational transitions. In this work we evaluate the first full-dimensional potential energy surface for the CS-H$_2$ system using high-level electronic structure theory and perform explicit quantum close-coupling calculations of rovibrational transitions in CS induced by H$_2$ collisions. Cross sections and rate coefficients for rotational transitions are compared with previous theoretical results obtained within a rigid-rotor model. For rovibrational transitions, state-to-state rate coefficients are evaluated for several low-lying rotational levels in the first excited vibrational level of CS. Results are presented for both para-H$_2$ and ortho-H$_2$ collision partners.

$^1$Work at UGA and Emory are supported by NASA grant No. NNX16AF09G, at UNLV by NSF Grant No. PHY-1505557, and at Penn State by NSF Grant No. PHY-1503615.
D1.00153 Electric field controlled collisions between polar molecules and Rydberg atoms, MARTIN ZEPPENFELD, FERDINAND JARISCH, MPI of Quantum Optics — Controlling collisions and chemical reactions via external electric or magnetic fields provides unprecedented control over such processes, with applications including Feshbach association of ultracold molecules from ultracold atoms. We present electric field controlled collisions between polar molecules and Rydberg atoms. State changing collisions between polar molecules and Rydberg atoms are mediated by Förster resonant energy transfer. Changing the resonance condition via electric fields allows the collision cross section to be varied. Our work is a first step towards quantum control of hybrid molecule-Rydberg-atom systems, with possible applications including efficient nondestructive detection of polar molecules[1]. [1] M. Zeppenfeld, arXiv:1611.08893 [physics.atom-ph] (2016).

D1.00154 Quantum chaos analysis of energy and resonant spectra of ultracold molecules, LUCIE AUGUSTOVICOVA, JOHN BOHN, JILA, University of Colorado - Boulder — Quantum chaos that appears in ultracold collisions of highly magnetic lanthanide atoms is investigated using both microscopic models of dysprosium atoms and a schematic model. Our model of dysprosium spectra includes an anisotropic interaction potential that scrambles Zeeman levels, and whose presence reveals degrees of chaos even for partial interaction strength. We perform statistical analyses of the energy spectrum at B=0 as well as the spectrum of magnetic field Fano-Feshbach resonances at E=0. We find that chaos is preserved in the mapping from energy spectra to magnetic field spectra within fit uncertainty. The relation between these two spectra is semiquantitatively studied within a model based on a spin Hamiltonian, mixed by potential matrices drawn at random from a Gaussian orthogonal ensemble. This work was supported by an AFOSR MURI grant.

D1.00155 Three-atom recombination through a narrow Feshbach resonance in $^6$Li, JIAMING LI, LEONARDO DE MELO, LE LUO, Indiana University Purdue University Indianapolis, BO GAO, University of Toledo — We experimentally measure, and theoretically analyze the three-recombination rate, $L_3$, around a narrow $\omega$ wave magnetic Feshbach resonance of $^6$Li-$^6$Li around 543.3 Gauss. By examining both the magnetic field dependence and especially the temperature dependence of $L_3$ over a wide range of a few $\mu$K to 200 $\mu$K, we show that three-atom recombination through a narrow resonance follows a universal behavior as determined by the long-range van der Waals potential, and can be described by a set of rate equations in which three-body recombination proceeds via successive pairwise interactions. We expect the underlying physical picture to be applicable not only to the narrow $\omega$ wave resonances, but also to resonances in other partial waves, and not only at ultracold temperatures, but also at higher temperatures. It points to some future directions towards a more complete understanding of three-body physics in general and molecule formation in particular.

D1.00156 ATOMIC, MOLECULAR AND CHARGED PARTICLE COLLISIONS —

D1.00157 Separating sequential from concerted three-body fragmentation of molecules1, T. SEVERT, JYOTI RAJPUT, BEN BERRY, BETHANY JOCHIM, PEYMAN FEIZOLLA, KANAKA RAJU P., M. ZOHRAKI, U. ABLIKIM, TARZANEH ZAIEE, BALRAM KADERIYA, D. ROLLES, A. RUDENKO, K. D. CARNES, B. D. ESRY, L. BEN-ITZHAK, J.R. McDonald Laboratory, Physics Department, Kansas State University, Manhattan, KS 66506, USA — The ability to disentangle successive pairwise interactions. We expect the underlying physical picture to be applicable not only to the narrow $\omega$ wave resonances, but also to resonances in other partial waves, and not only at ultracold temperatures, but also at higher temperatures. It points to some future directions towards a more complete understanding of three-body physics in general and molecule formation in particular.

1Supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office for Science, U.S. Department of Energy.

D1.00158 The generalized Onsager model and DSMC simulations of high-speed rotating flows with product and waste baffles, DR. SAHADEV PRADHAN, Department of Chemical Engineering, Indian Institute of Science, Bangalore- 560 012, India — The generalized Onsager model for the radial boundary layer and of the generalized Carrier-Maslen model for the axial boundary layer in a high-speed rotating cylinder ((S. Pradhan & V. Kumaran, J. Fluid Mech., 2011, vol. 686, pp. 109-159); (V. Kumaran & S. Pradhan, J. Fluid Mech., 2014, vol. 753, pp. 307-359)), are extended to a multiply connected domain, created by the product and waste baffles. For a single component gas, the analytical solutions are obtained for the sixth-order generalized Onsager equations for the master potential, and for the fourth-order generalized Carrier-Maslen equation for the velocity potential. In both cases, the equations are linearized in the perturbation to the base flow, which is a solid-body rotation. An explicit expression for the baffle stream function is obtained using the boundary layer solutions. These solutions are compared with direct simulation Monte Carlo (DSMC) simulations and found excellent agreement between the analysis and simulations, to within 15%, provided the wall-slip in both the flow velocity and temperature are incorporated in the analytical solutions.

D1.00159 Electron-interacting WIMPs: Can dark matter scattering on electrons explain the DAMA modulation signal?, BENJAMIN ROBERTS, Univ of Nevada - Reno, VLADIMIR DZUBA, VICTOR FLAMBAUM, UNSW Australia, GLEB GRIBAKIN, Queens University, Belfast, MAXIM POSPELOV, University of Victoria, BC, YEVGENY STANDIK, UNSW Australia — Atoms can become ionised during the scattering of a slow, heavy particle off a bound electron. Such an interaction involving leptophilic WIMP dark matter is a potential explanation for the anomalou...
D1.00160 A simple method to obtain very accurate whole atom Compton profiles from photon scattering doubly differential cross sections in relativistic regimes  

LARRY LAJOHN, University of Pittsburgh — Compton profiles (CP) are used in many ways such as for assessing the bonding properties of molecules and solids including semiconductors. The simplest approach to obtain a CP from doubly differential cross sections (DDCS) is to use the nonrelativistic (nr) impulse approximation (IA) expression DDCS=KJ where K is the kinematic factor and J is the CP. A relativistic version of this expression is referred to as RKJ, an approximation to the full relativistic IA expression is used for relativistic regimes, but it does not give accurate results for the inner and middle shells of moderate to heavy atoms. For example the RKJ error ranges from 3% (Z=30) to about 28% (Z=92) for the K-shell and about 3% (Z=50) to 17% (Z=92) for the 2p shell and is at 0% for 3d (Z=92). In the present work, expressions from nonrelativistic hydrogen-like wavefunctions (with a relativistic QED K) to correct RKJ beyond the K-shell to L and M shells were derived such that relativistic contributions as well as the momentum distribution range of any subshell CP.

D1.00161 Theoretical study of the D− + H2 → H− + HD reaction at low energies  

HONG YUEN, University of Central Florida, MÉHDI AYOUZ, LGPM, CentraleSupelec, Universit´e Paris-Saclay, VIATCHESSLAV KOKOOULINE, University of Central Florida — The rearrangement reaction D− + H2 → H− + HD has been studied in a recent experimental work at low temperatures (10,19,and 23K) [1]. An upper limit of about 10−15 cm3/s for the rate coefficient is obtained. A fully-quantum reactive scattering calculation of the rate coefficient is performed using the hyperspherical coordinates and the potential energy surface in Ref. [2]. Eigenchannel R-matrix approach with modified slow variable discretization [3] is used to represent continuum wave functions of the system to obtain the scattering matrix describing the scattering from the initial rovibrational channel of the H2+D− into possible channels of H− + HD. At low collision energies between H2 in the ground state and D−, only three rotational channels of HD(v,j) + H− are open for the reaction with v = 0 and j = 0, 1, 2. Formulas for the cross section and rate coefficient for reactive scattering in hyperspherical coordinates are derived. Preliminary results for the rate coefficient of the D− + H2 → H− + HD reaction is obtained. [1] Endres et al, in press, PRA (2017) [2] Ayouz et al, JCP 132, 19 (2010) [3] Yuen and Kokouline, EPJD, 71,19 (2017)

D1.00162 Theoretical Studies of Dissociative Recombination of Electrons with SH+ Ions  

D. O. KASHINSKI, O. E. DI NALLO, United States Military Academy, A. P. HICKMAN, Lehigh University, J. ZS. MEZEL, F. COLBOC, I. F. SCHNEIDER, Université du Havre, K. CHAKRABARTI, University of Kolkata, D. TALBI, Université Montpellier — We are investigating the dissociative recombination (DR) of electrons with the molecular ion SH+, i.e. e− + SH+ → S + H. SH+ is found in the interstellar medium (ISM), and little is known concerning its chemistry. Understanding the role of DR of electrons with SH+ will lead to more accurate astrophysical models. Large active-space multi-reference configuration interaction (MRCI) electronic structure calculations were performed using the GAMESS code to obtain ground and excited 2Π state potential energy curves (PECs) for several values of SH separation. Core-excited Rydberg states have proven to be of huge importance. The block diagonalization method was used to disentangle interacting states and form a diabatic representation of the PECs. Currently we are performing dynamics calculations using Multichannel Quantum Defect Theory (MQDT) to obtain DR rates. The status of the work will be presented at the conference.

D1.00163 Nonperturbative distorted-wave approach for asymptotic solutions of coupled-channel scattering problems  

D. SHU, I. SIMBOTIN, R. CÔTÉ, University of Connecticut — We developed and implemented a numerical method using distorted waves for coupled-channel scattering problems. Solutions of the full problem are expressed as F = A(r)f + B(r)g, where f and g are solutions of the single-channel problem including the full diagonal potential. The uncorrected distorted-waves f and g are obtained using our newly developed scheme for Milne's phase-amplitude method. The differential equations for A(r) and B(r) are recast in the new variable x = 1/r, and are solved using a spectral integration method based on Chebyshev polynomials. Our approach takes advantage of the fact that Milne’s phase and amplitude, as well as A(r) and B(r), are slowly varying functions. Moreover, the simple change of variable x = 1/r allows one to take fully into account the infinite tail of the potentials in a very efficient way.

D1.00164 X-ray emission measurements following charge exchange between O8+ and Kr+  

R. T. ZHANG, C. C. HAVENER, Physics Div., Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, D. G. SEELY, Dep. of Physics, Albion College, Albion, Michigan 49224, V. M. ANDRIANARIJAONA, Dep. of Physics, Pacific Union College, Angwin, California 94508, M. FOGLE, Dep. of Physics, Auburn University, Auburn, Alabama 36849, P. C. STANCIL, Dep. of Physics and Astronomy, University of Georgia, Athens, Georgia 30602-2451, D. WULF, D. MCCAMMON, Dep. of Physics, University of Wisconsin, Madison, Wisconsin 53706 — Lyman spectra and line-ratios for soft X-ray following charge exchange between O8+ and Kr were measured using a beam-gas technique and a high resolution microcalorimeter X-ray detector for the collision velocities from 293 km/s to 1256 km/s. Ly-α, Ly-β, Ly-γ, Ly-δ, Ly-ε lines of O7+ ion were identified, as well as minor transition lines from O6+. Our observed line ratios are compared to a single charge exchange model, specifically with theoretical calculations for O8+ - H. Good agreement is found for the line ratio from the dominant n = 5 capture states, with direct capture and cascade having an influence on the line ratio for the n = 4 states. Moreover, for velocities lower than 600 km/s, X-ray emission following autoionizing double capture results in Ly-α and Ly-β enhancement, the former leads to the Ly-ε/Ly-α line ratios significantly smaller than theoretical calculations, the latter leads to the Ly-δ/Ly-α line ratios larger than theory. The apparatus is being modified to perform measurements with H using a merged-beam technique.

1Supported by the National Science Foundation, Grant No PHY-15-06391

2travel supported by DoD-HPCMP

1This work is partially funded by the MURI US Army Research Office Grant No. W911NF-14-1-0378.

NASA Grant No. NNX13ZDA001N and NNX13AF31G
D1.00165 Stable thermophoretic trapping of generic particles at low pressures1

LONG FUNG FRANKIE FUNG2, Univ of Chicago — We demonstrate levitation and three-dimensionally stable trapping of a wide variety of particles in medium vacuum through thermophoresis. Typical sizes of the trapped particles are between 10 µm and 1 mm; air pressure is between 1 and 10 Torr. We describe the experimental setup to produce the temperature gradient, as well as our procedure for introducing particles into the experimental setup. To determine the levitation force and test various theoretical models, we examine the levitation heights of spherical polyethylene spheres under various conditions. A good agreement with two theoretical models is concluded. Our system offers a platform to discover various thermophoretic phenomena and to simulate dynamics of interacting many-body systems in a microgravity environment.

1NSF MRSEC Grant No. DMR-1420709
2Full author list: Frankie Fung, Mykhaylo Usatyuk, Benjamin Foster, B. J. DeSalvo, and Cheng Chin

D1.00166 Control and analysis of atomic breakup dynamics, NISHSHANKA ARUMA HANDI DESILVA, SACHIN SHARMA, DANIEL FISCHER, Missouri University of Science & Technology — Understanding the dynamics of coupled few-body systems is one of the most fundamental and challenging tasks in physics. The theoretical obstacle is solving the equations of motion, which is analytically not possible for more than two-bodies. Therefore, the advancement of our knowledge on few- and many-body phenomena relies on the comparison of theoretical predictions with detailed experimental observations. The experimental study of few-body dynamics requires, first, the control of the system in a well-characterized initial state and second, the analysis of the evolution of the system after an external interaction. In this poster, we report on an experiment, where laser cooling and manipulation techniques are employed for controlling atomic few-body system (Lithium atoms) by exciting, trapping, and cooling the atoms even to degeneracy. For the analysis, a ‘reaction microscope’ is used to coincidently measure the momenta of atomic fragments after ionization. This is achieved in a MOTReMI, the unique implementation of a magneto-optical trap in a reaction microscope. There are fundamental and diverse questions, to be answered in the planned experiments, among them: How ionization dynamics and timing depend on electronic correlation and relative helicity of field and atom? How does the environment of the atoms influence their ionization? How to image the correlated wave function of atomic samples in dependence on the particle number, interaction type and strength?

Tuesday, June 6, 2017 5:30PM - 7:00PM –
Session D2 DAMOP Diversity Reception 304-305 -
5:30PM D2.00001 DAMOP Diversity Reception –

Tuesday, June 6, 2017 6:00PM - 8:00PM –
Session E10 Industry Careers in AMO Physics: An Interactive Panel Discussion 308 -
6:00PM E10.00001 Industry Careers in AMO Physics: An Interactive Panel Discussion, CRYSTAL BAILEY, American Physical Society — Representatives from industry will provide information about physics careers for people with AMO backgrounds in private sector environments. Topics will include research opportunities for physicists in industry, strategies for successfully pursuing industrial jobs, and advice on how to thrive in these exciting and challenging work environments. Light refreshments will be served.

Tuesday, June 6, 2017 8:00PM - 9:00PM –
Session F1 TAMOC Business Meeting 309 -
8:00PM F1.00001 TAMOC Business Meeting –

Wednesday, June 7, 2017 8:00AM - 10:00AM –
Session G2 Systems with Long-range Interactions 306-307 - Dominik Schneble, Stony Brook University
8:00AM G2.00001 Contaminant-State Broadening Mechanism in a Driven Dissipative Rydberg System1, J. V. PORTO, Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, Gaithersburg, Maryland 20899, USA — The strong interactions in Rydberg atoms make them an ideal system for the study of correlated many-body physics, both in the presence and absence of dissipation. Using such highly excited atomic states requires addressing challenges posed by the dense spectrum of Rydberg levels, the detrimental effects of spontaneous emission, and strong interactions. A full understanding of the scope and limitations of many Rydberg-based proposals requires simultaneously including these effects, which typically cannot be described by a mean-field treatment due to correlations in the quantum coherent and dissipative processes. We study a driven, dissipative system of Rydberg atoms in a 3D optical lattice, and observe substantial deviation from single-particle excitation rates, both on and off resonance. The observed broadened spectra cannot be explained by van der Waals interactions or a mean-field treatment of the system. Based on the magnitude of the broadening and the scaling with density and two-photon Rabi frequency, we attribute these effects to unavoidable blackbody-induced transitions to nearby Rydberg states of opposite parity, which have large, resonant dipole-dipole interactions with the state of interest. Even at low densities of Rydberg atoms, uncontrolled production of atoms in other states significantly modifies the energy levels of the remaining atoms. These off-diagonal exchange interactions result in complex many-body states of the system and have implications for off-resonant Rydberg dressing proposals.

1This work was partially supported by the ARL-CDQI program.
and study self-bound droplets which can interfere with each other. These droplets are 100 million times less dense than liquid helium droplets and do not collapse. We find that this unexpected stability is due to beyond mean-field quantum corrections of the Lee-Huang-Yang type. We observe we could recently observe the formation of a droplet crystal. In contrast to theoretical mean field based predictions the superfluid droplets did in classical magnetic ferrofluids self-organized structure formation was expected. In our experiments with quantum gases of Dysprosium atoms possible to study degenerate gases of lanthanide atoms among which one finds the most magnetic atoms. Similar to the Rosensweig instability dipolar effects in a quantum gas were observed in an ultracold Chromium gas. By the use of a Feshbach resonance a purely dipolar quantum gas from the usual van der Waals forces in real gases. Besides the anisotropy the dipolar interaction is nonlocal and as such allows for self organized structure formation. Candidates for dipolar species are polar molecules, Rydberg atoms and magnetic atoms. More than ten years ago the first dipolar effects in a quantum gas were observed in an ultracold Chromium gas. By the use of a Feshbach resonance a purely dipolar quantum gas was observed three years after. By now dipolar interaction effects have been observed in lattices and also for polar molecules. Recently it become possible to study degenerate gases of lanthanide atoms among which one finds the most magnetic atoms. Similar to the Rosensweig instability in classical magnetic ferrofluids self-organized structure formation was expected. In our experiments with quantum gases of Dysprosium atoms we could recently observe the formation of a droplet crystal. In contrast to theoretical mean field based predictions the superfluid droplets did not collapse. We find that this unexpected stability is due to beyond meanfield quantum corrections of the Lee-Huang-Yang type. We observe and study self-bound droplets which can interfere with each other. These droplets are 100 million times less dense than liquid helium droplets and open new perspectives as a truly isolated quantum system.

Wednesday, June 7, 2017 8:00AM - 10:12AM
Session G3 Improve Training of Undergraduates in Experimental Physics 308 - Heather Lewandowski, University of Colorado/JILA

8:00AM G3.00001 Investigating student learning in upper-division laboratory courses on analog electronics , MACKENZIE STETZER, University of Maine — There are many important learning goals associated with upper-division laboratory instruction; however, until recently, relatively little work has focused on assessing the impact of these laboratory-based courses on students. As part of an ongoing, in-depth investigation of student learning in upper-division laboratory courses on analog electronics, we have been examining the extent to which students enrolled in these courses develop a robust and functional understanding of both canonical electronics topics (e.g., diode, transistor, and op-amp circuits) and foundational circuits concepts (e.g., Kirchhoffs laws and voltage division). This focus on conceptual understanding is motivated in part by a large body of research revealing significant student difficulties with simple dc circuits at the introductory level and by expectations that students finish electronics courses with a level of understanding suitable for building circuits for a variety of practical, real-world applications. We have also recently extended the scope of our investigation to include more laboratory-focused learning goals such as the development of (1) troubleshooting proficiency and (2) circuit chunking and design abilities. This talk will highlight findings from written questions and interview tasks that have been designed to probe student understanding in sufficient depth to identify conceptual and reasoning difficulties. Specific examples will be used to illustrate the ways in which this research may inform instruction in upper-division laboratory courses on analog electronics.

1This material is based upon work supported by the National Science Foundation under Grant Nos. DUE-1323426, DUE-1022449, DUE-0962805, and DUE-0618185.


1FUNDING: NSF (PHY-1506093), NNSF of China (61475123)

9:00AM G2.00003 Dipolar quantum gases and liquids , TILMAN PFAU, S. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universitaet Stuttgart, Germany — Dipolar interactions are fundamentally different from the usual van der Waals forces in real gases. Besides the anisotropy the dipolar interaction is nonlocal and as such allows for self organized structure formation. Candidates for dipolar species are polar molecules, Rydberg atoms and magnetic atoms. More than ten years ago the first dipolar effects in a quantum gas were observed in an ultracold Chromium gas. By the use of a Feshbach resonance a purely dipolar quantum gas was observed three years after. By now dipolar interaction effects have been observed in lattices and also for polar molecules. Recently it become possible to study degenerate gases of lanthanide atoms among which one finds the most magnetic atoms. Similar to the Rosensweig instability in classical magnetic ferrofluids self-organized structure formation was expected. In our experiments with quantum gases of Dysprosium atoms we could recently observe the formation of a droplet crystal. In contrast to theoretical mean field based predictions the superfluid droplets did not collapse. We find that this unexpected stability is due to beyond meanfield quantum corrections of the Lee-Huang-Yang type. We observe and study self-bound droplets which can interfere with each other. These droplets are 100 million times less dense than liquid helium droplets and open new perspectives as a truly isolated quantum system.
9:00AM G3.00003 Re-thinking intro physics labs: Teaching and assessing critical thinking , NATASHA HOLMES, Cornell University — Taking a scientific approach to understanding and improving how we teach physics starts with figuring out what it is we are trying to measure and, therefore, what we are trying to teach. The goals of instructional lab courses have been highly debated for decades with not much research to back up either side. In this talk, I will describe new research into the efficacy of lab courses with different aims: from teaching conceptual physics to fostering critical thinking. I will demonstrate how new pedagogies are taking advantage of the unique affordances of labs to teach experimentation skills and critical thinking about data and models, without sacrificing learning traditional physics content.

9:30AM G3.00004 Students' views about the nature of experimental physics1 , BETHANY WILCOX, Colorado School of Mines — The physics community explores and explains the physical world through a blend of theoretical and experimental studies. The future of physics as a discipline depends on training of students in both the theoretical and experimental aspects of the field. However, while student learning within lecture courses has been the subject of extensive research, lab courses remain relatively under-studied. In particular, there is little, if any, data available that addresses the effectiveness of physics lab courses at encouraging students to recognize the nature and importance of experimental physics within the discipline as a whole. To address this gap, we present the first large-scale, national study (N institutions = 71 and N students = 7167) of undergraduate physics lab courses through analysis of students' responses to a research-validated instrument designed to investigate students' beliefs about the nature of experimental physics. We find that students often enter and leave physics lab courses with ideas about experimental physics that are inconsistent with the views of practicing experimental physicists, and this trend holds at both the introductory and upper-division levels. Despite this inconsistency, we find that both introductory and upper-division students are able to accurately predict the expert-like response even in cases where their personal views disagree. These findings have implications for the recruitment, retention, and adequate preparation of students in physics.

1This work was funded by the NSF-IUSE Grant No. DUE-1432204 and NSF Grant No. PHY-1125844.

10:00AM G3.00005 Phys21:Preparing Physics Students for 21st Century Careers . ELIZABETH MCCORMACK, Bryn Mawr College — The Phys21: Preparing Physics Students for 21st Century Careers report was commissioned by the APS and the AAPT and prepared by the Joint Task Force on Undergraduate Physics Programs (J-TUPP). It addresses the question: What skills and knowledge should the next generation of undergraduate physics majors possess to be well prepared for a diverse set of careers? J-TUPP members were particularly interested to understand better the needs of students who do not plan to pursue academic research careers. The major findings of the report and a summary of the guidelines that were developed for revising the undergraduate curriculum, addressing the needs of an increasingly diverse population of students, providing professional skills development, and enhancing student engagement through high impact teaching practices will be presented.

Wednesday, June 7, 2017 8:00AM - 10:00AM – Session G4 Spectroscopy, Lifetimes, and Oscillator Strengths 309 - Peter Beiersdorfer, LLNL

8:00AM G4.00001 Hyperfine quenching of the 2s2p53s 3P0 state of Ne-like ions1 , U. I. SAFRONOVA, A. STAFFORD, A. S. SAFRONOVA, University of Nevada, Reno — The many-body perturbation theory (RMBPT) is used to calculate energies and multipole matrix elements to evaluate hyperfine quenching of the 2s2p53s 3P0 state in Ne-like ions. In particular, the 3P0 excited state decays to the 1S0 ground state by M2 emission, while both 1P1 and 1P0 states decay to the ground-state by E1 emission, which is substantially faster. For odd-A nuclei, the hyperfine interaction induces admixtures of 1P1 and 1P0 into the 3P0 state, resulting in an increase of the 3P0 transition rate and a corresponding reduction of the 3P0 lifetime. We consider 22 Ne-like ions with Z = 14 - 94 and nuclear moment I = 1/2. We found that the largest hyperfine quenching contribution by a factor of 2 are for Ne-like 53P and 53D1. The smallest (less than 1%) induced contribution are the following Ne-like ions: 25Fe, 107Ag, 109Ag, 105W, and 187Os ions. For another 15 Ne-like ions the hyperfine quenching contribution is between 15% and 35%. Applications to x-ray line polarization of Ne-like lines is considered.

1This work is supported by the Department of Energy, National Nuclear Security Administration, under Award Number DE-NA0002954.

8:12AM G4.00002 Kr X-ray spectroscopy to diagnose Inertial Confinement Fusion implosions on the National Ignition Facility , ARATI DASGUPTA, NICHLAS QUART, JOHN GIULIANI, Naval Research Laboratory, ROBERT CLARK, Berkeley Research Associates, MARILYN SCHNEIDER, HOWARD SCOTT, Lawrence Livermore National Laboratory — X ray spectroscopy is used on the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) to diagnose the plasma conditions in the ignition target in indirect drive Inertial Confinement Fusion (ICF) implosions [1]. A platform is being developed at NIF where small traces of krypton are used as a dopant to the fuel gas for spectroscopic diagnostics using krypton line emissions. Simulations of the krypton spectra using a small atomic fraction of krypton in direct-drive exploding pusher with a range of electron temperatures and densities show discrepancies when different atomic models are used. We use our non-local thermodynamic equilibrium (non-LTE) atomic model with a detailed fine-structure level atomic structure and collisional-radiative rates to investigate the krypton spectra at the same conditions and generate synthetic spectra with a detailed frequency-by-frequency radiation transport scheme from the emission regions of interest to analyze the experimental data and compare and contrast with the existing simulations at LLNL. [1] T. Ma, et al., RSI 87 (2016). Work supported by DOE/NNSA; Part of this work was also done under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No DE-AC52-07NA27344.

8:24AM G4.00003 Dielectronic Satellite Lines of L-shell Mo at LLNL EBIT1 , A. STAFFORD, A.S. SAFRONOVA, V.L. KANTSAREV, U.I. SAFRONOVA, E.E. PETKOV, V.V. SHLYAPTEVA, University of Nevada, Reno, P. BEIERSDORFER, N. HELL, G.V. BROWN, Lawrence Livermore National Laboratory — Dielectronic recombination, an important atomic process for astrophysical and laboratory plasma, has been studied in detail for low-Z and recently for W ions. However, there are still many details missing for other materials including molybdenum (Mo). New calculations were done for Ne-like Mo dielectronic recombination transitions using the COWAN code, HULLAC, and the relativistic many-body perturbation theory method. The EBIT-I electron beam ion trap at Lawrence Livermore National Laboratory (LLNL) was used to benchmark the new calculations. EBIT-I was operated to create Ne-like Mo using a ~3 keV energy beam and then using broad energy beams (0.6 – 1.2 keV) to account for dielectronic recombination. The new theoretical calculations were compared to Na-like Mo satellite spectra collected from LLNL EBIT-I experiments with consideration to polarization sensitivities.

1This work was supported by NNSA under DOE grant DE-NA0002954. Work at LLNL was performed under the auspices of the U.S. DOE under Contract No. DE-AC52-07NA27344.
Here, we will report on our ongoing efforts of a search using a pulsed VUV laser system as light source, which allows us to enhance our sensitivity over the ALS and extend the accessible frequency range over the entire ROF [3]. An updated exclusion region will be presented.

1Supported by CAS and NSF.

9:00AM G4.00006 Measurement of hyperfine structure and isotope shifts in the 8p excited states of thallium and the 7p excited states of indium using two-step laser spectroscopy1. P. MILINDA RUPASINGHE, SAUMAN CHENG, NATHANIEL VILAS, ELI HOENIG, BINGYI WANG, P.K. MA-JÜMDER, Williams College — Using a two-color, two-step vapor cell spectroscopy technique we have completed measurements of hyperfine splittings of 8p states in 205Tl and 203Tl, as well as the 7s—8p transition isotope shifts. The same experimental scheme has been used to measure the hyperfine splitting of the 315In 7p1/2 state and the hyperfine a, b, c constants within the 7p1/2 state. An external-cavity diode laser locked to the 1st step transition excites atoms to an intermediate state and a second, red laser diode overlaps the first within a heated atomic vapor cell in both a co-propagating and counter-propagating configuration. Analysis of subsequent Doppler-free absorption spectra of the second-step transitions (7s1/2 → 8p1/2,3,3/2 in thallium and 6s1/2 → 7p1/2,3,3/2 in indium) allows us to extract both hyperfine and isotope shift information with uncertainties well below 1 MHz. Frequency modulation of the red laser provides convenient in situ frequency calibration. For the case of thallium 205Tl 8p3/2 state hyperfine splitting, our results disagree with older measurements and show a well-resolved hyperfine anomaly not previously observed for this state.

1Work supported by NSF grant #1404206

9:12AM G4.00007 Direct search for the thorium-229 nuclear isomeric transition with a pulsed VUV laser. JUSTIN JEET, CHRISTIAN SCHNEIDER, University of California, Los Angeles, EUGENE V. TKALYA, Lomonosov Moscow State University and Nuclear Safety Institute of Russian Academy of Science, ERIC R. HUDSON, University of California, Los Angeles — The nucleus of thorium-229 has an exceptionally low-energy isomeric transition in the vacuum-ultraviolet (VUV) spectrum around 7.8 ± 0.5eV [1]. While inaccessible to standard nuclear physics techniques, there are various prospects for a laser-accessible nuclear transition. Our direct search for the transition uses thorium-doped crystals as samples. In a previous experiment [2] at the Advanced Light Source (ALS) synchrotron, LBNL, we were able to exclude a large portion of the transition lifetime-vs.-frequency region-of-interest (ROF) [3]. Here, we will report on our ongoing efforts of a search using a pulsed VUV laser system as light source, which allows us to enhance our sensitivity up to 10^5× over the ALS and extend the accessible frequency range over the entire ROF [3]. An updated exclusion region will be presented.


9:24AM G4.00008 High precision spectroscopy of p-state Rubidium Rydberg molecules. TANITA EICHERT, THOMAS NIEDERPRM, Department of Physics and research center OPTIMAS, University of Kaiserslautern, OLIVER THOMAS, Department of Physics and research center OPTIMAS, University of Kaiserslautern / Graduate School Materials Science in Mainz, CARSTEN LIPPE, HERWIG OTT, Department of Physics and research center OPTIMAS, University of Kaiserslautern — In an ultracold gas the scattering interaction of a ground state atom and the highly excited electron of a Rydberg atom gives rise to an oscillatory potential that supports molecular bound states. We use high resolution time-of-flight spectroscopy over a range of several 10GHz to precisely determine the binding energies and lifetimes of molecular states in the vicinity of the 25P-state. For the so-called butterfly molecules, that originate from a shape resonance in the p-wave electron-atom scattering and strongly mix high angular momentum states, we investigate their rotational structure in an external electric field allowing us to extract the precise bond length and huge dipole moments. By exciting ultralong-range Rydberg molecules we are able to observe a spin-flip of the ground state atom. This induced spin-flip is based on mixed singlet-triplet potentials containing contributions of both hyperfine states of the ground state atom. In addition, we resolve molecular states which feature strong entanglement between the orbital angular momentum of the Rydberg electron and the nuclear spin of the ground state atom due to nearly degenerate spin-orbit splitting of the Rydberg atom and hyperfine splitting in the ground state.

1This work has been supported by the Office of Air Force Scientific Research.
2 of the intensity ratios of astrophysically important 1s → 2p transitions for Ne-like Kr⁶⁺ and Mo⁵²⁺. The experiment was done at the EBIT-I electron beam ion trap at Lawrence Livermore National Laboratory and utilized an x-ray microcalorimeter. The Mo⁵²⁺ experiment is the highest Z-measurement of such type to date, where the dominant role of the interference line, known to increase with Z, puts the measurement firmly into the relativistic regime. Compared to the earlier measurements of ions with lower atomic numbers, the measurement for Mo⁵²⁺ shows much a closer agreement with theory. Our results support the hypothesis that the disagreement should narrow with atomic number. This implies that the disagreement with theory may be confined to the range of atomic numbers where the correlation effects are largest.

This work was performed under the auspices of the U.S. DoE by LLNL, contract DE-AC52-07NA27344, and was supported in part by NASA’s APRA program and by the ESA, contract 400014313/15/NL/CB.

Wednesday, June 7, 2017 8:00AM - 10:00AM –
Session G5 Gravity and Searches for Exotic Forces

8:00AM G5.00001 Testing the universality of free fall with atoms in different quantum states
ZHONG-KUN HU, XIAO-CHUN DUAN, MIN-KANG ZHOU, LU-SHUAI CAO. MOE Key Laboratory of Fundamental Physical Quantities Measurement, School of physics, Huazhong university of science and technology — We present the results of the universality of free fall by comparing the gravity acceleration of the ⁸⁷Rb atoms in mF = -1 versus those in mF = -1, of which the corresponding spin orientations are opposite. A Mach-Zehnder-type atom interferometer is exploited to alternately measure the free fall acceleration of the atoms in these two magnetic sublevels, and the resultant Etwa ratio is 1.0(2.1). This also gives an upper limit of 5.4 10⁻⁹ m/s² for a possible gradient field of the timescale of the atom interferometer. We present the interferometer arm separation, which act as rulers for the atomic position. We measure the differential acceleration of two magnetic species simultaneously to test the weak equivalence principle. Long interferometer times and large momenta transfer techniques are crucial for improving the precision of this fundamental test. [1] T. Kovanchy, P. Asenbaum, C. Overstreet, C. Donnelly, S. Dickerson, A. Sugarbaker, J. M. Hogan and M. A. Kasevich. Quantum superposition at the half-metre scale, Nature 528, 530–533 (2015) [2] P. Asenbaum, C. Overstreet, T. Kovanchy, D.D. Brown, J. M. Hogan and M. A. Kasevich. Phase shift in atom interferometry due to spacetime curvature, arXiv:1610.03832 (2016)

8:12AM G5.00002 Test of the equivalence principle using dual species atom interferometry

8:24AM G5.00003 Testing sub-gravitational forces on atoms from a miniature, in-vacuum source mass
MATTHEW JAFFE, PHILIPP HASLINGER, VICTORIA XU. University of California, Berkeley, PAUL HAMILTON, University of California, Los Angeles, AMOL UPADHYE, University of Wisconsin - Madison, BENJAMIN ELDER, JUSTIN KHOURY, University of Pennsylvania, HOLGER MUELLER, University of California, Berkeley — In this talk, I will discuss our recent measurement of the gravitational attraction between cesium atoms in free fall and a centimeter-sized source mass using atom interferometry. Placing the source mass in vacuum provides sensitivity to a wide class of “fifth force” interactions that would otherwise be suppressed beyond detectability in regions of high matter density. Examples include so-called chameleon and symmetron fields, proposed as dark energy candidates. Our measurement tightens constraints on such theories by over two orders of magnitude.

8:36AM G5.00004 Phase shift in atom interferometry due to spacetime curvature
CHRIS OVERSTREET, PETER ASENBAUM, TIM KOVACHY, DANIEL BROWN, JASON HOGAN, MARK KASEVICH, Stanford University — In previous matter wave interferometers, the interferometer arm separation was small enough that gravitational tidal forces across the arms can be neglected. Gravitationally-induced phase shifts in these experiments arise from the acceleration of the interfering particles with respect to the interferometer beam splitters and mirrors. By increasing the interferometer arm separation, we enter a new regime in which the arms experience locally different gravitational forces. Using a single-source gravity gradiometer, we measure a phase shift associated with the tidal forces induced by a nearby test mass. This is the first observation of spacetime curvature across the spatial extent of a single quantum system.

CO acknowledges funding from the Stanford Graduate Fellowship.

8:48AM G5.00005 Development of a force sensor using atom interferometry to constrain theories on dark matter and dark energy
CHANDLER SCHLUFF, ROBERT NIEDERRITZER, ELIOT BOHR, SAMI KHAMIS, YOUNA PARK, ERIK SZWED, PAUL HAMILTON, Univ of California - Los Angeles — Atom interferometry has been used in many precision measurements such as Newton’s gravitational constant, the fine structure constant, and tests of the equivalence principle. We will perform atom interferometry in an optical lattice to measure the force felt by an atom due to a test mass in search of new forces suggested by dark matter and dark energy theories [1]. We will be developing a new apparatus using laser-cooled ytterbium to continuously measure this force by observing their B2 transitions [2]. Using test masses in an optical lattice allows continuous measurements in a small volume over a long period of time, enabling our device to be sensitive to time-varying forces while minimizing vibrational noise. We present the details of this experiment and the progress on it thus far. [1] P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Muller, and J. Khoury, “Atom-interferometry Constraints on Dark Energy.” Science, 349, 849-851 (2015). [2] B. Prasanna Venkatesh, M. Truppe, E. A. Hinds, and D. H. J. O’Dell, “Atomic Bloch-Zener oscillations for sensitive force measurements in a cavity” Physical Review A, 80, 063834 (2009).
9:00AM G5.00006 $^3\text{He}^{129}\text{Xe}$ co-magnetometer shifts from $^{87}\text{Rb}$ decoupling sequences, MARK LIMES, MICHAEL ROMALIS, Princeton University — We are developing a $^3\text{He}^{129}\text{Xe}$ co-magnetometer for use as an NMR gyro and to search for spin-gravity interactions. Our $^3\text{He}^{129}\text{Xe}$ co-magnetometer has achieved a long-term bias drift of 7.7 nHz at 7 h. For detection of $^3\text{He}^{129}\text{Xe}$ precession, we use a $^{87}\text{Rb}$ magnetometer with fast magnetic field $\pi$ pulses and $\sigma_+\sigma_-$ optical pumping, which results in suppression of spin-exchange relaxation. We use a Ramsey scheme that allows the noble gases to precess freely ‘in-the-dark’. During this free precession we apply additional decoupling pulses to eliminate Rb-Xe back-polarization along all three axes. The presence of the decoupling magnetic fields causes additional frequency shifts which we can eliminate by rotating the decoupling fields. We are presently studying the absolute accuracy of the co-magnetometer by detecting Earth’s rotation. We will describe the procedure to characterize remaining frequency shifts and our progress on mitigating them.

$^1$DARPA and NSF

9:12AM G5.00007 Search for long-range spin-mass forces, JUNYI LEE, ATTAALLAH ALMASI, MICHAEL ROMALIS, Princeton University — We report on the progress in the search for anomalous spin-mass interactions that can be mediated by light particles, for example axion-like particles, which are also potential candidates for dark matter. In this experiment, we measure energy shifts of spin polarized atoms in a $^3\text{He}-\text{K}$ co-magnetometer as the positions of two nearby 200 kg unpolarized source masses are modulated. Bounds on possible anomalous spin-mass interactions can be extracted from correlations in these measurements. The sensitivity of the co-magnetometer should allow us to exceed for the first time the astrophysical limits on spin-dependent forces. Various systematic effects due to the motion and positions of the weights have also been studied and quantified. Supported by NSF PHY-1404325.

9:24AM G5.00008 Synchronous Spin Exchange Comagnetometry, JOSHUA WEBER, DANIEL THRASHER, SUSAN SORENSEN, ANNA KORVER, THAD WALKER, University of Wisconsin - Madison — Comagnetometry is achieved using synchronous spin exchange optical pumping of two Xe isotopes with Rb. Both isotopes are simultaneously polarized transverse to a pulsed bias magnetic field through spin exchange collisions with polarized Rb atoms. The bias field is applied as a sequence of $\pi$ pulses, which allows the magnetometer to operate near spin exchange relaxation free sensitivity. The Rb atoms are optically pumped transverse to the bias field, greatly suppressing the alkali fields contribution to bias instability. The Rb polarization is simultaneously modulated at the nuclear magnetic resonance of each Xe isotope as well as at a third frequency, which enables lock-in detection far from 1/f electronic noise. With this technique we approach photon-shot-noise-limited detection of longitudinal-relaxation-limited Xe linewidths of less than 10 mHz. Furthermore, the bias magnetic field is stabilized to the probe noise detection limit using the magnetic field fluctuations detected by one of the isotopes. With magnetic noise suppressed, the second isotope is used to detect non-magnetic interactions.

$^1$Research supported by the NSF and Northrop-Grumman Corp.

9:36AM G5.00009 Searching for anomalous spin-spin interactions, HIMAWAN WINARTO, JUNYI LEE, MICHAEL ROMALIS, Princeton University — We report our progress and preliminary results of a newly designed experiment to search for anomalous spin-spin interactions using an electron spin source and a nuclear spin co-magnetometer. These interactions can be generated by pseudoscalar axion-like bosons or other light particles beyond the Standard Model. In our experiment, we look for an anomalous correlation between the signal of a Rb-Ne co-magnetometer and the orientation of a SmCo$_5$ magnet with an iron flux return. The spin source generates a net electron spin while cancelling most of the magnetic field, while the co-magnetometer cancels coupling to ordinary magnetic fields. Several layers of magnetic shielding provide additional suppression of ordinary magnetic field interactions. We collect the data as the direction of the spin source is rotated. We will present the data collected to date and discuss the limiting systematic effects.

9:48AM G5.00010 Effect of atomic diffusion on spin noise spectroscopy with a tightly focused beam, VITO GIOVANNI LUCIVERO, NATHANIEL DAVID MCDONOUGH, NEZIH DURAL, MICHAEL ROMALIS, Princeton University, ROMALIS GROUP TEAM — Atomic diffusion can limit the sensitivity of atomic sensors and optical magnetometers. Here we introduce an analytical model for explaining the atomic diffusion component of the spin time-correlation function under different conditions of beam focusing and buffer gas pressure. For a tightly focused probe beam we find that the decay of the diffusion correlation function follows a power law rather than exponential, as it does in the collimated case. Counter-intuitively, this results in a narrowing of the spin-noise linewidth and significant increase in the noise peak amplitude. We are currently performing experimental measurements of the atomic diffusion effects in the spin noise spectra as a function of probe beams focus size down to 2 $\mu$m and as a function of the buffer gas pressure. We will present detailed comparison of theory and experiment and discuss implications of the atomic diffusion on sub-shot noise measurements in atomic sensors.

Wednesday, June 7, 2017 8:00AM - 10:00AM — Session G6 Hybrid Systems 311-312 - Kenton Brown, Georgia Tech Research Institute

leading to the observation of strong coupling phenomena. For our work, the Rydberg transition from 87S^1 to 87P^2 can be achieved with a dilute atomic ensemble and a proper superlattice design according to our calculations. With submicron periodically poled metamaterial surface. We present our theoretical results and initial experiments on the possibilities for achieving strong coupling. Due to of Rochester, 206 Bausch and Lomb Hall, Rochester, NY 14627, USA, JAMES P. SHAFFER, Homer L. Dodge Department of Physics and Astronomy, University of Wisconsin-Madison — A primary candidate for converting quantum information from microwave to optical frequencies is the use of Rydberg states of a single atom trapped near a surface. The fact that the Rydberg states possess both large electric dipole moments and microwave transition frequencies allows them to interact with superconducting mesoscopic circuits. By considering a concrete example, that of a Cesium atom, and using numerical search methods to optimize the control protocols, we determine the fidelities and transmission rates of mediating strong atom-light interactions and open new avenues for quantum transport and quantum many-body phenomena. In particular, coupling atoms to the band edge of a photonic crystal waveguide (PCW) provides a unique platform for generating tunable range coherent atom-atom interactions which are mediated by the guided mode photons. Due to the evanescent nature of the field in the band gap, dissipation into the structure is suppressed exponentially. We have experimentally observed the transition into the bandgap for the first time by shifting the band edge frequency of the PCW relative to the D1 line of atomic cesium with an average of 3 atoms trapped along the PCW [1]. In addition, we have developed a formalism that provides a clear mapping between the transmission spectra and the local Greens function, which allows us to identify signatures of dispersive and dissipative interactions between the atoms [2]. [1] J. D. Hood et al., PNAS 113, 1050710512 (2016). [2] A. Asenjo-Garcia, J. D. Hood, D. E. Chang, H. J. Kimble, arXiv:1606.04977 (2016).

8:24AM G6.00003 Microwave-to-optical frequency conversion with a Rydberg atom coupled to a coplanar waveguide

8:36AM G6.00004 A Rydberg Atom Ensemble-Surface Phonon Polariton Quantum Hybrid System, ANA ASENJO-GARCIA, Caltech, JONATHAN D. HOOD, Harvard, AKIHISA GOBAN, JILA, MINGWU LU, JQI, SU-PENG YU, Homer L. Dodge Department of Physics and Astronomy, The University of Rochester, 206 Bausch and Lomb Hall, Rochester, NY 14627, USA, JAMES P. SHAFFER, Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, 440 W. Brooks St. Norman, OK 73019, USA — We investigate a quantum hybrid system in the strong coupling regime, formed by a Rydberg atom ensemble and a surface phonon polariton (SPhP) propagating on a periodically poled piezoelectric metamaterial surface. We present our theoretical results and initial experiments on the possibilities for achieving strong coupling. Due to the large Rydberg transition dipole moments and the local field enhancement of confined SPhP excitations, the strong coupling regime can be achieved with a dilute atomic ensemble and a proper superlattice design according to our calculations. With submicron periodically poled crystals, even when the atomic ensemble is mms away from the crystal surface, the collective atom-surface coupling can exceed the loss rates, leading to the observation of strong coupling phenomena. For our work, the Rydberg transition from 87S^1/2 to 87P^1/2 in rubidium is chosen to couple to a SPhP mode at ~5 GHz, corresponding to a periodically poled Lithium Niobate (PPLN) surface with a period of ~1 µm. To fabricate the PPLN we use the direct e-beam write poling method.

8:48AM G6.00005 Photonic band gap induced in an atomic ensemble confined inside a hollow-core optical fiber, TAE HYUN YOON, FERESHTEH RAJABI, JEREMY FLANNERY, SREESH VENUTURUMILLI, MICHAL BAJCSY, Institute for Quantum Computing, University of Waterloo, NANO PHOTONICS AND QUANTUM OPTICS TEAM — We implement a dynamically controlled photonic bandgap in an ensemble of laser cooled cesium atoms confined inside a hollow-core photonic crystal fiber (HPCF). This photonic bandgap is induced in the ensemble by combining electromagnetically induced transparency (EIT) conditions with an off-resonant standing light wave, which in turn produces a rapid spatial modulation of the index of refraction experienced by the probe light. We investigate the formation of stationary light pulses through dynamic control of this bandgap.

9:00AM G6.00006 Strongly Interacting mm-Wave and Optical Photons with Rydberg Atoms, AZIZA SULEYMANZADE, MARK STONE, SCOTT EUSTICE, JONATHAN SIMON, DAVID SCHUSTER, University of Chicago — We describe progress towards a hybrid experimental system for engineering strong interactions between single optical and mm-wave photons using Rydberg atoms as an interface. Entanglement between photons with gigahertz and optical frequencies creates a new platform to access exotic photonic quantum states as well as powerful new techniques in quantum computing and simulation. We will present recent experimental developments including trapping and cooling atoms in a cryogenic MOT, measuring high-Q superconducting cavities at 100 GHz and coupling atoms to an optical cavity inside a cryostat at 3 Kelvin.

9:12AM G6.00007 Non-destructive photon detection using a single rare earth ion coupled to a photonic cavity, CHRIS O'BRIEN, Material Science, Lynntech, Inc., TIAN ZHONG, ANDREI FARAON, T.J. Watson Laboratory of Applied Physics, California Institute of Technology, CHRISTOPH SIMON, Institute for Quantum Science and Technology and Department of Physics and Astronomy, University of Calgary — We study the possibility of using single rare-earth ions coupled to a photonic cavity with high cooperativity for performing non-destructive measurements of photons, which would be useful for global quantum networks and photonic quantum computing. We calculate the achievable fidelity as a function of the parameters of the rare-earth ion and photonic cavity, which include the ion’s optical and spin dephasing rates, the cavity linewidth, the single photon coupling to the cavity, and the detection efficiency. We suggest a promising experimental realization using current state of the art technology in Nd:YVO_4.

This work was supported by NSERC (Canada). AF and TZ acknowledge support from National Science Foundation CAREER award 1454607.
shell. is observed during the first few picoseconds. Classical calculations trace this phenomenon to transient decoupling of the molecule from its He angulon quasiparticle [5]. 2) With increasing fluence the revivals disappear – instead, rotational dynamics as rapid as for an isolated molecule.

The coherence, although decaying, persists for many hundreds of picoseconds – long enough to allow the composite molecule-He-shell system to exhibit rotational revivals.

At low to moderate fluences the alignment pulse sets the molecule and a non-superfluid fraction of the He droplet into coherent motion. For example, dispersion-engineered photonic crystal waveguides (PCWs) permit not only stable trapping and probing of atoms via interactions with guided mode (GM) light, but also the possibility to study the physics of strong, photon-mediated interactions between atoms, as well atom mediated photon-photon interactions. Our current system at Caltech consists of a quasi-one-dimensional PCW whose band structure arises from periodic modulation of the dielectric structure. Here, we report a moving optical lattice utilized for transport of trapped atoms into and through the PCW in a phase-sensitive fashion. Single atoms can then be transferred from the moving lattice into optical traps formed in unit cells of the PCW by GMs of the waveguide. We present data for the optical spectra of the GM transmission and reflection that allow inference of coherent atom transport. Progress towards trapping atoms along the PCW will also be discussed.

Electron-spin systems are investigated using a reduced-density-matrix description. Applications of interest include trapped atomic systems in optical lattices, semiconductor quantum dots, and vacancy defect centers in solids. Complimentary time-domain (equation-of-motion) and frequency-domain (resolvent-operator) formulations are self-consistently developed. The general non-perturbative and non-Markovian formulations provide a fundamental framework for systematic evaluations of corrections to the standard Born (lowest-order-perturbation) and Markov (short-memory-time) approximations. Particular attention is given to decoherence and relaxation processes, as well as spectral-line broadening phenomena, that are induced by interactions with photons, phonons, nuclear spins, and external electric and magnetic fields. These processes are treated either as coherent interactions or as environmental interactions. The environmental interactions are incorporated by means of the general expression derived for the time-domain and frequency-domain Liouville-space self-energy operators, for which the tetradic-matrix elements are explicitly evaluated in the diagonal-resolvent, lowest-order, and Markov (short-memory time) approximations.

L. G. acknowledges financial support from Carl-Zeiss Stiftung (0563-2.8/508/2).

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Wednesday, June 7, 2017 8:00AM - 10:00AM –
Session G7 Coherent Molecular Spectroscopy 313 - Lou DiMauro, Ohio State University
8:30AM G7.00002 Opto-Optical Phase Control of Coherent Extreme Ultraviolet Light Pulses
1. JOHAN MAURITSSON, Lund University — We present an experimental and theoretical study of opto-optical phase modulation of extreme ultraviolet (XUV) free induction decay (xFID). Coherent XUV light, from high-order harmonic generation [2], is used to promote an ensemble of atoms to a superposition of the ground state and a series of excited states. The technique is demonstrated for a number of different target atoms and includes both bound states and higher lying auto ionizing states. When an ensemble of atoms is exposed to a short, coherent light pulse it will respond collectively and the excited atoms will act as oscillating dipoles. These dipoles may continue to oscillate coherently for a long time after the excitation pulse has passed, resulting in forward scattered light known as free induction decay (FID) [3,4]. This forward scattered light has the same spatial properties as the excitation pulse, but the phase is shifted by \( \pi \). The overlap between the two fields will therefore yield the normal absorption spectrum observed in optical spectroscopy. Applying an infrared probe pulse after the excitation pulse we can control the phase of the emitted light. If the delay controlled IR pulse is co-linear, but non-coaxial, with the XUV pulse a Stark induced phase gradient can be induced resulting in a precise control of the direction and timing of the xFID emission. With a single IR control pulse we can form an opto-optical switch, or with multiple pulses an opto-optical modulator. Applications for the opto-optical phase modulator include reducing the temporal jitter in optical-FEL pump-probe experiments, background free 2D spectroscopy in the XUV, and ultrafast which-way interferometry. [1] S. Bengtsson et al. submitted [2] M. Ferray et al. J. Phys. B 21, L31 (1988) [3] R. G. Brewer and R. L. Shoemaker, Phys. Rev. A 6, 2001 (1972) [4] F. A. Hopf, R. F. Shea, and M. O. Scully, Phys. Rev. A 7, 2105 (1973)

1This research was supported by the Swedish Foundation for Strategic Research, the Crafoord Foundation and the Swedish Research Council.

9:00AM G7.00003 A self referencing attosecond interferometer with zeptosecond precision
1. CARLOS TRALLERO, Kansas State Univ — We present a controlled interferometric measurement of two beating train of attosecond pulses. The attosecond pulse train is generated by higher order harmonics from two sources in a gas phase. By controlling the offset phase between the two train of attosecond pulses we are able to measure the phase of all the harmonics relative to the offset phase of the fundamental \( f_0 \). Somewhat surprisingly we find that the phase evolution for all the measured harmonics follows the linear relation \( \delta \phi_n = (2n+1)f_0 \). This represents an ideal source for heterodyne spectroscopic measurements in the XUV regime. Phase measurements were performed with a resolution of 12.5 attoseconds or half of the atomic unit of time. The precision of the measurement is in the hundreds of zeptoseconds which can be enhanced in further experiments. Finally, no carrier-envelope phase stabilization nor generation of isolated attosecond pulses is required for the presented measurements, thus reducing the complexity of future experiments.

1U.S. Department of Energy (DOE), Office of Basic Energy Sciences, Chemical Sciences, Geosciences, and Biosciences Division, (DE-FG02-86ER13491)

Wednesday, June 7, 2017 8:00AM - 9:48AM — Session G8 Ultracold Gas Dynamics

8:00AM G8.00001 Imaging transport of ultracold atoms through a quantum wire
1. SAMUEL HAUSLER, MARTIN LEBRAT, DOMINIK HUSMANN, LAURA CORMAN, SEBASTIAN KRINNER, ETH Zurich, SHUTA NAKAJIMA, Kyoto University, JEAN-PHILIPPE BRANTUT, EPFL Lausanne, TILMAN ESSLINGER, ETH Zurich — We report on a scanning gate technique to experimentally image the transport of fermionic lithium atoms through a quantum wire, similar to what is applied to solid state devices. The gate is created with a tightly focused repulsive laser beam whose aberrations are holographically corrected. By scanning its position over the wire and measuring the subsequent variation of conductance, we spatially map the transport at a resolution close to the transverse wave function of atoms inside the channel. The gate extends on the scale of the Fermi wavelength making it sensitive to quantum tunneling. Furthermore, our knowledge of the optical potential allows a direct comparison with an analytical and a numerical model for non-interacting particles. The flexibility offered by programmable holograms make it relatively simple to imprint more complex structures, such as a one-dimensional lattice inside the wire. This opens the path to study metal-insulator physics with strong attractive interactions.

8:12AM G8.00002 Formation of matter-wave soliton trains by modulational instability
1. JASON H. V. NGUYEN, DE LUO, RANDALL G. HULET, Rice University — Matter-wave soliton trains were initially observed following an interaction quench in a condensate of \(^7\)Li atoms. The solitons in the train were observed to interact repulsively, an indication of a phase difference of \( \pi \) between neighboring solitons. Although the formation of soliton trains can be understood as resulting from a modulational instability, an explanation for the observed phase-structure remains elusive. We study the formation of soliton trains by characterizing modulational instability across a wide range of scattering lengths. We find universal scaling laws for the number of solitons created by the quench and for the decay in atom number. Through minimally-destructive imaging, we observe real-time dynamics, and show that soliton trains are created with an alternating phase structure, rather than evolving into one.

1Work supported by the NSF, an ARO MURI grant, and the Welch Foundation.

8:24AM G8.00003 Quantum Breakup of Higher Order Bright Solitons
1. LINCOLN CARR, Department of Physics, Colorado School of Mines, Golden, Colorado, USA, CHRISTOPH WEISS, Joint Quantum Centre (JQC) Durham-Newcastle, Department of Physics, Durham University, Durham, UK — Semiclassical mean field theory in the form of the nonlinear Schrodinger equation (NLS) has had incredible success in modeling the dynamics of repulsive Bose-Einstein condensates (BECs): experimentally observed predictions range from dark solitons to skyrmions. A key prediction for attractive BECs is the bright soliton. An order-two soliton can be produced in a BEC simply by increasing the interaction strength by a factor of four, via a Feshbach resonance. The NLS is exactly solvable in this case and predicts a beautiful time-periodic dynamical pattern. Using matrix-product state methods, we show that such far-from-equilibrium higher order bright solitons exhibit quantum depletion and in fact break up rapidly in the more complete underlying quantum theory. Such break-up presents a smoking gun signal for emergent phenomena in quantum systems that do not have a semiclassical limit, and are therefore truly quantum in nature at macroscopic scales. They also indicate a breakdown of semiclassical integrability at a more fundamental quantum level.

1Funded by NSF, AFOSR, and ESPRC.
Several attempts have been made to measure the force between two modes of vibration in a system of bosons. This method is used to study the breathing dynamics in a system of bosons. The precision of our method is compared to other methods, and we find that our method is more accurate. We also develop a new method based on the notion of conditional wavefunctions to solve the time-dependent Schrödinger equation with the help of Bohmian trajectories. In this work, we utilize the Bohmian trajectories as a computational tool to tame the many-body problem in quantum dynamics of large systems. In this work, we show that the cat fidelity can be simply deduced from the subsequent revival. Finally, in a full multimode description, we induced generation of small Schrödinger cat states from an initial phase state in bimodal Bose-Einstein condensates. We present a strategy to make use of this phenomenon in real experiments.

1ONR, NSF, ARO, AFOSR

9:00AM G8.00006 Quantum memory effects through interaction imbalance in ultracold bosonic and fermionic atoms. CHEN-YEN LAI, CHIH-CHUN CHIEN, Univ of California - Merced — Memory effects result from history dependent behavior and have board applications. While ground states of noninteracting systems are not expected to exhibit memory effects in dynamic variables such as the mass current, interacting systems can support memory effects which may be measured in novel quantum simulators such as ultracold atoms. Here, we simulate real time dynamics of systems undergo an interaction change only on half of the system using the time-dependent density matrix renormalization group method. The quasi steady state current (QSSC) driven by the interaction imbalance exhibits a plateau lasting for a few period of time and can be tuned by the period of a forcing term. By comparing the value of the QSSC from different driving schemes, memory effects can be quantified. Here, two kinds of memory effects induced by interaction imbalance are discussed for both fermionic and boson systems. Starting from different initial states quenched to the same final configurations, memory of the initial quantum state can be observed. Secondly, driving the same initial configuration to the same final configuration linearly with different ramping times further leads to time-dependent memory effects. Those memory effects are from pure quantum origin and we will discuss possible experimental realizations.

9:12AM G8.00007 Observation of quantum-limited spin transport in strongly interacting two-dimensional Fermi gases. BEN A. OLSEN, CHRIS LUCIUK, SCOTT SMALE, University of Toronto, FLORIAN BÖTTLCHER, Universität Stuttgart, HAILLE SHARUM, STEFAN TROTZKY, University of Toronto, TILMAN ENSS, Universität Heidelberg, JOSEPH H. THYWISSEN, University of Toronto — Conjectured quantum bounds on transport appear to be respected in many strongly interacting many-body systems. Since transport occurs as a system relaxes to equilibrium, many such bounds can be recast as an upper bound on the local relaxation rate $k_B T / h$. Systems saturating this "Planckian" bound lack well defined quasiparticles promoting transport. We measure the transport properties of 2D ultracold Fermi gases of $^{40}$K during transverse demagnetization in a magnetic field gradient. Using a phase-coherent spin-echo sequence, we distinguish bare spin diffusion from the Leggett-Rice effect, in which demagnetization is slowed by the precession of spin current around the local magnetization. When the 2D scattering length is tuned near an $s\bar{s}$-wave Feshbach resonance it is comparable to the inverse Fermi wave vector $k_F^{-1}$, we find that the bare transverse spin diffusivity reaches a minimum of $1.7(6) h/nm$. Demagnetization is also reflected in the growth rate of the $s\bar{s}$-wave contact, observed using time-resolved rf spectroscopy. At unitarity, the contact rises to $0.28(3)k_F^2$ per particle, measuring the breaking of scaling symmetry. Our observations support the conjecture that under strong scattering, the local relaxation rate is bounded from above by $k_B T / h$.

9:24AM G8.00008 Mesoscopic quantum superpositions in bimodal Bose-Einstein condensates: decoherence and strategies to counteract it. KRZYSZTOF PAWLOWSKI, Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotnikow 32/46, 02-668 Warsaw, Poland, MATTEO FADEL, PHILIPP TREUTLEIN, Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, YVAN CASTIN, ALICE SINATRA, Laboratoire Kastler Brossel, Ecole Normale Superieure, UPMC and CNRS, 24 rue Lhomond, 75231 Paris Cedex 05, France — We study theoretically the interaction-induced generation of small Schrödinger cat states from an initial phase state in bimodal Bose-Einstein condensates. We present a strategy to obtain the cats, despite severe intrinsic and experimental constraints, including particle losses and Poissonian fluctuations of the total particle number. We show that the cat fidelity can be simply deduced from the subsequent revival. Finally, in a full multimode description, we study the effect of preexisting thermal fluctuations.

1We acknowledge support from National Science Center UMO-2014/13/D/ST2/01883.

9:36AM G8.00009 Quantum Dynamics of Many-Body Systems using Bohmian Trajectories. TAREK ELSAYED, KLAUS MOELMEL, LARS BOJER MADSEN, Aarhus University — Several attempts have been made to utilize the Bohmian trajectories as a computational tool to tame the many-body problem in quantum dynamics of large systems. In this work, we develop a new method based on the notion of conditional wavefunctions to solve the time-dependent Schrödinger equation with the help of Bohmian trajectories. This method is used to study the breathing dynamics in a system of bosons. The precision of our method is compared with the Multiconfigurational Time-Dependent Hartree method for Bosons (MCTDHB).

Wednesday, June 7, 2017 8:00AM - 10:00AM –
Session G9 Quantum Phases of Atoms in Optical Lattices 315 - Brian DeMarco, University of Illinois at Urbana-Champaign
8:00AM G9.00001 Mean-field scaling of the superfluid to Mott insulator transition in a 2D optical superlattice , THOMAS BARTER, CLAIRE THOMAS, TSZ-HIM LEUNG, MASAYUKI OKANO, University of California, Berkeley, GYU-BOONG JO, Hong Kong University of Science and Technology, JENNIE GUZMAN, California State University, East Bay, ITAMAR KIMCHI, Massachusetts Institute of Technology, ASHVIN VISHWANATH, Harvard University, DAN STAMPER-KURN, University of California, Berkeley — The mean-field treatment of the Bose-Hubbard model predicts that the properties of lattice-trapped gases are insensitive to the specific lattice geometry once system energies are scaled by the coordination number. We test this prediction by studying the superfluid to Mott insulator transition in an ultracold gas of rubidium atoms trapped in a two-dimensional optical superlattice which can be tuned from triangular (z = 6) to kagome (z = 4) geometries. We observe the coherent fraction to be less robust in the kagome lattice by tuning the ratio of the interaction energy U to the tunneling energy J. Comparison of the coherent fraction in the triangular lattice to that in the kagome lattice in terms of the scaled ratio U/Jz is consistent with the mean-field prediction.

8:12AM G9.00002 Inter-orbital interactions in state-dependent optical lattices , LUIS RIEGGER, NELSON DARKWAH OPPONG, MORITZ HOEFER, IMMANUEL BLOCH, SIMON FOELLING, LMU, Munich, Germany; MPQ, Garching, Germany — We report on the realization of a state-dependent optical lattice for the ground state 1S0 and metastable excited state 3P0 of fermionic 173Yb. While excited-state atoms are pinned by the lattice, ground-state atoms retain their mobility. Moreover, the optical lattice is nuclear-spin independent, conserving the SU(N) symmetry of the interactions, typical for earth-alkaline-like atoms. Together, these features make it a natural platform for the realization of Kondo-type physics. The effective inter-orbital interactions are influenced by the recently discovered magnetic Feshbach resonance as well as the lattice potential, inducing mixed dimensionality for the two atomic orbitals. We probe these interactions experimentally using high-resolution clock-line spectroscopy as well as collision dynamics.

8:24AM G9.00003 Compressibility phase diagram for the disordered Bose-Hubbard model1 , PHILIP RUSS, LAURA WADLEIGH, BRIAN DEMARCO, University of Illinois Urbana-Champaign — Developing a complete understanding of the effects of disorder in quantum many-particle systems is an outstanding problem with key implications for condensed matter physics and quantum information science. We report progress towards this goal in a 3D disordered Bose lattice gas consisting of strongly interacting 87Rb atoms, which realizes the disordered Bose-Hubbard model (DBHM). One of the distinguishing properties of the phases in the DBHM is compressibility. We experimentally map the compressibility of the DBHM phase diagram by measuring the change in double binding and unbinding of Cooper pairs in this system using rf spectroscopy, changes in Tc by measuring the condensate fraction, and transport properties by observing the response to an applied impulse. We will discuss progress towards these measurements.

8:36AM G9.00004 Progress towards localization in the attractive Hubbard model , W. MORONG, W. XU, B. DEMARCO, University of Illinois — The interplay between fermionic superfluidity and disorder is a topic of long-standing interest that has recently come within reach of ultracold gas experiments. Outstanding questions include the fate of Cooper pairs in a localized superfluid and the effect of disorder on the superfluid transition temperature. We report progress on tackling this problem using a realization of the Hubbard model with attractive interactions. Our system consists of two spin states of fermionic potassium-40 trapped in a cubic optical lattice. Disorder is introduced using an optical speckle potential, and interactions are controlled via a Feshbach resonance. We study the binding and unbinding of Cooper pairs in this system using rf spectroscopy, changes in Tc by measuring the condensate fraction, and transport properties by observing the response to an applied impulse. We will discuss progress towards these measurements.

8:48AM G9.00005 Quantum Engineering of a Low-Entropy Gas of Heteronuclear Bosonic Molecules in an Optical Lattice , ANDREAS SCHINDEWOLF, LUKAS REICHSSÖLLNER, HANNS-CHRISTOPH NÄGERL, Institut für Experimentalphysik, Universität Innsbruck, Austria, TETSU TAKEKOSHI, RUDOLF GRIMM, Institut für Experimentalphysik, Universität Innsbruck, Austria; Institut fr Quantenoptik, und Quanteninformation IQOQI, Innsbruck, Austria — We present a novel method to prepare low-entropy samples of heteronuclear molecules confined to an optical lattice as an ideal starting point for dipolar quantum gas experiments based on ultracold molecules. Starting from two spatially separated BECs we efficiently form Rb-Cs atom pairs by overlapping a Cs Mott insulator with a superfluid Rb sample in an optical lattice. For sample mixing the Cs-Cs interaction is nulled at a Feshbach resonance. We study the binding and unbinding of Cooper pairs in this system using rf spectroscopy, changes in Tc by measuring the condensate fraction, and transport properties by observing the response to an applied impulse. We will discuss progress towards these measurements.

9:00AM G9.00006 Analysis of spontaneous emission of a lattice trapped atom into free space1 , MICHAEL STEWART, LUDWIG KRINNER, ARTURO PAZMINO, DOMINIK SCHNEBEL, Stony Brook University — It has been predicted2 that an atom confined in an optical lattice well that is coupled to free space through an internal state transition can exhibit behavior analogous to that of spontaneous emission in a photonic band gap material. We have recently performed a detailed theoretical analysis of such a system in a 1D geometry, including the lattice- confined population evolution, the momentum distribution of the emitted matter waves, and the structure of an evanescent matter-wave state below the continuum boundary. We compare our results for the transition from Markovian to non-Markovian behaviors to those previously obtained for three dimensions, and propose an experimental realization of the system.

1Supported by NSF grants No. PHY-1205894 and No. PHY-1607633
9:12AM G9.00007 Observing Spontaneous Emission Phenomena Using Lattice-Trapped Atoms Coupled to Free Space. Ludwig Krinner, Michael Stewart, Arthur Pazmino, Joohn-Hyuk Kwon, Dominik Schnelle, Stony Brook University — It has been predicted that quantum optical models for spontaneous emission in photonic band gap materials can be realized with ultracold atomic systems. We experimentally implement such a scenario using ultracold Rb-87 atoms initially trapped in a state selective optical lattice. Coupling to a freely propagating internal state releases matter-waves (wave-continuum), while a populated/unpopulated lattice site simulates the excited/ground states of an “artificial atom”. We present recent experimental results on the time evolution of the system, for which we find both Markovian as well as strongly non-Markovian dynamics. We characterize the momentum distribution of the emitted matter waves, for which we find close agreement with theoretical predictions. A careful analysis allows for an identification of the equivalent of a Lamb shift, and provides indirect evidence for the analog of the atom-photon bound state in photonic band gap materials.

1This work is supported by the National Science Foundation, grant No. PHY-1607633.


9:24AM G9.00008 Bipolarons in one-dimensional extended Peierls-Hubbard models. John Sous, Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1, Monodeep Chakraborty, Indian Institute of Technology, Kharagpur, India, Roman Krems, Department of Chemistry, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1, Mona Berciuc, Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1 — We study two particles in an infinite chain and coupled to phonons by interactions that modulate their hopping as described by the Peierls/Su-Schrieffer-Heeger (SSH) model. In the case of hard-core bare particles, we show that exchange of phonons generates effective nearest-neighbor repulsion between particles and also yields rise to interactions that move the pair as a whole. The two-polaron phase diagram exhibits two sharp transitions, leading to light dimers at strong coupling and the flattening of the dimer dispersion at some critical values of the parameters. This dimer (quasi)self-trapping occurs at coupling strengths where single polarons are mobile. On the other hand, in the case of soft-core particles/spinful fermions, we show that phonon-mediated interactions are attractive and result in strongly bound and mobile bipolarons in a wide region of parameter space. This illustrates that, depending on the strength of the phonon-mediated interactions and statistics of bare particles, the coupling to phonons may completely suppress or strongly enhance quantum transport of correlated particles.

1This work was supported by NSERC of Canada and the Stewart Blusson Quantum Matter Institute.

9:36AM G9.00009 Equilibration dynamics of a many-body quantum system across the superfluid to Mott insulator phase transition. Andreas Mullers, Christian Baals, Bodhadiya Santra, Ralf Labouvie, Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Germany, Thomas Mertz, Aruya Dhara, Institute for Theoretical Physics, Goethe-University Frankfurt, Frankfurt/Main, Germany, Ivana Vasic, Scientific Computing Laboratory, Institute of Physics Belgrade, University of Belgrade, Serbia, Agnieszka Cichy, Walter Hofstetter, Institute for Theoretical Physics, Goethe-University Frankfurt, Frankfurt/Main, Germany, Herwig Ott, Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Germany — We report on the center-of-mass motion of ultracold 87Rb atoms on displacing an underlying potential. The atoms are adiabatically loaded into an optical lattice superimposed onto an optical dipole trap. The CO2 laser beam forming the dipole trap is then shifted by 1 mm which forces the system out of equilibrium. The subsequent motion of the atoms center-of-mass is imaged with a scanning electron microscope for various depths of the optical lattice spanning the superfluid to Mott-insulator phase transition. The observed dynamics range from fast oscillations in the superfluid regime to a steady exponential movement towards the new equilibrium position for higher lattice depths. By piecewise analysis of the system, we can also identify a thermal phase at the edges which moves with velocities in between those of the superfluid and the insulating phase. We will present the experiment and the results of theoretical modelling currently in progress.

9:48AM G9.00010 Real-space renormalization group methods and the prospect of observing conformal Calabrese-Cardy scaling. Judah Unmuth-Yockey, University of Iowa, Jin Zhang, University of California Riverside, Philipp Preiss, Physikalisches Institut, Li-Ping Yang, Chongqing University, Shan-Wen TsaI, University of British Columbia, Vancouver, British Columbia, Canada, Mona Berciuc, Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1 — We study two particles in an infinite chain and coupled to phonons by interactions that modulate their hopping as described by the Peierls/Su-Schrieffer-Heeger (SSH) model. Using numerical renormalization group methods have contributed greatly to understanding the phase structure of lattice models in both condensed matter physics and lattice gauge theory over the past few decades. Using two of these methods, the tensor renormalization group and the density matrix renormalization group, we consider the possibility of experimentally observing the conformal Calabrese-Cardy scaling, and measuring the conformal charge in the superfluid phase of the Bose-Hubbard model in one spatial dimension. We propose using existing experimental methods to measure the quantum purity, for which we find close agreement with theoretical predictions. A careful analysis allows for an identification of the equivalent of a Lamb shift, and provides indirect evidence for the analog of the atom-photon bound state in photonic band gap materials.

1This work was supported by the National Science Foundation, grant No. PHY-1607633.


Wednesday, June 7, 2017 10:30AM - 12:30PM
Session H2 Scientific Legacy of D. S. Jin
10:30AM H2.00001 From the First Atomic Fermi Gas to a Bad Metal. Brian Demarco, Univ of Illinois - Urbana — One of the most exciting frontiers in physics is ultracold quantum gases. They play a role in unraveling the physics of superfluids, exotic solids, and nuclear and quark matter. Like all particles, quantum gases come in two flavors: bosons and fermions. In this talk, I will briefly tell a few stories related to how Deborah Jin and I realized the first Fermi gas of atoms in 1999, including how we created the first enriched potassium sources, measured the 40K elastic collision cross-section, and a developed methods for detecting quantum degeneracy. I will describe how the legacy of this work is carried on by my group at Illinois in experiments on strongly correlated 40K lattice gases. I will discuss recent measurements of mass-current decay, the detection of incoherent transport, and the observation of a surprising decrease in the transport lifetime at higher temperatures. The connection between this discovery and T-linear resistivity in bad metals will be described.

1This research is supported by the National Science Foundation and the Army Research Office.
11:00AM H2.00002 Improving interferometric displacement detection with quantum correlations. CINDY REGAL, JILA, University of Colorado Boulder and NIST — Interferometers enable ultrasensitive measurement in a wide array of applications from gravitational wave searches to force microscopes. We now have the ability to study interferometers in the interesting limit in which quantum backaction places constraints on measurement sensitivity for a solid-state object. To enter this new regime we have constructed micromechanical devices at cryogenic temperatures that respond appreciably to radiation pressure in an optical cavity. Our most recent experiments show we can access quantum correlations that improve upon the standard quantum limit for continuous displacement detection.

11:30AM H2.00003 Making a molecular gas in the quantum regime. KANG-KUEN NI, Department of Chemistry and Chemical Biology, Harvard University — Ultracold molecules are exciting systems for a large range of scientific explorations including studies of novel phases of matter and precision measurement. In this talk, I will present a brief story of the first quantum gas of molecules, KRb, created under my PhD advisor, Deborah Jin, in 2008. A complete surprise was finding ultracold chemistry in such a system through measurements of reactant losses. In particular, long-range physics that determines KRb reactant collision rates, including van der Waals interactions, quantum statistics, and dipolar interactions, were studied extensively. However, the short-range behavior of these chemical reactions remains unknown. A legacy of her work is carried out in my lab at Harvard, where we are integrating physical chemistry tools with cold atom techniques to study ultracold chemistry with KRb molecules. In particular, we aim to elucidate the four-center reaction $2K + Rb \rightarrow K_2 + Rb_2$ by detecting the reaction products through ionization both identify the product species and mapping out their complete quantum states.

12:00PM H2.00004 Dual Bose-Fermi Superfluids. CHRISTOPHE SALOMON, laboratoire Kastler Brossel, Ecole Normale superieure, Paris, France — We study the dynamics of superfluid counterflow in a Bose-Fermi mixture of lithium atoms. First, by tuning the interaction strength we measure the critical velocity $v_c$ of the system in the BEC-BCS crossover in the low temperature regime and we compare it to the recent prediction of Castin et al., Comptes Rendus Physique,16, 241 (2015). Second, raising the temperature of the mixture slightly above the superfluid transitions reveals an unexpected phase-locking of the oscillations of the clouds induced by dissipation. Finally, we investigate the lifetime of the Bose-Fermi mixture. We show theoretically and experimentally that, for weak inter-species coupling, the loss rate is proportional to Tan’s contact parameter. At unitarity where the fermion-fermion scattering length diverges, we show that the loss rate is proportional the $1/3$ power of the fermionic density. This study demonstrates that impurity-induced losses can be used as a quantitative probe of many-body correlations.

Wednesday, June 7, 2017 10:30AM - 12:30PM

Session H3 Atomic and Nuclear Measurements in Ion Traps 308 - Thad Walker, University of Wisconsin

10:30AM H3.00001 Precision ion trap measurements in nuclear physics. JENS DILLING, TRIUMF and University of British Columbia — Nuclear Physics is a fundamental science discipline, which started over 100 years ago, and is concerned with the understanding of how nuclear matter is held together in its innermost and how its structures behave and evolve. Recent progress in experimental and theoretical techniques has advanced the field significantly, but some questions remain. Moreover, new nuclear phenomena have been discovered, this includes so-called nuclear halo nuclei and the appearance of different nuclear shells. Ion trap technologies, originally developed for atomic and molecular physics, have been adapted to the specific requirements stemming from nuclear physics, for example, to couple ion traps to accelerators and achieve very high speed and efficiencies. In this talk I will show some examples and technical developments pertaining to nuclear physics questions and phenomena and how they are addressed with precision ion trap measurements.

11:00AM H3.00002 Ultrasensitive magnetometer using a single atom. CHRISTOF WUNDERLICH, University of Siegen — Precision sensing, and in particular high precision magnetometry, is a central goal of research into quantum technologies. The precision, and thus the sensitivity of magnetometry scales as $1/\sqrt{T_2}$ with the phase coherence time $T_2$ of the sensing system. Typical quantum sensing protocols prolong $T_2$ of the quantum states used for sensing by using dynamical decoupling (DD), that is, applying a continuous or pulsed electromagnetic driving field. In the case of pulsed DD, the required repetition rate of pulses — with each pulse having a well defined pulse area — is proportional to the frequency of the field to be detected with high sensitivity, thus effectively limiting the frequency range of the sensor. To achieve a long coherence time $T_2$ using continuous DD, the amplitude of the driving field has to be kept highly stable for time $T_2$, another technologically challenging problem. Here, we implement a decoupling scheme using two continuous decoupling fields in an atomic $4$-level scheme. Thus, the coherence time is no longer limited by fluctuations of the amplitude of the decoupling fields. Instead, $T_2$ is determined by the frequency stability of the driving fields which is straight forward to maintain with high precision using, for instance, a commercial atomic clock. Using a single trapped $^{171}$Yb$^+$ ion as a sensor, we experimentally attain a sensitivity of $4.6 \text{ pT}/\sqrt{\text{Hz}}$, to our knowledge the best sensitivity so far realized with a single atom. The detected magnetic field is an alternating-current (AC) magnetic field near 14 MHz. Based on the principle demonstrated here, this unprecedented sensitivity together with its tunability from direct-current to the gigahertz range could be used for magnetic imaging in as of yet inaccessible parameter regimes.

11:30AM H3.00003 Precision mass ratios of mass-3 ions. EDMUND G MYERS, SAEED HAMZELOUI, JORDAN R SMITH, DAWID J FINK, Florida State University — Precise atomic masses of hydrogen, deuterium and helium-3 are important fundamental constants with application to a wide range of physical science. Using a rebuilt and improved Penning trap mass spectrometer, we are measuring the ion mass ratios HD$^+$/H$^+$, $^3$He$^+$/H$^+$ and $^3$He$^+$/HD$^+$. The results will help resolve the current four-sigma discrepancy for the mass of $^3$He.

1Work supported by NSF
11:42AM H3.00004 Reducing time-dilation uncertainty in the NIST Al+ quantum-logic clock. SAMUEL BREWER, National Institute of Standards and Technology (NIST), JWO-SY CHEN, NIST, University of Colorado at Boulder, AARON HANKIN, NIST, ETHAN CLEMENTS, NIST, University of Colorado at Boulder, CHIN-WEN CHOU, DAVID WINELAND, NIST, DAVID LEIBRANDBT, NIST, University of Colorado at Boulder, DAVID HUME, NIST — Previous optical atomic clocks based on quantum-logic spectroscopy of the 1S0 → 1P1 transition in 27Al+ have reached an uncertainty of δν/ν = 8.0 × 10^-18 dominated by time-dilation shifts due to driven motion (i.e., micromotion) and thermal (secular) motion of the trapped ions. Excess micromotion is typically the result of imperfections in trap fabrication while the uncertainty in the thermal motion has been limited by difficulties in determining the ion temperature near the Doppler cooling limit. We report on Raman sideband cooling of 25Mg+ to sympathetically cool the secular modes of motion in a 25Mg+–27Al+ two-ion pair near the three-dimensional (3D) ground state. We characterize the residual energy and heating rates of all of the secular modes of motion and estimate a secular motion time-dilation shift of -(1.9 ± 0.1) × 10^-18 for a 27Al+ clock at a typical clock probe duration of 150 ms. This is a 50-fold reduction in the secular motion time-dilation shift uncertainty in comparison with previous 27Al+ clocks. Furthermore, we present a preliminary characterization of the micromotion time-dilation shift uncertainty in an improved ion trap.

1 Work supported by DARPA and ONR. S.M.B. was supported by ARO through MURI grant W911NF-11-1-0400.

11:54AM H3.00005 Isotopic shift measurement of Na-like Xe ions as a new method to measure absolute and relative charge radii of rare isotopes. R. SILWAL, Clemson Univ., A. LAPIERRE, Michigan State Univ., J.D. GILLASPY, NSF, A.C.C. VILLARI, Michigan State Univ., G. GWINNER, Univ. of Manitoba, S.A. BLUNDELL, CEA-INAC, B.H. RUDRAMADEVI, Clemson Univ., A. BOROVIK, JR., Univ. of Geissen, J.M. DREILING, YU. RALCHENKO, NIST, E. TAKACS, Clemson Univ. — The absolute charge radius of unstable (radioactive) isotopes is mostly unavailable for elements heavier than Bi as current measurement techniques, e.g. electron scattering and m u n i c x-ray spectroscopy, require macroscopic amounts of the elements. Relative shifts in charge radii along isotopic chains, obtained from optical frequency shifts, strongly depend on semi-empirical approaches thereby adding further uncertainties. Transition energies of Na-like ions are sensitive to nuclear size, and because of their simple electronic structure, ab-initio atomic structure calculations can reach high accuracy. For heavy elements, it has even been noted that the precision of such calculations is limited by the large uncertainty in charge radii. This suggests a new method for charge radius measurements using Na-like ions. We have measured energy shifts associated with the D1 and D2 3s-3p transitions for Na-like 124Xe and 136Xe. The relative shift in charge radius of these isotopes is inferred by comparing experiment and high-precision calculations. We present preliminary results obtained from EUV and x-ray spectra observed in an electron beam ion trap. [1] Gillaspy et al., PRA 87, 062503 (2013).

12:06PM H3.00006 Progress towards a Lutetium-ion optical clock. KYLE ARNOLD, RAT-TAKORN KAEWUAM, ARPAN ROY, MURRAY BARRETT, Centre for Quantum Technologies, National University of Singapore — Recently singly ionized Lutetium has been proposed as a promising ion-clock candidate. It has multiple potential clock transitions from the T27 Lu isotope has been isolated by laser photo-ionization and can be now be loaded and cooled without a sympathetic cooling agent. Laser spectroscopy has been performed to measure the frequencies of the allowed dipole transitions and clock transitions relevant for clock operation. In addition, the hyperfine structure of the 1P1, 2D1, and 3D2 states has been measured. Progress towards implementation of the hyperfine averaging clock protocol and direct measurement of the differential scalar polarizability of the 1S0 to 3D1 transition will be presented.

12:18PM H3.00007 An Ultra-Cooled Atomic Quantum Sensor for Precision Detection of Oscillating Electric Signals. DANIEL RODRIGUEZ, J. BERROCAL, F. DOMINGUEZ, M. J. GUTIERREZ, R. RICA, Departamento de Física Atómica, Molecular y Nuclear, Universidad de Granada, Spain, TRAPSENSOR TEAM — Non-destructive detection of oscillating charges with minute strengths is important for several applications, particularly to perform ultra-accurate mass measurements by means of Penning traps. There are remarkable results obtained using electronic circuits [Nature 506, 467 (2014)], while the trapped charged particle is more than 100 times lighter than a superheavy atom. In this contribution, we will report on a novel concept under commissioned at the University of Granada, to replace the circuit immersed in a liquid-helium tank, by a laser-cooled Ca+ ion held in an ion trap with rotational symmetry, that should be coupled to another bound particle, following a previous idea published in the nineties [PRA 42, 2977 (1990)]. So far, we have studied the milliKelvin ion reservoir (after Doppler cooling), theoretically and experimentally, in collaboration with the QUTIS group (E. Solano et al.), to obtain the full characterization [arXiv:1612.08577]. We work currently towards applying ground-state cooling to replace the circuit immersed in a liquid-helium tank, by a laser-cooled Ca+ ion held in an ion trap with rotational symmetry, that should be coupled to another bound particle, following a previous idea published in the nineties [PRA 42, 2977 (1990)].

1 Acknowledgement: Projects 278648-TRAPSENSOR (ERC grant), and FPA2015-67694-P (Spanish Government).

Wednesday, June 7, 2017 10:30AM - 12:30PM — Session H5 AMO in Astrophysics

10:30AM H5.00001 Laboratory Astrophysics in Support of the Study of Nucleosynthesis. BETSY DEN HARTOG, University of Wisconsin - Madison — One of the outstanding questions in our understanding of the Universe is how the elements were made. Only a few of the lightest or primordial nuclei were made just after the Big Bang. Other light nuclei up to the iron (Fe)-group are made by fusion reactions in the interior of stars. Heavier nuclei are made primarily via neutron-capture events which are categorized as either slow or rapid, the s-process or r-process, respectively. Although s-process neutron-capture is fairly well understood, the r-process, which occurs in neutron dense (explosive) environments, remains more elusive. In recent years, progress has been made in the understanding of r-process nucleosynthesis through the study of elemental abundances in metal-poor stars. These stars, which are among the oldest objects in our Galaxy, contain a fossil record of the elemental mix of the surrounding interstellar medium when they formed. The improvement of both the accuracy and precision of elemental abundances in metal-poor stars has required a long-term effort to improve the laboratory data necessary for these rare elements and more recently for the Fe-group. In this talk I will describe our laboratory effort measuring atomic transition probabilities, which are determined from a combination of radiative lifetimes and emission branching fractions. I will then show some examples of the application of our laboratory data to the determination of metal-poor star elemental abundances and discuss insights that can be gleaned from these improved data.

1 Work in collaboration with (and supported by) Jim Lawler (NSF grant AST-1516182, NASA grant NNX16AE96G), Chris Suenon (NSF grant AST-1211585) and John Cowan (NSF grant PHY-1430152 (JINA Center for the Evolution of the Elements)), among others.
Combined with complementary data obtained from the Cassini Saturn orbiter, as well as theoretical models and laboratory studies, our observed observations provide instantaneous snapshot mapping of Titan’s entire Earth-facing hemisphere, for gases inaccessible to previous instruments. Branes (similar to the cells of terrestrial biology), and the astrobiological implications of this discovery will be discussed. Furthermore, ALMA (vinyl cyanide) on Titan. Liquid-phase simulations of Titan's seas indicate that vinyl cyanide molecules could combine to form vesicle membranes. In this talk, results will be presented from our studies using the Atacama Large Millimeter/submillimeter Array (ALMA) during the period 2012-2015, focussing in particular on the detection and mapping of emission from various nitrile species. By combining data from multiple ALMA observations, our spectra have reached an unprecedented sensitivity level, enabling the first spectroscopic detection and mapping of C2H3CN entering into the ISM. The observations are quantitatively described by an effective field theory of Rydberg-induced photon-photon interactions, with photon-photon interactions being achieved by coupling the light to highly excited, strongly interacting Rydberg states in a cold atomic gas. The photonic trimer, visible world around us. In contrast, photon-photon interactions are weak and need to be specifically engineered in the form of nonlinear optical media. Here we report the observation of a three-photon bound state inside a quantum nonlinear optical medium. The strong photon-photon interaction is achieved by coupling the light to highly excited, strongly interacting Rydberg states in a cold atomic gas. The photonic trimer, which can be viewed as a quantum soliton, is observed via bunching and a strongly nonlinear phase in the three-photon correlation function of the emerging light. The observations are quantitatively described by an effective field theory of Rydberg-induced photon-photon interactions, and agree with direct numerical simulations. This work paves the way towards the realization, understanding, and control of strongly interacting quantum gases of light.

1 Support for this work was provided by NASA through Einstein Postdoctoral Fellowship grant number PF6-170149 awarded by the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NAS8-03060.
Multiparameter estimation with single photons

SUSHOVIT ADHIKARI,
CHENGLONG YOU, MARGARITE LABORDE, JONATHAN DOWLING, Louisiana State Univ. - Baton Rouge. JONATHAN OLSON, Department of Chemistry and Chemical Biology, Harvard University — It was suggested in [Phys. Rev. Lett. 111, 070403] that optical networks with relatively simple preparation and measurement devices single photon Fock states and on-off detectors — can show significant improvements over classical strategies for multiparameter estimation when the number of modes in the network is small. This was further developed in [arXiv:1610.07128] for the case of single parameter estimation, and shown to be sub-shotnoise only for \( n < 7 \). In this paper, we show that this simple strategy can give asymptotically post-classical sensitivity for multiparameter estimation even when the number of modes is large. Additionally, we consider the effects of several other measurement techniques that can increase the efficiency of this device.

Ultra-broadband photon storage in hot atomic barium vapor

BIN FANG, SHUAI DONG, University of Illinois at Urbana-Champaign. SETH MEISELMAN, OFFIR COHEN, University of Delaware, VIRGINIA LORENZ, University of Illinois at Urbana-Champaign — Quantum memories are critical in quantum computing and quantum communication, where they enable synchronization and deterministic photon output. Here we experimentally demonstrate storage of THz-bandwidth optical pulses in a hot atomic barium vapor using the off-resonance Raman protocol, indicating its potential for an ultra-broadband quantum memory. The large energy splitting in barium between the ground and storage states of \( \sim 340 \) THz enables storage of \( < 100 \) fs photons, leading to a time-bandwidth product \( > 1000 \) and minimal thermal population in the storage state, resulting in low noise in single-photon operation. Our preliminary results show storage of 500 fs photons with an efficiency of 0.4\% at barium densities of \( 5.1 \times 10^{19} \text{m}^{-3} \). As a next step we are amplifying the control field and anticipate substantial improvement in efficiency. To date, researchers have shown storage of GHz-bandwidth photons in atomic systems and THz-bandwidth photons in molecular and solid state systems, but not broadband storage in the telecom range. Barium has a transition between state \( 6s6p^1P_1 \) and \( 6s6d^1D_2 \) at telecom wavelengths, making it feasible for telecom photon storage if one prepares the ground state \( 6s^2 \) \(^1S_0 \) as the storage state.

Detection and control of motion of single atoms or ions in an optical cavity

MOJTABA MOAZZEZI, YURI V. ROSTOVTSVEV, Center for Nonlinear Sciences and Department of Physics, University of North Texas — Using quantum coherence effects, we have developed a new technique of detection of motion of single atoms or ions in an optical cavity. We have theoretically demonstrated that a three-level atom inside a cavity can act as an ultra-dispersive medium and the group velocity of light becomes ultrasonic. If the atom is in motion, it causes a phase shift because of the Fizeau effect due to dragging of light, which can be observed. It has been shown that the change of phase is extremely sensitive to probe detuning in vicinity of resonance frequency and is in the order of \( 10^{-9} \) even for speed of a few meter per seconds.

Rydberg electromagnetically induced transparency in Radio-Frequency Field

JINMING ZHAO, Shandong University Taiyuan China, GEORG RAITHEL, Univ of Michigan - Ann Arbor — We investigate the electromagnetically induced transparency (EIT) involved a Rydberg level which is modulated with (40-100) MHz RF field. The cesium ground state \( 6S_{1/2} \), excited state \( 6P_{1/2} \) and Rydberg \( nD_{3/2} \) state consist of three-level atomic system, where a strong coupling laser drives the Rydberg transition, \( (6P_{3/2}) \rightarrow (nD_{3/2}) \), while a weak probe laser detects the EIT signal. The RF-dressed Rydberg EIT spectra show the Stark splitting and the even-th harmonic sidebands. The \( m_j \), \(-5/2 \) Stark line intersected with the \( m_j \), \(-1/2 \), \(-3/2 \) sidebands, which provides an Rydberg-based method for the accurate calibration of the RF electric field. We also investigate the dependence of the EIT spectra on the polarization of RF field and laser beams, the results show that \( m_j = 5/2 \) strength increase with the angle \( \theta \), defined between the polarizations of the lasers beams and RF field, whereas the \( m_j = 1/2 \), \( 3/2 \) sidebands strength decrease with \( \theta \). We model the experimental results using a Floquet model, the simulations are excellent agreement with the measurements. The investigation in this work provides an atom-based calibration of the polarization and amplitude of the RF-field using Rydberg-atom EIT.

Controlling the Collective Rabi Oscillation of N Rydberg Atoms with Ancillary Atoms


Superradiance in Inverted Multi-level Atomic Clouds

R.T. SUTHERLAND, FRANCIS ROBICHEAUX, Purdue University — This work examines superradiance in initially inverted clouds of multi-level atoms. We simulate clouds containing hundreds of radiating atoms, while eschewing the approximation of symmetric dipole-dipole interactions. We then examine the effects of both dephasing and excited state decays, as well as competition between multiple transitions on superradiance. Both of these mechanisms place strong restrictions on a given transition's ability to superradiate. These results are important to recent experiments that probe superradiance in Rydberg atoms.

Progress towards broadband Raman quantum memory in Bose-Einstein condensates

ERHAN SAGLAMYUREK, TARAS HRUSHEVSKYI, BENJAMIN SMITH, LINDSAY LEBLANC, Department of Physics, University of Alberta — Optical quantum memories are building blocks for quantum information technologies. Efficient and long-lived storage in combination with high-speed (broadband) operation are key features required for practical applications. While the realization has been a great challenge, Raman memory in Bose-Einstein condensates (BECs) is a promising approach, due to negligible decoherence from diffusion and collisions that leads to seconds-scale memory times [2], high efficiency due to large atomic density [3], the possibility for long-lived storage in combination with high-speed (broadband) operation are key features required for practical applications. While the realization has been a great challenge, Raman memory in Bose-Einstein condensates (BECs) is a promising approach, due to negligible decoherence from diffusion and collisions that leads to seconds-scale memory times [2], high efficiency due to large atomic density [3], the possibility for...
12:18PM H6.00010 Cooperative resonances in light scattering from two-dimensional atomic arrays1. EPHRAIM SHAHAMOON, DOMINIK WILD, MIKAIL LUKIN, SUSANNE YELIN, Harvard Univ — We consider light scattering off a two-dimensional (2D) dipolar array and show how it can be tailored by properly choosing the lattice constant of the order of the incident wavelength. In particular, we demonstrate that such arrays can shape the emission pattern from an individual quantum emitter into a well-defined, collimated beam, and operate as a nearly perfect mirror for a wide range of incident angles and frequencies. These results can be understood in terms of the cooperative resonances of the surface modes supported by the 2D array. Experimental realizations are discussed, using ultracold arrays of trapped atoms and excitons in 2D semiconductor materials, as well as potential applications ranging from atomically thin metasurfaces to single photon nonlinear optics and nanomechanics.

1We acknowledge the financial support of the NSF and the MIT-Harvard Center for Ultracold Atoms

Wednesday, June 7, 2017 10:30AM - 12:30PM –
Session H7 Focus Session: Ultrafast and Nonlinear X-ray Processes 313 - Gilles Doumy, Argonne National Laboratory

10:30AM H7.00001 Coherent Multidimensional Core Spectroscopy of Molecules with Multiple X-ray pulses, SHAUL MUKAMEL, University of California, Irvine — Multidimensional spectroscopy uses sequences of optical pulses to study dynamical processes in complex molecules through correlation plots involving several time delay periods. Extensions of these techniques to the x-ray regime will be discussed. Ultrafast nonlinear x-ray spectroscopy is made possible by newly developed free electron laser and high harmonic generation sources. The attosecond duration of X-ray pulses and the atomic selectivity of core X-ray excitations offer a uniquely high spatial and temporal resolution. We demonstrate how stimulated Raman detection of an X-ray probe may be used to monitor the phase and dynamics of the nonequilibrium valence electron state wavepacket created by e.g. photoexcitation, photoionization and Auger processes. Spectroscopy of multiphoton excitations provides a new window into electron correlations. Applications will be presented to long-range charge transfer in proteins and to excitation energy transfer in porphyrin arrays. Conical intersections (CoIn) dominate the pathways and outcomes of virtually all photophysical and photochemical molecular processes. Despite extensive experimental and theoretical effort CoIns have not been directly observed yet and the experimental evidence is being inferred from fast reaction rates and some vibrational signatures. Novel ultrafast X-ray probes for these processes will be presented. Short X-ray pulses can directly detect the passage through a Coln with the adequate temporal and spectral sensitivity. The technique is based on a coherent Raman process that employs a composite femtosecond/attosecond X-ray pulse to directly detect the electronic coherences (rather than populations) that are generated as the system passes through the Coln. Streaking of time-resolved photoelectron spectroscopy (TRPES) signals offers another powerful window into the joint electronic/vibrational dynamics at conical intersections. Strong coupling of molecules to the vacuum field of micro cavities can modify the potential energy surfaces thereby manipulating the photophysical and photochemical reaction pathways. The photonic vacuum state of a localized cavity mode can be strongly mixed with the molecular degrees of freedom to create hybrid field-matter states known as polaritons. Simulations of the avoided crossing of sodium iodide in a cavity which incorporate the quantized cavity field into the nuclear wave packet dynamics will be presented. Numerical results show how the branching ratio between the covalent and ionic dissociation channels can be strongly manipulated by the optical cavity.

11:00AM H7.00002 Pulse energy and pulse duration dependence of multi-photon ionization and fragmentation of iodomethane by ultraintense hard X-rays,1. X. LI, S.J. ROBATJAZI, D. ROLLES, A. RUDENKO, Kansas State University, B. ERK, R. BOLL, C. BOMME, E. SAVELYEV, DESY, Hamburg, B. RUDEK, PTB Braunschweig, L. FOUCAR, MPI for Medical Research, Heidelberg, CH. BOSTEDT, C.S. LEHMANN, B. KRAESSIG, S.H. SOUTHWORTH, L. YOUNG, M. BUCHER, Argonne National Laboratory, T. MARCHENKO, M. SIMON, UPMC Paris, K. UEDA, Tohoku University, Sendai, K.R. FERGUSON, T. GORKHOVER, R. ALONSO-MORI, S. CARRON, G. WILLIAMS, S. BOUTET, LCLS, SLAC — Ionization and fragmentation dynamics of iodomethane molecules (CH3I) irradiated by ultraintense 8.3 keV X-ray pulses from the Linac Coherent Light Source has been studied as a function of pulse energy and pulse duration. As intuitively expected, the measured ion charge state distributions (CSD) are very sensitive to the pulse energy. On the contrary, when varying the pulse duration from 20 to 60 fs at a fixed pulse energy, we did not observe any systematic change of the CSD, indicating that in this regime ionization level is defined by the pulse fluence rather than the intensity. The measured ion kinetic energies for a given charge state, however, exhibit the opposite trend, depending on the pulse energy, we did not observe any systematic change of the CSD, indicating that in this regime ionization level is defined by the pulse fluence rather than the intensity. The measured ion kinetic energies for a given charge state, however, exhibit the opposite trend, depending on the pulse energy, we did not observe any systematic change of the CSD, indicating that in this regime ionization level is defined by the pulse fluence rather than the intensity. The measured ion kinetic energies for a given charge state, however, exhibit the opposite trend, depending on the pulse energy, we did not observe any systematic change of the CSD, indicating that in this regime ionization level is defined by the pulse fluence rather than the intensity. The measured ion kinetic energies for a given charge state, however, exhibit the opposite trend, depending on the pulse energy, we did not observe any systematic change of the CSD, indicating that in this regime ionization level is defined by the pulse fluence rather than the intensity. The measured ion kinetic energies for a given charge state, however, exhibit the opposite trend, depending on the pulse energy, we did not observe any systematic change of the CSD, indicating that in this regime ionization level is defined by the pulse fluence rather than the intensity. The measured ion kinetic energies for a given charge state, however, exhibit the opposite trend, depending on the pulse energy, we did not observe any systematic change of the CSD, indicating that in this regime ionization level is defined by the pulse fluence rather than the intensity.

1This work is supported by the Chemical Science, Geoscience, and Bio-Science Division, Office of BES, Office of Science, U. S. DOE.

11:12AM H7.00003 X-ray and Laser-Induced Fragmentation of 2,6- and 3,5-difluoroiodobenzene1. UTUQ ABLIKIM, FARZANEH ZIAEE, RAJESH KUSHWAHANA, ARTEM RUDENKO, DANIEL ROLLES, J. R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, KS, CEDRIC BOMME, EVGENY SAVELYEV, Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany, HUI XIONG, NORA BERRAH, Department of Physics, University of Connecticut, Storrs, CT, TIMUR OSIPOV, SLAC National Accelerator Laboratory, Menlo Park, CA — Studying the intramolecular dynamics of complex (bio-) molecules is challenging both theoretically and experimentally. These large molecules typically exhibit multiple structural isomers, which are distinct species with different physical and chemical properties. We carried out coincidence momentum imaging experiments on gas-phase 2,6- and 3,5-difluoroiodobenzene isomers, using both soft X-rays and ultrafast lasers. Using the momentum correlation between iodine and fluorine cations in three-fold coincidence channels, we can distinguish the two isomers experimentally. We also find that the majority of the many-body fragmentations happen in a two-step process, where the iodine-carbon bond is broken first and the second-step Coulomb explosion occurs when the metastable C6H5F2+ dication fragments into smaller ionic species.

1Supported by DOE Award Number DE-FG02-86ER13491(Kansas group), Award Number DE-SC0012376 (U Conn group). D.R. acknowledges Helmholtz Young Investigator program from DESY, U.A. acknowledges Advanced Light Source Doctoral fellowship from LBNL.
short-pulse XUV ionization of neon.


1Supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, US Dept of Energy, Contract DE-AC02-06CH11357.

11:36AM H7.00005 Rotational coherence as an alternative to coincidence techniques at x-ray free electron lasers¹

RYAN COFFEE, KAREEM HEGAZY, NICK HARTMANN, PETER WALTER, TIMUR OSIPOV, SLAC, ANTON LINDAHJ, Qamrock Research, WOLFRAM HELML, TU Munich, MARKUS ILCHEN, ANDREAS GALLER, JIA LIU, JENS BUCK, EuroXFEL, IVAN SHEVCHEK, JENS VIEFAUS, DESY, GREGOR HARTMANN, ANDRE KNEIE, PHILIPP DEMEKHIN, U Kassel, LUDGER INHESTER, ZHENG LI, BEATA ZIAJA-MOTYKA, CFEL, NIKITA MEDVEDEV, Czech Acad. of Sci., CHRISTOPH BOSTEDT, ANL, RENAUD GUillimin, MARC SIMON, CNRS, MARIA NOVELLA-PIANCASTELLI, Uppsala U., CATALIN MIRON, ELLI-DC, LCLS-AMOIO314 TEAM. We demonstrate an alternative approach to coincidence particle detection, based on impulsive rotational Raman excitation, for molecular frame measurements at x-ray FELs. A train of 8 infrared laser pulses induces the lab-frame observable coherence. At a field-free alignment revival, we register the angle-resolved laboratory frame Auger and photo-electron spectral feature variations with the tumbling molecular body frame. The time and angle dependence of the electron emission patterns that constrain theory are amenable to large numbers of interactions per pulse and, more importantly, has no axial recoil requirement for kinematic reconstruction. We see this as a method to bypass experimental challenges at XFELs by accepting new experimental data [3].

¹The Linac Coherent Light Source (LCLS) is supported by the U.S. DoE-BES Contract No. DE-AC02-76SF00515.

11:48AM H7.00006 Coherent control of the photoelectron angular distribution in short-pulse XUV ionization of neon.¹

N. DOUGUET, K. BARTSCHAT, Drake University, A. N. GRUM-GRZHIMAILO, E. V. GRYZLOVA, E. I. STARELSKAYA, Moscow State University — Light-induced coherent control of the photoelectron angular distribution (PAD) in neon was recently achieved using the Free-Electron Laser (FEL) at FERMI [1]. To gain a better understanding of these processes, which promise a rich field of possibilities in the control of matter, we investigated two-pathway interferences in the ionization of neon induced by the fundamental and second harmonic of a femtosecond XUV pulse when either $(2p^53s^1)^1P$ or $(2p^53s^1)^3P$ are chosen as intermediate states to enhance the two-photon ionization probability. Using a time-dependent approach supported by a perturbative formalism, we analyze the effects of varying the fundamental frequency, intensity ratio between harmonics, and carrier envelope phase. Our results are compared with new experimental data [3]. We also discuss the additional degree of freedom provided by adding an infrared field [4] and comparing the PADs of the sidebands obtained by time-dependent calculations and the strong-field approximation. [1] K. C. Prince et al., Nature Photon. 10 (2016) 176. [2] N. Douguet et al., Eur. Phys. J. D 71 (2017), in press. [3] G. Sansone et al., private communication (2017). [4] N. Douguet, A. N. Grum-Grzhimailo, and K. Bartschat, Phys. Rev. A 95 (2017) 013407.

¹Work supported by the NSF under PHY-1403245 and XSEDE-090031.

12:00PM H7.00007 Time and momentum-resolved phonon decay³

DAVID REIS, Stanford PULSE Institute — The high brightness of x-ray free-electron lasers provides us a unique opportunity to measure lattice dynamics directly in the time domain and out of equilibrium. As a first step in this direction we demonstrate how ultrafast optical excitation creates temporal coherences in the mean-square phonon displacements spanning the Brillouin zone by a second-order squeezing process. This leads to broad-bandwidth high-resolution measurements of the phonon dispersion without the need for high-resolution monochromators or analyzers. We will also show how anharmonic phonon decay can be viewed as a parametric squeezing process, and present first momentum-resolved measurements of the downconversion of a coherent phonon into pairs of high-wavevector acoustic modes, information that cannot be obtained by spectroscopic measurements in the frequency domain.

³Supported by the Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division, under Contract DE-AC02-76SF00515.

Wednesday, June 7, 2017 10:30AM - 12:30PM – Session H9 Long Range Interactions II 315 - Georg Raithel, University of Michigan

10:30AM H9.00001 Strongly dipolar Bose gases, Krzysztof Jachymski, Univ Stuttgart, Rafal Oldziejewski, Center for Theoretical Physics, Polish Academy of Sciences — Strongly dipolar Bose gases can form liquid droplets stabilized by quantum fluctuations. In a theoretical description of this phenomenon, the low-energy scattering amplitude is utilized as an effective potential. We show that for magnetic atoms corrections with respect to the Born approximation should be included in theoretical description. We derive a modified pseudopotential using a realistic interaction model. We then discuss the construction of the effective low-energy Hamiltonian for trapped systems with long-range interactions. Our results are relevant to recent experiments with erbium and dysprosium atoms.

10:42AM H9.00002 Dipolar dark solitons, Kazimierz Rzazewski¹, Center for Theoretical Physics PAN — We study dark soliton-like excitations in the BEC dominated by long range dipolar forces. We do it in a one dimensional ring geometry, in a 1D and 3D elongated harmonic trap. We show that these solitons interact at a distance and undergo inelastic collisions. We also show that in the harmonic trap, in contrast with solitons in the contact interacting gas, the oscillation frequency depends on the strength of interaction. We also determine the boundary of stability of these excitations.

¹al. Lotnikow 32/46, 02-608 Warsaw, Poland
11:06AM H9.00004 Dipolar lattice bosons in the presence of long-range hopping, CHAO
ZHANG, Univ of Oklahoma, ARGAHAVAN SAFAVI-NAINI, JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, 440 UCB, Boulder, CO 80309, USA, BARBARA CAPOGROSSO-SANSONE, Department of Physics, Clark University, Worcester, MA 01610, USA — We report on numerical results based on quantum Monte Carlo simulations of a system of two-dimensional hard-core lattice bosons in the presence of long-range hopping and long-range two-body interactions resulting from dipole-dipole interactions. This is equivalent to the XXZ model in the presence of dipolar interactions which can be realized by a lattice gas of polar molecules, creating a flexible platform for the study of quantum magnetism. The system features three phases: a superfluid, a supersolid, and a checkerboard solid. Next we mimic the current experimental conditions, that is a lattice of polar molecules away from unit filling, by adding static disorder. Under these conditions we study the localization of particles and the stabilization of a disorder-induced insulating phase.  

11:18AM H9.00005 Excitations of dipolar quantum droplets, RYAN WILSON, US Naval Academy, DANNY BALLIE, P. BLAIR BLAKIE, University of Otago — A wave of exciting experiments with atomic Dysprosium and Erbium have demonstrated the stabilization of a collapsing dipolar Bose-Einstein condensate into long-lived droplet states, which can exist without the support of an external trapping potential. This stabilization is likely due to the unique effects of beyond mean-field quantum fluctuations in dipolar systems. We study the elementary excitations of these droplets using an appropriately modified Bogoliubov theory, for both trapped and free droplets. Interestingly, these droplets support the number of which is found to increase with increasing quantum scattering length. We analyze the properties of these excitations, and discuss their implications for modern experiments with dipolar gases.

11:30AM H9.00006 Manifestations of dipolar collisions in thermal and BEC gases of dysprosium, YUJIN TANG, Stanford University, ANDREW SYKES, LPTMS, CNRS, Univ.Paris Sud, Université Paris-Saclay, NATHANIEL BURDICK, Stanford University, DMITRY S. PETROV, LPTMS, CNRS, Univ.Paris Sud, Université Paris-Saclay, BENJAMIN LEV, Stanford University — Ultracold and quantum gases of dysprosium provide the opportunity to explore the physics of strongly dipolar gases. In this talk, we report on two recent experiments that highlight this physics. The first is a direct measurement of collisions between two Bose-Einstein condensates with strong dipolar interactions. A collision halo corresponding to the two-body differential scattering cross section is observed. The results demonstrate a novel regime of quantum scattering, relevant to dipolar interactions, in which a large number of angular momentum states become coupled during the collision. We perform Monte Carlo simulations to provide a detailed comparison between theoretical two-body cross sections and the experimental observations. The second is a measurement of the anisotropic expansion of ultracold bosonic dysprosium gases at temperatures above quantum degeneracy. We develop a theory to express the post-expansion aspect ratio in terms of temperature and microscopic collisional properties by incorporating Hartree-Fock mean-field interactions, hydrodynamic effects, and Bose-enhancement factors. Our results extend the utility of expansion imaging by providing accurate thermometry for dipolar thermal Bose gases.

11:42AM H9.00007 Dilute magnetic droplets of a bosonic erbium quantum fluid, LAURIANE CHOMAZ, SIMON BAIER, DANIEL PETTER, GIULIA FARAONI, JAN-HENDRIK BECHER, RICK VAN BIJNEN, MANFRED J. MARK, FRANCESCA FERLAINO, University of Innsbruck — Due to their large magnetic moment and exotic electronic configuration, atoms of the lanthanide family, such as dysprosium (Dy) and erbium (Er), are an ideal platform for exploring the competition between inter-particle interactions of different origins and behaviors. Recently, a novel phase of dilute droplet has been observed in an ultracold gas of bosonic Dy when changing the ratio of the contact and dipole-dipole interactions and setting the mean-field interactions to slightly attractive. This has been attributed to the distinct, non-vanishing, beyond-mean-field effects in dipolar gases when the mean interaction cancels. Here we report on the investigation of droplet physics in fluids of bosonic Er. By precise control of the scattering length, we quantitatively probe the Bose-Einstein condensate (BEC)-to-droplet phase diagram and the rich underlying dynamics. In a prototypical geometry, we observe a crossover from a BEC to a single macro-droplet, prove the stabilizing role of quantum fluctuations and characterize the special dynamical properties of the droplet. In an oblate geometry, we observe the formation of assemblies of tinier droplets arranged in a chain and explore the special state dynamics following a quench of $a$, marked by successive merging and reformation events.

11:54AM H9.00008 Quantum Dynamics in the HMF Model, RYAN PLESTID, DUNCAN O’DELL, McMaster University — The Hamiltonian Mean Field (HMF) model represents a paradigm in the study of long-range interactions but has never been realized in a lab. Recently Shutz and Mori (PRL 113) have come close but ultimately fallen short. Their proposal relied on cavity-induced interactions between atoms. If a design using cold atoms is to be successful, an understanding of quantum effects is essential. We will outline the natural quantum generalization of the HMF assuming a BEC by using a generalized Gross-Pitaevskii equation (gGPE). We will show how quantum effects modify features which are well understood in the classical model. More specifically, by working in the semi-classical regime (strong interparticle interactions) we can identify the universal features predicted by catastrophe theory dressed with quantum interference effects. The stationary states of gGPE can be solved exactly and are found to be described by self-consistent Mathieu functions. Finally, we will discuss the connection between the classical description of the dynamics in terms of the Vlasov equation, and the gGPE.

1We would like to thank the Government of Ontario’s OGS program, NSERC, and the Perimeter Institute of Theoretical Physics
12:06PM H9.00009 Localization of quantum particles with long-range hopping in finite-sized lattices1, JOSHUA T CANTIN, Univ of British Columbia, TIANRUI XU, Univ of California, Berkeley, ROMAN V KREMS, Univ of British Columbia — Non-interacting particles with long-range hopping are known to be delocalized in disordered systems of infinite size. It is thus natural to assume that such particles can traverse any finite-sized lattice. We show that this is not true. Particles with long-range hopping can localize in lattices of finite size, even macroscopically finite. This leads to a rather unusual phenomenon: quantum particles can transverse a disordered lattice of size 10^4, but not a lattice of size 4. As evidence for this, we demonstrate spatial localization in dynamical calculations at long-times, inverse participation ratio distributions characteristic of localized systems, and log-normal fluctuations of the wavefunction. We map out the phase diagram for a particle with long-range hopping in a 3D lattice as a function of on-site disorder strength and filling fraction. Using scaling arguments, we determine the size-dependence of the localization-diffusion crossover line as a function of the system size, which predicts localization in macroscopically finite systems.

1This work was funded by NSERC of Canada.

12:18PM H9.00010 Trapping Ions in an optical lattice for quantum simulation, MATT GRAU, CHRISTOPH FISCHER, OLIVER WIFFLER, JONATHAN HOME, ETH Zurich — Quantum many-body spin Hamiltonians are important tools for describing condensed matter systems, but many such Hamiltonians are difficult to simulate on classical computers. Quantum simulation offers an avenue for overcoming these limitations. Arrays of trapped ions are an attractive platform for quantum simulation due to the high level of control combined with the intrinsic long-range Coulomb interaction that can be used to engineer tunable spin-spin couplings. However, varying lattice geometry is challenging with current trapping techniques. We are developing a new apparatus to trap arrays of ions in optical lattices for the purpose of quantum simulation. This should allow trapping two and three-dimensional crystals with a designed geometry. We present results of simulations of equilibrium positions and normal modes of such a system, which indicate that in a first design arrays of around 40 ions could be trapped with ion-ion distances of under 10 microns, and also with low residual heating rates due to off-resonant scattering and laser fluctuations. By using Magnesium ions, we expect to be able to cool and image the ions while trapped in a deep optical lattice formed by a high finesse optical cavity. Experimental progress towards these goals will be described.

Wednesday, June 7, 2017 2:00PM - 4:00PM — Session J2 Strongly interacting quantum gases 306-307 - Martin Zwierlein, Massachusetts Institute of Technology

2:00PM J2.00001 Impurities strongly interacting with a Fermi sea1, RUDOLF GRIMM, IQOQI Innsbruck, Austrian Academy of Sciences — Impurities immersed in a Fermi sea show a wealth of exciting phenomena when the interaction is tuned via a Feshbach resonance. We report on experiments with fermionic or bosonic potassium atoms in a large, deeply degenerate Fermi sea of 40Li. In the case of fermionic impurities (41K), we focus on the low-concentration limit and apply a Ramsey technique to study the fast response of the impurities to sudden changes of the interaction strength [Cetina et al., Science 354, 96 (2016)]. For near-resonant conditions, we observe the formation dynamics of quasiparticles (Fermi polarons) in real time and, in the resonance case, an interference between the repulsive and the attractive quasiparticle branch. For bosons (40K) in the Fermi sea, a small condensate is formed, which then acts as a mesoscopic impurity. For strongly repulsive conditions we find phase separation, such that the condensate is in the center of the Fermi sea and compressed by the fermion pressure. We show that three-body recombination can be used to probe the spatial overlap at the interface between the two species. The comparison with a theoretical model reveals behavior beyond the local-density approximation. We also study collective modes of the BEC in the Fermi gas across the transition to the phase-separated state, demonstrating dramatic changes of the collective mode frequencies.

1Austrian Science Fund FWF, SFB BoQuS (F4004-N23)

2:30PM J2.00002 Strongly interacting bulk Bose gases1, ZORAN HADZIBABIC, University of Cambridge — I will give an overview of our recent experiments on strongly interacting Bose gases, produced in either a harmonic trap or the uniform potential of an optical box trap. Our recent work includes the interferometric measurement of the three-body contact in the unitary Bose gas, the measurement of the quantum depletion in a homogeneous strongly-interacting BEC, and studies of the universal decay dynamics in the homogeneous degenerate unitary Bose gas.

1ERC, EPSRC, ARO, AFOSR, Royal Society

3:00PM J2.00003 Bloch oscillations in the absence of a lattice, HANNS-CHRISTOPH NAEGEL, University of Innsbruck — We experimentally study the dynamics of strongly-correlated quantum many-body systems of ultracold atoms with particular focus on bosons confined to one-dimensional geometry. We have investigated the quantum motion of an impurity atom that is immersed in a strongly interacting Bose liquid and is subject to an external force [1]. We find that the momentum distribution of the impurity exhibits characteristic Bragg reflections at the edge of an emergent Brillouin zone. While Bragg reflections are typically associated with lattice structures, in our strongly correlated quantum liquid they result from the interplay of short-range crystalline order and kinematic constraints on the many-body scattering processes in the one-particle excitation spectrum. As a consequence, the impurity exhibits periodic dynamics that we interpret as Bloch oscillations. These arise even though the quantum liquid is translationally invariant. Our observations are supported by large-scale numerical simulations. [1] F. Meineert et al., arXiv:1608.08200 (2016).

3:30PM J2.00004 Bragg spectroscopy of near-homogeneous Fermi gases, CHRISTOPHER VALE, Swinburne Univ of Tech — We have used Bragg spectroscopy to probe the excitation spectra of strongly interacting Fermi gases in the low and high momentum regimes. Using two laser beams focused into the center of trapped clouds we obtain Bragg spectra of systems with varying lattice geometry. As Bloch oscillations. These arise even though the quantum liquid is translationally invariant. Our observations are supported by large-scale numerical simulations. [1] F. Meineert et al., arXiv:1608.08200 (2016).
investigate the time required by the phase to homogenize between two condensates. We control both the number of condensates to be merged (from one to twelve) and their merging formation of supercurrents depending on the relative phases of the domains. As a next step of this study, we now design ourselves the patches domains of phase are created during the quench, with a characteristic size depending of its duration. In our case this results in a stochastic transition in an annular trap geometry, inducing the formation of supercurrents. Their magnitude and direction were detected by measuring through a second-order phase transition. This was studied in our group with a temperature quench across the normal-to-superfluid phase transitions — An important step in the study of out-of-equilibrium physics is the Kibble-Zurek theory which describes a system after a quench evolving it in time leads to substantial intricately-structured correlations between sites — even without interactions during the dynamics. Because including interactions challenges existing theoretical methods (both numerical and analytic) we are developing tools that exploit the nature of the high-temperature initial conditions to calculate these dynamics. We will describe and analyze the accuracy of one such method, a dynamic numerical linked cluster expansion, and its applications to spin systems relevant to cold atoms.

2:24PM J3.00003 Quenches from finite-temperature ultracold matter — IAN G. WHITE, KADEN R. A. HAZZARD, Rice University — Although interaction quenches are known to drive interesting dynamics, much prior work has focused on quenches initiated from states that are near the ground state. In contrast, experiments in ultracold matter - from fermionic atoms in optical lattices to dipolar molecules - are often outside this regime, necessitating the study of quenches from higher temperature states. Although in equilibrium, high temperatures are usually associated with trivial, structureless, disordered states, driving such states out of equilibrium can lead to rich behavior. For example, we have recently shown that starting from a hot, uncorrelated state of fermions in an optical lattice and evolving it in time leads to substantial correlations between sites — even without interactions during the dynamics. Because including interactions challenges existing theoretical methods (both numerical and analytic) we are developing tools that exploit the nature of the high-temperature initial conditions to calculate these dynamics. We will describe and analyze the accuracy of one such method, a dynamic numerical linked cluster expansion, and its applications to spin systems relevant to cold atoms.

2:36PM J3.00004 ABSTRACT WITHDRAWN —

2:48PM J3.00005 Non-equilibrium phase transitions in a driven-dissipative system of interacting bosons — JEREMY T. YOUNG, Joint Quantum Institute, MICHAEL FOSS-FEIG, Army Research Lab, ALEXEY V. GORSHKOV, Joint Quantum Institute, MOHAMMAD F. MAGREBNI, Michigan State University — Atomic, molecular, and optical systems provide unique opportunities to study simple models of driven-dissipative many-body quantum systems. Typically, one is interested in the resultant steady state, but the non-equilibrium nature of the physics involved presents several problems in understanding its behavior theoretically. Recently, it has been shown that in many models, it is possible to map the steady-state phase transitions onto classical equilibrium phase transitions. In the language of the Keldysh field theory, this relation typically only becomes apparent after integrating out massive fields near the critical point, leaving behind a single massless field undergoing near-equilibrium dynamics. In this talk, we study a driven-dissipative XXZ bosonic model and discover critical points at which two fields become gapless. Each critical point separates three different possible phases: a uniform phase, an anti-ferromagnetic phase, and a limit cycle phase. Furthermore, a description in terms of an equilibrium phase transition does not seem possible, so the associated phase transitions appear to be inherently non-equilibrium.
3:24PM J3.00008 Spin diffusion of ultracold $^{87}$Rb in inhomogeneous spin-dependent potentials

JEFFREY MCGUIRK, DORNA NIROOMAND, SEAN GRAHAM, Simon Fraser University — We study the effect of an inhomogeneous differential potential on the relaxation dynamics of spin structures in ultracold $^{87}$Rb near degeneracy. In a homogeneous differential potential, the diffusion of spin inhomogeneities has been shown to exhibit instabilities that interconvert longitudinal and transverse spin. These instabilities couple transverse and longitudinal spin dynamics and lead to large-scale coherent spin fluctuations. However, the addition of a spatially inhomogeneous spin-dependent potential is predicted to suppress this instability and decouple the spin dynamics. We present progress towards observing this phenomenon by measuring the diffusion of a longitudinal domain wall in the presence of an optically-created inhomogeneous differential potential. We observe trapping of a transverse spin wave within the domain wall and a separation of timescales for transverse and longitudinal spin relaxation, indicative of anisotropic spin diffusion. We also study the role of coherence in these dynamics.

3:36PM J3.00009 Faster than Exponential Decay of Out-of-Time-Ordered Correlators

LEA SANTOS, Yeshiva University, USA, E. JONATHAN TORRES-HERRERA, Benemérita Universidad Autónoma de Puebla, Mexico — In studies of nonequilibrium quantum dynamics, several attempts have been made to connect the exponential decay rate of the Loschmidt echo and the survival probability with the classical Lyapunov exponent. The same idea has been recently extended to the out-of-time-ordered four-point correlator (OTOC). We show that the OTOC, just like the survival probability, may in fact show faster than exponential decays. This occurs not only for chaotic many-body quantum systems with level repulsion, but also for integrable models.

3:48PM J3.00010 Parametric Cooling of Ultracold Atoms

MATTISH BOGUSLAWSKI, BHARATH H. M., MARYROSE BARRIOS, MICHAEL CHAPMAN, Georgia Inst of Tech — An oscillator is characterized by a restoring force which determines the natural frequency at which oscillations occur. The amplitude and phase-noise of these oscillations can be amplified or squeezed by modulating the magnitude of this force (e.g. the stiffness of the spring) at twice the natural frequency. This is parametric excitation; a long-studied phenomena in both the classical and quantum regimes. Parametric cooling, or the parametric squeezing of thermo-mechanical noise in oscillators has been studied in micro-mechanical oscillators [1] and trapped ions [2]. We study parametric cooling in ultracold atoms. This method shows a modest reduction of the variance of atomic momenta, and can be easily employed with pre-existing controls in many experiments. Parametric cooling is comparable to delta-kicked cooling [3], sharing similar limitations. We expect this cooling to find utility in microgravity experiments where the experiment duration is limited by atomic free expansion. [1] D. Rugar and P. Grutter, Phys. Rev. Lett., 67:699 (1991) [2] V. Natarajan, et al., Phys. Rev. Lett., 74:2855(1995) [3] H. Ammann, N. Christensen, Phys. Rev. Lett., 78:2088 (1997) T. Kovachy, et al., Phys. Rev. Lett., 114:143004 (2015)

Wednesday, June 7, 2017 2:00PM - 3:48PM –
Session J4 Photoionization, Photodetachment, and Photodissociation

2:00PM J4.00001 K-shell Photodetachment of C$_{n}^-$ Anions

SAMANTHA FONSECA DOS SANTOS, Drake University, A. E. OREL, UC Davis, T. N. RESCIGNO, LBNL — The cross section for inner-shell ionization of the C$_{n}^-$ anion is known to be characterized by a single, prominent 1s $\rightarrow$ kp shape resonance just above the K-edge. More recently, Berrah and coworkers [1] have found similar behavior in the heavier carbon anion chains C$_{n}^-$, n = 2, 3, ...8, but with the added feature that in the longer chains the single peak seen in C$^-$ inner-shell photodetachment splits into multiple peaks, depending on the length of the chain. To understand this finding, we have undertaken a theoretical study of inner-shell photodetachment of the molecular anions using the complex Kohn variational method. Our preliminary results for photodetachment of C$_{3}^-$ and C$_{4}^-$ are found to be in good agreement with experiment and exhibit both bound resonances below threshold and shape resonances above the K-edge. We will also discuss the basic physical mechanism underlying the splitting of the observed shape resonances in these systems.

2:12PM J4.00002 Single Photon Double Ionization of Atomic Oxygen

MADHUSHANI WICKRAMARATHNA, THOMAS GORCZYCA, Western Michigan University, CONNON BALLANCE, Queen’s University Belfast, WAYNE STOLTE, National Security Technologies, SSRL, and ALS — Single photon double ionization cross sections are calculated using an R-matrix with pseudostates (RMPS) method [P. G. Burke, R-matrix Theory of Atomic Collisions, Springer 2011] which was recently applied by Gorczyca et al. (JPB, 46, 195201, 2013) for the double photoionization of helium. With the convergence of these theoretical calculations for the simple case of helium, we extend this methodology to consider the more complex case of oxygen double photoionization. We compare our calculated results with recent measurements at the Advanced Light Source, as well as earlier experimental measurements (Angel and Sampson, PRA, 38, 5578, 1988). Our RMPS results agree well, qualitatively, with the experimental measurements, but there exist outstanding discrepancies to be addressed.

1This project is supported by NASA APRA award NNX17AD41G
2:24PM J4.00003 Double photoionization of H₂ using a hybrid Gaussian-discrete variable representation basis for molecular continuum processes. FRANK L. YIP, California State University-Maritime Academy, C. WILLIAM MCCURDY, UC Davis and Lawrence Berkeley National Lab, THOMAS N. RESCIGNON, Lawrence Berkeley National Lab — A hybrid basis that combines Gaussian basis functions typically used in bound-state molecular electronic structure calculations with a grid-based discrete variable representation (DVR) suitable for continuum processes involving one or more electrons is used to fully describe the double ionization of molecular H₂ by a single photoabsorption. Comparison will be made with the most detailed information that has been calculated and measured for this Coulomb explosion: the triply differential cross sections that relate the angular distribution and energy sharing of all of the particles in the frame of the molecule. The advantages of utilizing this hybrid basis for double ionization processes beyond this simplest molecular target will be highlighted.

1Work supported by the National Science Foundation, No. PHY-1509971 and the US Dept. of Energy, Division of Chemical Sciences Contract DE-AC02-05CH11231

2:36PM J4.00004 Photodetachment microscopy in time-dependent fields. HARINDRANATH AMBALAMPITIYA, ILYA FABRIKANT, University of Nebraska-Lincoln — Photodetachment microscopy studies spatial distribution of photodetected electrons in static electric fields. The theory of this phenomenon was recently extended [1] to time-dependent electric fields in the terahertz range. In the present paper we use the semiclassical propagator (time-dependent Green’s function) for investigation of temporal and spatial interference of classical electron trajectories in ac fields within a broad frequency range from radio to terahertz frequencies. The chosen length scale corresponds to the geometry of a traditional photodetachment microscopy experiment [2]. The propagator approach allows us to treat singularities in temporal and spatial distributions due to bifurcations, when the trajectories emerge in pairs from frequencies. The propagator method comes in two flavors: simple and full simulations, where the simple model ignores dissociation and full simulations take dissociation into account. Both methods convolute a tunable laser with an underlying rovibronic spectrum to find corresponding transition rates. By fitting the simulated spectrum to the experimental spectrum, physical constants and information, such as transition frequency, transition dipole moments, rotational constants, and dissociation pathway, is extracted. Assuming the Born-Oppenheimer Approximation (BOA), the vibronic transitions require a 687 cm⁻¹ shift from their theoretically predicted values to match both CaH⁺ and CaD⁺. Both transition dipoles and rotational constants match relatively well with theory, and we will describe possible dissociation paths through excited Σ and Π states.

1Supported by the US National Science Foundation.

2:48PM J4.00005 Molecular Simulations of Multi-Photon Dissociation of CaH⁺ and CaD⁺. SMITHA JANARDAN, AARON CALVIN, JOHN CONDOLUCI, RENE RUGANGO, GANG SHU, KENNETH BROWN, Georgia Inst of Tech — The vibronic and rovibronic 1Σ⁺, ν = 0 → 2Σ⁺, ν = 0, 1, 2, 3 transitions are measured using molecular simulations of resonance enhanced multi-photon dissociation (REMPD) of CaH⁺ and CdD⁺. These measurements are vital for measuring rotational state preparation of CaH⁺. The simulation method comes in two flavors: simple and full simulations, where the simple model ignores dissociation and full simulations take dissociation into account. Both methods convolute a tunable laser with an underlying vibronic spectrum to find corresponding transition rates. By fitting the simulated spectrum to the experimental spectrum, physical constants and information, such as transition frequency, transition dipole moments, rotational constants, and dissociation pathway, is extracted. Assuming the Born-Oppenheimer Approximation (BOA), the vibronic transitions require a 687 cm⁻¹ shift from their theoretically predicted values to match both CaH⁺ and CaD⁺. Both transition dipoles and rotational constants match relatively well with theory, and we will describe possible dissociation paths through excited Σ and Π states.

1Acknowledgements: Minori Abe, Chris Seck, Army Research Office (ARO), the National Science Foundation, an ARO Multi-University Research Initiative

3:00PM J4.00006 Intermolecular Coulombic Decay (ICD) Occurring in Triatomic Molecular Dimer. WAEIL ISKANDAR, AVERELL CATTON, BISHWANATH GAIRE, ELIO CHAMPENOIS, KIRK LARSEN, NI-RANJAN SHIVARAM, Lawrence Berkeley National Laboratory, ALI MORADMAND, Auburn University, TRAVIS SEVERT, Kansas State University, JOSHUA WILLIAMS, University of Nevada, DANIEL SLAUGHTER, THORSTEN WEBER, Lawrence Berkeley National Laboratory — For over two decades, the production of ICD process has been extensively investigated theoretically and experimentally in different systems bounded by a weak force (ex. van-der-Waals or Hydrogen force). Furthermore, the ICD process has been demonstrated a strong implication in biological system (DNA damage and DNA repair mechanism) because of the production of genotoxic low energy electrons during the decay cascade. Studying large complex system such as triatomic molecular dimer may be helpful for further exploration of “Auger electron driven cancer therapy”. The present experiment investigates the dissociation dynamics happened in collision between a photons and CO₂ dimer. We will focus more specifically on the CO₂⁺+CO₂ enrichmentment channel and the detection in coincidence of the two ionic fragments and the two electrons will be done using a Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS). The measurements of the Kinetic Energy Release of the two fragments and the relative angular distribution of the electrons in the molecular frame reveal that the ICD is the only mechanism responsible for the production of this fragmentation channel.

3:12PM J4.00007 Photoionization and Recombination of Astrophysically Important ION CI II⁺. SULTANA NAHAR, Ohio State Univ - Columbus — Photoionization of CI II → e + CI III is of importance in nebular models since it determines the fractional abundance of [CI III]. Intensity ratios of collisionally excited forbidden [CI III] lines are electron density diagnostics, analogous to the prominent [S II] lines. I will present extensive relativistic calculations using Breit-Pauli R-Matrix (BPRM) method aimed at obtaining photoionization cross section up to high energies, and unified recombination cross sections including radiative and di-electronic components (RR and DR). The configuration interaction expansion of the target wavefunctions comprise of 3s₂2p³, 3s₂p⁵, 3s²3p²3d, 3s²3p²4s, 3s²3p²2p₂, 3s²3p²4p, 3s²3p²2d, 3s²3p²5s, 3p²3d, 3s²3p²3f₂, 3p². The preliminary photoionization cross sections of the 8 lowest levels, 3s²3p³(₂P₁/₂, ₁D₂, ₁S₀, ₃S₀, ₃P₁) of CI II are compared with the existing measured values at ALS and found to reproduce all features in the observed spectrum.

1NSF, DOE, OSC
3:24PM J4.00008 New Calculations for Plasma Opacities: Atomic Processes, Equation-of-State, and Astrophysical Models\textsuperscript{1} . ANIL PRADHAN, SULTANA NAHAR, LIANSHUI ZHAO, CHRIS ORBAN, Ohio State Univ - Columbus, WERNER EISSNER, Stuttgart U., REGNER TRAMPLEDACH, Space Science Institute — Existing plasma opacities have been brought into question by recent experimental results from the Sandia Z-pinch facility and theoretical works \textsuperscript{[1,2]}. Opacities calculations are complex and entail a nexus of fundamental issues in atomic physics, plasma physics and astrophysics. We report new calculations for iron ions, including ab initio treatment of autoionizing resonances and electron impact broadening for the first time, that result in significant opacity enhancements, as measured experimentally and required to reconcile solar abundances with helioseismological models. We discuss related issues of the equation-of-state in the “chemical picture” with realistic atomic description, perturbed by the plasma environment and dissolution of excited levels. We also note important astrophysical applications in stellar interior models and observable parameters.


\textsuperscript{1} NSF, DOE, OSC

3:36PM J4.00009 Strong-Field Molecular Ionization: Suppression Induced by Dimensionality\textsuperscript{1} . YOULIANG YU, BRETT ESRY, J. R. Macdonald Laboratory, Kansas State University, Manhattan, Kansas, 66506 — For highly non-perturbative strong-field dynamics such as tunneling ionization induced by a long-wavelength laser field, reduced-dimensional models are tempting when it comes to numerically solving the time-dependent Schrödinger equation (TDSE). Although such models can often be useful for qualitative predictions, their validity should always be examined. We study the impact of dimensionality for strong-field molecular ionization by solving the TDSE for H\textsubscript{2}\textsuperscript{+} with both a one-dimensional model and a full-dimensional Hamiltonian. We observe in both cases that the fixed-R ionization yield is suppressed relative to the atomic yield to fairly large internuclear distances for a range of laser wavelengths. Similar observations of suppression at 800 nm have been explained as frustrated tunneling ionization. Surprisingly, we find that the suppression is much stronger in one dimension than in three with the result that the one-dimensional ionization yield asymptotes to within 1\% of the atomic yield only when R approaches about 250 a.u. for 800 nm. In three dimensions, this agreement is reached already at R=90 a.u. We will explore these and other dependencies on dimensionality for this problem.

\textsuperscript{1} Supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy

Wednesday, June 7, 2017 2:00PM - 4:00PM –
Session J5 Ultrafast Dynamics Explored with XUV and Xray Pulses 310 - Luca Argenti, University of Central Florida

2:00PM J5.00001 Neutral Excited State Dynamics Studied with Time-Resolved UV-VUV Pump-Probe Experiments\textsuperscript{1} . YUSONG LIU, SPENCER HORTON, State University of New York at Stonybrook, PRATIP CHAKRABORTY, SPIRIDOULA MATSIKA, Temple University, THOMAS WEINACHT, State University of New York at Stonybrook — We have conducted UV/VUV pump-probe experiments to study excited state dynamics in polyatomic molecules. We are particularly interested in the competition between internal conversion and dissociation or population trapping of prototypical molecular systems. Here we present measurements of dynamics in pyrrole and uracil. Our measurements for pyrrole, in conjunction with electronic structure calculations, indicate that pyrrole undergoes rapid internal conversion to the ground state in less than 300fs. We find that internal conversion to the ground state dominates over dissociation. In uracil, our measurements indicate that there is substantial population trapping in the excited state in addition to rapid internal conversion back to the ground state.

\textsuperscript{1} Department of Energy

2:12PM J5.00002 Vibrationally Assisted Below Threshold Ionization . SPENCER HORTON, YUSONG LIU, State University of New York at Stony Brook, PRATIP CHAKRABORTY, SPIRIDOULA MATSIKA, Temple University, THOMAS WEINACHT, State University of New York at Stonybrook — We performed time-resolved UV pump (4.8 eV) and VUV probe (8 eV) measurements of internal conversion of 1,3-cyclohexadiene (CHD). Our measurements reveal a substantial ionization of the hot ground state, following internal conversion, despite the fact that our probe photon energy is below the ionization potential (8.25 eV). With the aid of electronic structure calculations, we interpret our results in terms of vibrationally assisted below threshold ionization, where vibrational energy is converted to electronic energy. The effect relies both on having vibrational modes which can lead to this conversion, and exciting these modes during the internal conversion. We contrast our measurements in CHD with another similar molecule, 1,3-cyclooctadiene (COD), for which we don’t see the effect.

2:24PM J5.00003 Multidimensional electron-nuclear wavepacket dynamics via Time-, Energy- and Angle-resolved Photoelectron Spectroscopy . K. VEYRINAS, V. MAKHUA, A. E. BOGUSLAVSKYI, University of Ottawa, R. FORBES, University of Ottawa, University College London, I. WILKINSON, Helmholtz-Zentrum Berlin, National Research Council, Ottawa, Canada, D. MOFFATT, R. LAUSTEN, National Research Council, Ottawa, Canada, A. STOLOW, University of Ottawa, National Research Council, Ottawa, Canada — Generating and probing a coherent superposition of coupled vibrational-electronic (vibronic) states — a multidimensional wavepacket — remains a challenging problem in molecular dynamics. Here, we present recent results using time-resolved photoelectron velocity map imaging (VMI) of complex vibronic wavepacket dynamics in the NO molecule following femtosecond single photon excitation in the vacuum ultraviolet (VUV) range ($\lambda_{\text{pump}} = 160$ nm, 80 fs). The induced ultrafast dynamics, involving highly excited valence and Rydberg states, is probed by single photon ionization ($\lambda_{\text{probe}} = 400$ nm, 40 fs). Varying the pump-probe time delay, the emitted photoelectrons are detected in a VMI spectrometer for time-, energy- and angle-resolved photoelectron spectroscopy. We observe that the different final vibrational states of the NO$^{+}$($X^1\Sigma^+_g$) cation, onto which this evolving vibronic wavepacket is projected, reveal different time dependences for the kinetic energy distribution and the laboratory frame photoelectron angular distribution (LFPAD). In particular, we observe unusually strong oscillations in the $\beta_4$ asymmetry parameter, indicating sensitivity to the higher angular momentum components of the electronic aspect of this complex vibronic wavepacket.
2:36PM J5.00004 Molecular Wavepacket Dynamics at a Jahn-Teller Conical Intersection, VARUN MAKHUA, KEVIN VEYRINAS, ANDREY E. BOGUSLAVSKIY, University of Ottawa, RUARIDH FORBES, University College London, University of Ottawa, IAIN WILKINSON, Heinz-Holzl-Zentrum Berlin, National Research Council, Ottawa, Canada, DOUG MOFFATT, SIMON NEVILLE, MICHAEL SCHUURMAN, RUNE LAUSTEN, National Research Council, Ottawa, Canada, ALBERT STOLOW, University of Ottawa, National Research Council, Ottawa, Canada — According to the Jahn-Teller theorem, any symmetric configuration of atoms in an electronically degenerate molecular state is unstable and distorts to a configuration of lower symmetry, hence lifting the degeneracy. Jahn-Teller dynamics feature in numerous, highly symmetric systems, such as fullerenes and doped rare-earth magnetites where they underly the phenomenon of colossal magneto-resistance. Here, we use ultrafast time-resolved photoelectron velocity-map imaging (VMI) to study the fundamental Jahn-Teller dynamics in an excited state of isolated ammonia (NH$_3$) molecules. Supersonically cooled NH$_3$ is resonantly excited by a 160 nm, 80 fs pump pulse. A time delayed 400 nm, 40 fs probe pulse photoionizes the molecule and the kinetic energy and angular distribution of the ejected photoelectron is measured as a function of time. Dramatic changes in the time-dependent angular distributions are observed, which reveal details of non-adiabatic wavepacket propagation on the coupled Jahn-Teller potential surfaces.

2:48PM J5.00005 Ultrafast dynamics in photoionized CO$_2$ studied by XUV-IR pump-probe experiments, SEYYED JAVAD ROBATJAZI, SHASHANK PATHAK, PEARSON WRIGHT LEE, KANAKA RAJU PANDIRI, JEFF POWELL, XIANG LI, BALRAM KADERIYA, ITZIK BEN-ITZHAK, DANIEL ROLLES, ARTEM RUDENKO, Kansas State Univ — The dynamics of CO$_2$ in the gas phase. The data gives a glimpse of electronic and nuclear relaxation pathways upon resonant oxygen K-edge excitation proceeding on time scales 40 fs. The experimental efforts are accompanied by theoretical work describing the time-resolved core-level photoemission with polychromatic X-ray micro-probe at the Advanced Photon Source.

3:00PM J5.00006 Observing the non-adiabatic photodissociation of neutral excited CH$_3$OH with few-femtosecond sensitivity, Elio Champenois, LOREN GREENMAN, NIRANJAN SHIVARAM, Kirik Larsen, Ali Belkacem, Lawrence Berkeley National Laboratory — The ultrafast dissociation dynamics of neutral excited methanol (CH$_3$OH) have been explored using time-resolved photoelectron imaging and excited state potential energy surface calculations. Nuclear motions on the initially populated $2 1A^+ (S2)$ state, through a region of strong non-adiabatic coupling, and on a dissociative state are resolved within the first 15 femtoseconds following excitation. A CH$_3$ hydrogen-loss channel is also observed and found to depend more strongly on OH rather than CH$_3$ deuterium. The measurements and calculations indicate that the previously ignored 1 $1A^+ (S3)$ state, rather than the 1 $1A^+ (S1)$ state, plays an important role in these dynamics.

3:12PM J5.00007 Probing molecular dynamics in solution with x-ray valence-to-core spectroscopy, Gilles Doumy, Anne Marie March, MING-FENG TU, Andre Al Haddad, Stephen Southworth, Linda Young, Donald Walko, Christoph Bostedt, Argonne National Laboratory — Hard X-ray spectroscopies are powerful tools for probing the electronic and geometric structure of molecules in complex or disordered systems and have been particularly useful for studying molecules in the solution phase. They are element specific, sensitive to the electronic structure and the local arrangements of surrounding atoms of the element being selectively probed. When combined in a pump–probe scheme with ultrafast lasers, X-ray spectroscopies can be used to track the evolution of structural changes that occur after photoexcitation. Efficient use of hard x-ray radiation coming from high brilliance synchrotrons and upcoming high repetition rate high brilliance free electron lasers requires MHz repetition rate lasers and data acquisition systems. High intensity content valence-to-Core x-ray emission is directly sensitive to the molecular orbitals involved in photochemistry. We report on recent progress towards fully enabling this photon-hungry technique for the study of time-resolved molecular dynamics, including efficient detection and use of polychromatic x-ray micro-probe at the Advanced Photon Source.

3:24PM J5.00008 Time-Resolved Two-Color X-ray Pump/ X-ray Probe Photoelectron Spectroscopy at LCLS, Andre Al Haddad, Gilles Doumy, Antonio Picon, Maximilian Bucher, Argonne National Lab, TAIS GORKHOVSKY, RYAN COFFEE, MICHAEL HOLMES, JACEK KRZYWINSKI, ALBERTO LUTMAN, AGOSTINO MARINELLI, STEFAN MOELLER, TIMUR OSIPOV, PETER WALTER, DAN RATNER, DIPANWITA RAY, SLAC National Lab, STEPHEN PRATT, LINDA YOUNG, STEPHEN SOUTHWORTH, CHRISTOPH BOSTEDT, Argonne National Lab — Recently, X-ray Free Electron Lasers (XFELs) proved the ability to produce two intense femtosecond x-ray pulses with controlled time delay and color. Combining these unique capabilities with x-ray photoelectron spectroscopy (XPS), a powerful tool for extracting chemical information of a specific site by measuring the binding energy of core electrons, enables femtosecond time-resolved XPS experiments with chemical and site specificity. We will present our X-ray pump/X-ray probe XPS experiment aimed at studying energy flow and relaxation dynamics in CO, i.e., small hetero-nuclear molecules, in the gas phase. The data gives a glimpse of electronic and nuclear relaxation pathways upon resonant oxygen K-edge excitation proceeding on time scales <40 fs. The experimental efforts are accompanied by theoretical work describing the time-resolved core-level photoemission with a time-dependent Schrodinger equation. This work lays the groundwork for further TR-XPS experiments following energy and charge transfer processes upon photo excitation in more complex molecules.

1Supported by the Chemical science, Geosciences, and Bio-science division, Office of Basic Energy Science, Office of science, U.S. Department of Energy. K.R.P. and W.L.P. are supported by National Science Foundation (NSF-EPSCOR) Award No. IIA-1430493.

1Work was supported by the U.S. Department of Energy, Office of Science, Chemical Sciences, Geosciences, and Biosciences Division.
3:36PM J5.00009 Photoinduced charge carrier dynamics at a dye-semiconductor interface probed by picosecond time-resolved X-ray photoelectron spectroscopy1. JOHANNES MAHL, STEFAN NEPP, HENDRIK BLUHM, OLIVER GESSNER, Lawrence Berkeley National Laboratory — We investigate laser-induced charge carrier dynamics at the interface between N3 dye molecules and a film of nanocrystalline ZnO using picosecond time-resolved laser pump–probe experiments. Pumping the sample with 532nm light pulses induces HOMO – LUMO excitations in the dye followed by electron injection into the ZnO conduction band. The subsequent electronic dynamics are marked by an interplay between transient charge carrier densities, corresponding interfacial potentials, and electron-hole recombination rates. Monitoring the picosecond dynamics of a dye-associated photo-line (Cl) and a substrate-associated photo-line (Zn3d), we find that both exhibit transient Rabi oscillations, with different amplitudes and different dynamic trends. The difference between these trends can be described by a bi-exponential decay with time constants of 400ps and around 20ns while the absolute shifts of both photo-lines decay on much longer timescales (tens of hundreds of nanoseconds). These results demonstrate how the element specificity of inner-shell transitions may be employed to gain a local perspective of photo-induced charge carrier dynamics from both sides of the interface. The findings will be discussed within the framework of charge-injection-induced band dynamics and transient interfacial dipoles.

1. J. Mahl acknowledges partial support from the ALS Doctoral Fellowship in Residence Program.

3:48PM J5.00010 Visualizing the femtosecond emergence and picosecond evolution of an anisotropic nanoplasma. C BACELLAR, A CHATTERLEY, F LACKNER, S PEMMARAJU, LBNL, R TANYAG, C BERNANDO, D VERMA, S OCONNELL, USG, M BUCHER, ANL, K FERGUSON, T GORKHOVER, R COFFEE, G COSLOVICH, D RAY, T OSIPOV, SLAC, D NEUMARK, UC BERKELEY, C BOSTEDT, ANL, A VILESOV, USG, O GESSNER, LBNL — The dynamics of strong-field induced nanoplasmas are studied using femtosecond time-resolved X-ray coherent diffractive imaging (CDI) at the Linac Coherent Light Source (LCLS). Intense 800nm laser pulses (≈1017 W/cm2, 50fs) are employed to initiate nanoplasma formation in sub-micron sized helium droplets. Plasma formation and evolution dynamics are probed by femtosecond x-rays pulses (≈100fs, 600eV) across time scales ranging from femtoseconds to hundreds of picoseconds. Anisotropic surface softening is observed within tens of femtoseconds after exposure to the NIR pulse. The softening continues over 300fs, after which the anisotropic surface profile stabilizes with ≈30% larger extension along the laser polarization axis compared to the perpendicular direction. The saturation of the surface width is contrasted by an increase in anisotropic material loss that is twice as pronounced along the laser polarization axis, resulting in significantly distorted shapes with aspect ratios of ≈1.5 and beyond. The results will be discussed within the framework of an anisotropic plasma expansion model that provides new insight into strong-field induced nanoplasma formation and relaxation dynamics.

Wednesday, June 7, 2017 2:00PM - 4:00PM
Session J6 Optomechanics 311-312 - Andrew Geraci, University of Nevada, Reno

2:00PM J6.00001 Proposal for an quantum optomechanical straight-twin engine . KEYE ZHANG, East China Normal University, WEIPING ZHANG, Shanghai Jiao Tong University — We propose a scheme to realize a quantum polarization heat engine in a hybrid microwave-opto-mechanical system. The engine transfers the heat obtained from the effective temperature difference between the microwave and optical cavity fields to the work extracted through the radiation pressure force. In our design a pair of polariton modes works alternately in the quantum Otto cycle, similar to a classical twin-cylinder four-stroke engine. And the other polariton is quasi-dark to suppress the disturbance from the mechanical noise. Different from its classical counterpart, the works from the two polariton modes are correlated in quantum fluctuations.

2:12PM J6.00002 Exploring the thermodynamic limit of optomechanical systems . STEPHEN RAGOLE, Joint Quantum Institute, HAITAN XU, Yale University, JOHN LAWALL, National Institute for Standards and Technology, JACOB TAYLOR, Joint Center for Quantum Information and Computer Science — Optomechanical systems enable exploration of novel nonlinear optical elements and even quantum domain experiments. Recently, symmetric membrane-in-the-middle systems have been driven into stable buckled configurations, where the membrane spontaneously breaks to a fixed position. We identify a parameter regime in which a natural thermodynamic limit arises for the optical spring even though the system is nominally out of equilibrium. In this regime, we describe the phase diagram for the experimental system, a many-mode membrane with two optical modes. We discuss potential realizations of a U(1) symmetry breaking experiment.

2:36PM J6.00004 Quantum optomechanics with superfluid helium density waves . ALEXEY SHKARIN, ANNA KASHKANOVA, CHARLES BROWN, Yale University, NATHAN FLOWERS-JACOBS, NIST, Boulder, LILIAN CHILDERESS, McGill University, SCOTT HOCH, Yale University, LEANDER HOHMANN, KONSTANTIN OTT, SEBASTIEN GARCIA, JAKOB REICHEL, Laboratoire Kastler Brossel, Paris, JACK HARRIS, Yale University — The field of optomechanics deals with the interaction between light and mechanical objects. One of the challenges in this field is to coherently manipulate mechanical states with single-quantum precision and to interface these states with electromagnetic radiation without loss. To achieve this goal, one generally aims to create a system with strong coupling between optical and mechanical systems, while maintaining low optical and mechanical losses and low temperature. Superfluid helium is a material which is uniquely well-suited to meet these requirements. In this talk I will describe a cavity optomechanics system in which we couple infrared light to a standing acoustic wave in superfluid helium. With this system, we used light to coherently excite acoustic vibrations and manipulate their frequency and damping rate using the dynamic back-action effect. In addition, we measured thermal fluctuations of the mechanical mode corresponding to mean phonon number of five. These measurements had sufficient precision to reveal quantum signatures in the motion of the acoustic waves and in their interaction with light. Specifically, we measure the quantum asymmetry and correlations between the motional sidebands.

2:48PM J6.00005 A hybrid quantum interface between a mechanical resonator and an ultracold spin ensemble . JIALUN LUO, YOGESH S PATIL, HIL F CHEUNG, MUKUND VENGALATTORE, Cornell University — Cavity optomechanical systems of a diverse range of mass and size scales have been realized both for fundamental studies of quantum measurement as well as technological applications of force and mass sensing. However, in contrast to cavity QED systems, the comparatively large rates of dissipation and weak optomechanical interactions have stymied the robust quantum state preparation and control of macroscopic mechanical resonators purely via optomechanical interactions. To circumvent these limitations, we demonstrate a hybrid quantum system in which a macroscopic resonator is optically coupled to an ultracold spin ensemble and show that the optomechanical interaction can be dramatically enhanced and dynamically tuned by the effective spin-phonon coupling, thereby creating a robust platform for quantum state preparation, transduction, and beyond-SQL measurements.
3:00PM J6.00006 Optical coupling of cold atoms to a levitated nanosphere, CRIS MONTOYA, APRYL WITHERSPOON, JACOB FAUSETT, JASON LIM. University of Nevada, Reno, JOHN KITCHING, National Institute of Standards and Technology, ANDREW GERACI, University of Nevada, Reno — Cooling mechanical oscillators to their quantum ground state enables the study of quantum phenomena at macroscopic levels. In many cases, the temperature required to cool a mechanical mode to the ground state is below what current cryogenic systems can achieve. As an alternative to cooling via cryogenic systems, it has been shown theoretically that optically trapped nanospheres could reach the ground state by sympathetically cooling the spheres via cold atoms. Such cooled spheres can be used in quantum limited sensing and matter-wave interferometry, and could also enable new hybrid quantum systems where mechanical oscillators act as transducers. In our setup, optical fields are used to couple a sample of cold Rubidium atoms to a nanosphere. The sphere is optically levitated in a separate vacuum chamber, while the atoms are trapped in a 1-D optical lattice and cooled using optical molasses. [1] G. Ranjit, C. Montoya, A. A. Geraci, Phys Rev. A 91, 013416 (2015).

1This work is partially supported by NSF, Grant No. PHY-1506431

3:12PM J6.00007 Trapped atoms along nanophotonic resonators, BRIAN FIELDS, MAY KIM, Tzu-Han Chang, Chen-Lung Hung, Purdue University — Many-body systems subject to long-range interactions have remained a very challenging topic experimentally. Ultracold atoms trapped in extreme proximity to the surface of nanophotonic structures provides a dynamic system combining the strong atom-atom interactions mediated by guided mode photons with the exquisite control implemented with trapped atom systems. The hybrid system promises pair-wise tunability of long-range interactions between atomic pseudo spins, allowing studies of quantum magnetism extending far beyond nearest neighbor interactions. In this talk, we will discuss our current status developing high quality nanophotonic ring resonators, engineered on CMOS compatible optical chips with integrated nanostructures that, in combination with a side illuminating beam, can realize stable atom traps approximately 100nm above the surface. We will report on our progress towards loading arrays of cold atoms near the surface of these structures and studying atom-atom interaction mediated by photons with high cooperativity.

3:24PM J6.00008 Controlling the temperature and chemical potential for light with laser-cooled motional modes in an optomechanical system, CHIAO-HSUAN WANG, QJ, QuiCS, and University of Maryland, JACOB TAYLOR, QJ, QuiCS, University of Maryland, and National Institute of Standards and Technology — Massless gauge bosons, including photons, do not exhibit particle conservation and thus have no chemical potential. However, in parametrically driven systems, near equilibrium dynamics can lead to equilibration of photons into a thermodynamic ensemble with a finite number of photons. This Gibbs-like ensemble then has an effective chemical potential. Here we build upon this general concept with an optomechanical implementation appropriate for a nonlinear photonic or microwave quantum simulator, as well as a parallel neutral atom approach. We consider how laser cooling of a narrow mechanical mode or atomic motion can provide an effective low frequency bath for other photon modes. In the optomechanical approach, the parametric interaction between the optical system and the low frequency bath is mediated through a beam-splitter coupling between the optical system and another laser-driven photonic mode, which can be potentially realized in a Michelson-Sagnac interferometry design. The engineered matter-light interaction enables control of both the chemical potential — by drive frequency — and temperature — by the effective temperature of the motional mode induced after laser cooling — of the resulting photonic grand canonical ensemble.

1Funding is provided by Physics Frontier Center at the QI and the NSF-funded MRSEC at Princeton

3:36PM J6.00009 Optomechanics in a Levitated Droplet of Superfluid Helium, CHARLES BROWN, GLEN HARRIS, JACK HARRIS, Yale Univ — A critical issue common to all optomechanical systems is dissipative coupling to the environment, which limits the system’s quantum coherence. Superfluid helium’s extremely low optical and mechanical dissipation, as well as its high thermal conductivity and its ability cool itself via evaporation, makes the mostly uncharted territory of superfluid optomechanics an exciting avenue for exploring quantum effects in macroscopic objects. I will describe ongoing work that aims to exploit the unique properties of superfluid helium by constructing an optomechanical system consisting of a magnetically levitated droplet of superfluid helium. The optical whispering gallery modes (WGMs) of the droplet, as well as the mechanical oscillations of its surface, should offer exceptionally low dissipation, and should couple to each other via the usual optomechanical interactions. I will present recent progress towards this goal, and also discuss the background for this work, which includes prior demonstrations of magnetic levitation of superfluid helium, high finesse WGMs in liquid drops, and the self-cooling of helium drops in vacuum.

3:48PM J6.00010 Detecting continuous gravitational waves with superfluid helium, SWATI SINGH, Williams College, LAURA DE LORENZO, Caltech, TGOR PIKOVSKI, ITAMP, KEITH SCHWAB, Caltech — We study the sensitivity to continuous-wave strain fields of a kg-scale optomechanical system formed by the acoustic motion of superfluid helium-4 parametrically coupled to a superconducting microwave cavity. This narrowband detection scheme can operate at very high $Q$-factors, while the resonant frequency is tunable through pressurization of the helium in the 0.1-1.5 kHz range. The detector can therefore be tuned to a variety of astrophysical sources and can remain sensitive to a particular source over a long period of time. For reasonable experimental parameters, we find that strain fields on the order of $h \sim 10^{-23}/\sqrt{\text{Hz}}$ are detectable. We show that the proposed system can significantly improve the limits on gravitational wave strain from nearby pulsars within a few months of integration time.

Wednesday, June 7, 2017 2:00PM - 4:00PM – Session J7 Bose-Einstein Condensates

2:00PM J7.00001 Measurement of quantum depletion in a homogeneous Bose-Einstein condensate, RAPHAEL LOPES, CHRISTOPH EIGEN, NIR NAVON, ROBERT SMITH, ZORAN HADZIBABIC, Unicambridge, AMOP TEAM — Using momentum selective Bragg scattering we measure the condensed fraction of a strongly interacting homogeneous BEC. When adiabatically increasing the scattering length, we see that the condensed fraction decreases linearly with $\sqrt{n}$ (where $n$ is the density), in excellent agreement with the Bogoliubov theory of quantum depletion. We also show the reversibility of this process by adiabatically reducing the scattering length.
2:12PM J7.00002 Bosonic Particle-Correlated States: A Nonperturbative Treatment Beyond Mean Field, ZHANG JIANG, NASA Ames Res Ctr, ALEXANDRE TACLA, Department of Physics and SUPA, University of Strathclyde, CARLTON CAVES, Center for Quantum Information and Control, University of New Mexico — We consider a natural generalization of the product ansatz for Bose-Einstein condensates; the particle-correlated state of $N = l \times n$ identical particles is derived by symmetrizing the $n$-fold product of an $l$-particle quantum state. Quantum correlations of the $l$-particle state “spread out” to any subset of the $N$ particles by symmetrization. The particle-correlated states can be simulated efficiently for large $N$, because their parameter spaces, which depend on $l$, do not grow with $n$. We pay special attention to the pure-state case for $l = 2$, where the many-body state is constructed from a two-particle pure state. These paired wave functions were introduced by Leggett [Rev. Mod. Phys. 73, 307 (2001)] as a particle-number-conserving version of the Bogoliubov approximation. For large $N$, we derive few-particle reduced density matrices (correlation functions) for these wave functions. To test the efficacy of our theory, we solve the two-site Bose-Hubbard model by minimizing the energy using the two-particle reduced density matrices that we derived analytically. We find that the relative errors of the ground state energy are within $10^{-5}$ for $N = 1000$ particles over the entire range from a single condensate to a Mott insulator.

2:24PM J7.00003 Bloch-Siegert shift in an interacting Bose-Einstein condensate, JINYI ZHANG, CHRISTOPH EIGEN, RAFAEL LOPEZ, SAM GARRATT, DAVID ROUSSO, ROBERT P. SMITH, ZORAN HADZIBABIC, NIK NAVON, Cavendish Laboratory, University of Cambridge — The Bloch-Siegert shift [1] (BSS) is a paradigmatic frequency shift that arises from the nonlinear response of a two-level system (TLS) subjected to strong driving fields. When a TLS is driven by a linearly polarized field, the co-rotating-wave component leads to the famous Rabi oscillations. By contrast the co-rotating-wave component, whose role is usually neglected in a weak driving, leads to a frequency shift of the TLS resonance frequency. This phenomenon is encountered in various areas, from quantum optics to nuclear magnetic resonance. Here, we investigate the BSS in a box-trapped $^{87}$Rb Bose-Einstein condensate (BEC) driven by a strong oscillating magnetic field gradient [2]. By tuning the chemical potential of the gas, we investigate how the BSS evolves from the ideal shift of the two lowest energy levels of a single particle in a box to the unexplored shift of long-wavelength collective excitations of the interacting BEC.

References

2:36PM J7.00004 Creating the first Bose-Einstein Condensate in Space, M. LACHMANN, S. SEIDEL, D. BECKER, H. AHLERS, T. WENDRICH, LU Hannover, J. GROSSE, H. MNTINGA, ZARM, Bremen, B. WEPS, DLR-SC, A. DINKELAKER, V. SCHKOLNIK, HUB Berlin, O. HELLMIG, U Hamburg, A. WENZLAWSKI, JGU Mainz, W. HERR, N. GAALOLU, E. RASEL, W. ERTMER, LU Hannover, QUANTUS COLLABORATION — On 23rd of January 2017 the first Bose-Einstein Condensate (BEC) in Space was created onboard the sounding rocket mission MAIUS-1. The successful launch marks a major advancement in the effort of performing matter wave interferometry with BECs on space vehicles. Their high BEC-flux enables more than 100 experiments during flight, characterizing the creation of BECs in space, their free evolution, state preparation, and the creation of cold atoms in highly dynamic environments. MAIUS-1 opens a new path towards space borne inertial sensing employing interferometers with high accuracy and sensitivity. Two follow-up missions will investigate dual-species interferometry. Recently several missions were proposed ranging from tests of the universality of free fall to gravimetry. Due to their small initial size and low expansion rates BECs are the ideal source for such an interferometric measurement. The findings of the mission will contribute to the NASA CAL project and BECCAL (NASA and DLR). DLR under grant 50WP1435

2:48PM J7.00005 Efimov Trimer Production in a Resonantly Interacting BEC, XIN XIE, CATHERINE KLAUSS, CARLOS ABADIA, JOSE D’INCAO, JILA, NIST and CU-Boulder, ZORAN HADZIBABIC, Cavendish Laboratory, University of Cambridge, DEBORAH JIN, ERIC CORNELL, JILA, NIST and CU-Boulder, JILA, NIST AND CU-BOULDER TEAM, CAVENDISH LABORATORY, UNIVERSITY OF CAMBRIDGE TEAM — Ultracold quantum gases with resonant interactions have been in focus for decades as an ideal and tunable model of many-body physics. Fermi gases have been widely studied owing to its direct relation to realistic materials. Resonantly interacting Bose gases, however, were first investigated only a couple of years ago due to its short lifetime caused by three-body recombination. Such three-body-interaction is an intriguing feature of Efimov physics which is absent in the Fermionic counterpart. We previously observed a relatively stable degenerate Bose gas by quenching to unitarity. This state equilibrates many times faster than the gas’s lifetime. In this work, we did a closer investigation into this quasi-equilibrium state by projecting it onto weakly interacting regimes and probing it therein. We discovered dramatic signatures of Efimov trimers by measuring their one-body decay time that agrees with theoretical calculations. We propose that such formation of trimers is related to the finite overlap between trimer wavefunctions and short-range correlations in the quenched state. And the study of molecules in their well-characterized states provide a unique pathway to understand the two-body and three-body correlations in resonantly interacting BEC.

3:00PM J7.00006 Density–density correlations and Hawking radiation in ultracold gases, YI-HSIEH WANG, Joint Quantum Institute, TED JACOBSON, University of Maryland, MARK EDWARDS, Georgia Southern University, CHARLE W. CLARK, Joint Quantum Institute — We simulate recent experiments on Bose-condensed gases in which the spontaneous production of analog Hawking radiation was inferred from the observation of density–density correlations. Even when the gas sample is a pure Bose-Einstein condensate, we find that such correlations are present in realistic simulations. This is due to the random shot-to-shot variation in the number of atoms in the sample. This simple effect of “sample inhomogeneity” is comparable to that of quantum fluctuations, and is comparable to what is observed in experiments.

3:12PM J7.00007 Quantitative many-body theory of unitarity BECs, MACKILLO KIRA, University of Michigan — Perturbative approaches, such as the Gross-Pitaevskii equation, can successfully explain weak interactions in BECs, while they become questionable at unitary where the scattering length diverges. The first unitary BEC experiment demonstrated that a surprisingly large BEC fraction survived a quench from weak to unitary interactions. I will show that introducing an excitation picture identifies how a quench creates noncondensed atoms in a strict sequential order, where large atom clusters only emerge from existing smaller ones. This observation yields an efficient nonperturbative many-body description of unitary BECs, based on a cluster-expansion approach developed originally for semiconductor quantum optics. I will discuss how this method quantitatively explains the first unitarity BEC measurement, and how it can be extended to explore, e.g., Efimov physics, universality, and entanglement in one or many strongly interacting BECs.


3:24PM J7.00008 Wave function based treatment of the unitary Bose gas1, MICHELLE WYNN SZE, JOHN CORSON2, JOSE D’ INCAO, Department of Physics, University of Colorado, Boulder; JILA, JOHN BOHN, JILA; NIST: Department of Physics, University of Colorado, Boulder — Understanding many body quantum systems remains a challenging task as recent experiments on ultracold gases extend to unitary regime. We study a system of \( N \) identical harmonically-trapped bosons interacting via a contact interaction by starting from a few body system, and employing the adiabatic hyperspherical method and Fadeev decomposition approach. In our formulation, we determine the hyperangular energy eigenstates (and consequently the total energy of the system) from the Bethe-Peierl’s boundary condition applied to the symmetrized wavefunction and where the only relevant parameters are the scattering length and the average size of the system given by the hyperradius \( R \). We reproduce the well-understood stationary properties and characteristics of weakly to strongly interacting three-body systems. Results from these are exploited for the study of larger \( N > 3 \) and the dynamics of three-body systems.

1NSF
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3:36PM J7.00009 Universal Loss Dynamics of a Degenerate Homogeneous Unitary Bose Gas , CHRISTOPH EIGEN, JAKE GLIDDEN, RAPHAEL LOPES, JINYI ZHANG, NIR NAVON, ZORAN HADZIBABIC, ROBERT SMITH, University of Cambridge — We study the loss dynamics of a degenerate \(^{133}\)K Bose gas confined in an optical box trap. Starting with a quasi-pure Bose-Einstein condensate in the Thomas-Fermi regime, where the density \( n \) is uniform, we quench the scattering length \( a \) to the unitary regime, where \( a \) diverges. Observing the cloud after a variable hold time at unitarity directly reveals a loss rate which is dictated solely by the density of the cloud and scales as \( n^{\frac{1}{2}} \). This is in stark contrast to measurements performed away from unitarity, where the more conventional \( n^{\frac{3}{2}} \) scaling is observed. Our measurements also provide insight into the time evolution of the momentum distribution at unitarity.

3:48PM J7.00010 Hollow shell geometry and topological change of spherical Bose-Einstein condensates1, KARMELA PADAVIC, University of Illinois at Urbana-Champaign, KUEI SUN, The University of Texas at Dallas, FRANCES YANG, Smith College, COURTNEY LANNERT, University of Massachusetts, SMITHA VISHVESHWARA, University of Illinois at Urbana-Champaign — We present our study [arXiv:1612.05809] and recent progress on a spherical BEC undergoing a topological change from a filled sphere to a novel hollow shell geometry. Motivated by the upcoming realization of these hollow systems by NASA’s Cold Atom Laboratory, we analyze their equilibrium properties and collective mode (CM) structure. We show that distinctive non-monotonic features in the CM spectrum of a spherical BEC indicate its deformation from a filled to a hollow geometry and the emergence of an inner boundary. This topological change produces the most drastic effect for high angular momentum CMs as they correspond to surface modes localized to condensate boundaries and undergo a redistribution of nodes once an additional boundary is present. Additionally, our numerical simulations show how the CM features can be probed in typical sudden-quench experiments. Finally, we go beyond the micro-gravity regime, discussing how the equilibrium and CM properties are modified as gravity breaks the spherical symmetry.

1NASA SUB JPL 1553869

Wednesday, June 7, 2017 2:00PM - 4:00PM –
Session J8 Quantum Metrology, Sensing and Hilbert Space Engineering 314 - Hartmut Haeflner, University of California, Berkeley

2:00PM J8.00001 Trapped atomic ions for quantum-limited metrology, DAVID WINELAND, NIST, Boulder, Colorado — Laser-beam-manipulated trapped ions are a candidate for large-scale quantum information processing and quantum simulation but the basic techniques used can also be applied to quantum-limited metrology and sensing. Some examples being explored at NIST are: 1) As charged harmonic oscillators, trapped ions can be used to sense electric fields; this can be used to characterize the electrode-surface-based noisy electric fields that compromise logic-gate fidelities and may eventually be used as a tool in surface science. 2) Since typical qubit logic gates depend on state-dependent forces, we can adapt the gate dynamics to sensitively detect additional forces. 3) We can use extensions of Bell inequality measurements to further restrict the degree of local realism possessed by Bell states. 4) We also briefly describe experiments for creation of Bell states using Hilbert space engineering. This work is a joint effort including the Ion-Storage group, the Quantum processing group, and the Computing and Communications Theory group at NIST, Boulder.

1Supported by IARPA, ONR, and the NIST Quantum Information Program
3:00PM J8.00003 Multi-component quantum gases: Entanglement and Phononic Lamb shift. MARKUS OBERTHALER, Kirchhoff Institute for Physics, Heidelberg University — Mixtures of quantum gases have been investigated in many different contexts. Here I will present recent results addressing two distinct topics. In the context of spinor condensates I will describe the realization of an atomic SU(1,1) interferometer. With these experiments we show that time reversal of nonlinear dynamics can be used to utilize many particle entanglement at the Heisenberg limit even in the limit of a noisy atom detector. This opens an alternative route for accessing quantum resources even with limited detection capabilities. As second topic I will report on the first observation of the phononic Lamb shift. It has been predicted in the context of the Fröhlich hamiltonian which describes a particle coupling to excitations of a bosonic system. For the realization we use trapped lithium atoms immersed in a sodium Bose Einstein condensate forming the synthetic vacuum. A precise determination of the self energies with motional Ramsey spectroscopy reveal additional energy shifts to the expected mass renormalization. The minute energy shifts become accessible since the atomic model system allows the direct comparison between quantum vacuum and truly empty space.

Wednesday, June 7, 2017 2:00PM - 3:48PM – Session J9 Atomic Clocks

2:00PM J9.00001 A Fermi-degenerate three-dimensional optical lattice clock. ROSS HUBSON, SARA CAMPBELL, EDWARD MARTI, AKIHISA GOBAN, WEI ZHANG, JOHN ROBINSON, LINDSAY SONDERHOUSE, JUN YE, JILA, NIST and University of Colorado Boulder — Ongoing advances in atomic clocks enable table top searches of dark matter and other physics beyond the Standard Model. Currently the most accurate and stable clocks are based on alkaline-earth-like) neutral atoms confined to one-dimensional optical lattices. A major obstacle in improving clock stability and accuracy is mitigating density-dependent frequency shifts due to contact interactions. We overcome this limitation by loading a two spin component degenerate Fermi gas of strontium atoms into a three-dimensional optical lattice. By tuning the thermal, kinetic, and interaction energy scales, we operate in the half-filled Mott insulating regime to suppress atomic collisions and leaves and any residual contact interactions spectroscopically resolvable. Additionally, we demonstrate control of the scalar, vector, and tensor components of the three-dimensional lattice induced ac Stark shifts, enabling the observation of a 6 second atom-light coherence time.

2:12PM J9.00002 Feasibility of hollow core fiber based optical lattice clock. EKATERINA ILINOVA, University of Nevada, Reno, NV 89557 USA, JAMES F. BABB, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS 14, Cambridge, Massachusetts 02138, USA, ANDREI DEREVIANKO, University of Nevada, Reno, NV 89557 USA, THEORETICAL ATOMIC AND MOLECULAR PHYSICS GROUP TEAM — The possibility of building the optical lattice clock based on the narrow $S_0^+\rightarrow P_3$ transition in Hg and other alkaline-earth like atoms optically trapped inside the hollow core fiber has been studied. The general form of the long range atom-capillary interaction potential at non-zero temperatures has been calculated for the hollow capillary geometry. The resulting $S_0^+\rightarrow P_3$ transition frequency shift has been calculated for Sr and Hg atoms as a function of their position inside the capillary. Its dependence on the geometric parameters and optical properties of the capillary material has been analyzed. The resonant enhancement of the atom-capillary interaction potential and radiative decay rate of the $P_3$ state at certain parameters of the waveguide has been studied. For the silica capillary with inner radius $R_{ivs}>15\ \mu m$ and thickness $d\sim 1\ \mu m$ the atom surface interaction induced $S_0^+\rightarrow P_3$ transition frequency shift on the capillary axis can be suppressed down to the level $\delta \nu/\nu < 10^{-18}$. The additional frequency shifts and atom loss from the optical trap due to the residual birefringence of the waveguide and collisions with the buffer gas molecules have been evaluated.

2:24PM J9.00003 A new approach to an accurate calculation of hyperpolarizabilities. SERGEY PORSEV, MARIANNA SAFRONOVA, University of Delaware, ULYANA SAFRONOVA, University of Nevada in Reno, MIKHAIL KOZLOV, Petersburg Nuclear Physics Institute — A systematic effect that yet to be addressed to further reduce uncertainty of optical atomic clocks is a lattice Stark shift caused by the term nonlinear in lattice intensity and determined by the hyperpolarizability. Due to complexity of the theoretical expression for this quantity no reliable calculations of hyperpolarizabilities are available even for simpler atoms and ions than used for clock applications. We have developed a new approach to calculate hyperpolarizabilities for atoms and ions based on a solution of the inhomogeneous equation, what allows us very effectively and accurately carry out summations over intermediate states. We applied our new method to the calculation of the hyperpolarizabilities for the $S_0^+$ and $P_3^-$ clock states in Sr and Yb. The results will be reported at the conference.

1This work was supported by NSF.
2:36PM J9.00004 Hyperpolarizability and operational magic wavelength in an optical lattice clock

2:48PM J9.00005 Searching for Dark Matter and Exotic Physics with Atomic Clocks and the GPS Constellation

3:00PM J9.00006 Experimental research of good-bad cavity dual-wavelength active optical clock

3:12PM J9.00007 Study of high SNR Ramsey-CPT spectrum with dispersion detection in Rb cell

3:24PM J9.00008 Power scaling of extreme ultraviolet frequency combs to the mW level per high harmonic
3:36PM J9.00009 Heisenberg-limited Rabi spectroscopy in decoherence free subspaces — TOM MANOVITZ, RAVID SHANIV, NITZAN AKERMANN, YOTAM SHAPIRA, RÖEE OZERI, Weizmann Institute of Science — One of the techniques for suppressing noise in quantum systems is through the use of decoherence free subspaces (DFSs). A quantum state can be engineered so that it resides in a subspace which is degenerate with respect to the primary noise operators. Any operation performed on the qubits which remains within this subspace is immune to the damages of decoherence. In this work we entangled two ions in a Paul trap in order to create a correlated measurement of their internal atomic transition while in a DFS. We generate an effective $\sigma_x \sigma_x + \delta \sum \sigma_z$ Hamiltonian and scan the detuning $\delta$ through the transition resonance, observing a Rabi-spectroscopy peak twice as narrow as the single-ion case. Such an interaction Hamiltonian acts separately on two orthogonal subspaces corresponding to the mean and differential transition frequency of the ions, separating the Hilbert space into two DFSs. Hence, one can measure the differential frequency while remaining immune to decohering mean frequency noise, and vice versa. Furthermore, the narrowing we observed due to the entangling Hamiltonian produces a Rabi spectroscopy measurement which is limited by the energy-time Heisenberg uncertainty relation, previously only demonstrated using Ramsey spectroscopy.

Wednesday, June 7, 2017 4:00PM — Session K1 Poster Session II (4:00pm-6:00pm) Exhibit Hall B —

K1.00001 ATOM INTERFEROMETERS —

K1.00002 Atom Interferometer inside a Hollow-Core Fiber — WUJ SEUNG LEONG, ZI LONG CHEN, MING JIE XIIN, SHAU-YU LAN, Nanyang Technological University — Light pulse atom interferometry under free fall is a common tool for gravity measurement at high precision level. However, its sensitivity scales with the size of experimental apparatus and optical power due to the diffraction of the Raman beam used in free space Mach-Zehnder interferometer. One of the solution is to use a waveguide such as single mode hollow-core fiber (HCF) to guide lights and atom simultaneously and perform interferometry in it. In this presentation, I will show the details of $\text{Rb}^{85}$ atoms loaded into a hollow-core photonic crystal fiber. $\text{Rb}^{85}$ atomic cloud of temperature $\sim 100\mu K$ is prepared above the HCF. It is loaded into HCF by gravity pulling with the aid of a 1mK deep intra-HCF dipole trap. Rabi flopping, Ramsey fringes, and spin echo signal using 3.035 732 439 GHz microwave antenna for the transition $5^2S_{1/2} F=2 \rightarrow F=3$ and Raman beams with 1.276(2) GHz red detuned from $F=3 \rightarrow F'=2$ and $F=2 \rightarrow F'=2$ transition, are also demonstrated. Moreover, I will also show Mach-Zehnder interferometry signal, using $\frac{\pi}{2} - T - \frac{\pi}{2} - T - \frac{\pi}{2}$ sequence.

K1.00003 Atom-chip-based interferometry with Bose-Einstein condensates — MARTINA GEBBE, ZARM, Uni Bremen, SVEN ABEND, MATTHIAS GERSEMMANN, HOLGER AHLERS, IQ, LU Hannover, HAUKE MUENTINGA, SVEN HERRMANN, CLAUS LAEMERZAHN, ZARM, Uni Bremen, WOLFGANG ERTMER, ERNST M. RASEL, IQ, LU Hannover, QUANTUS COLLABORATION — Due to their small spatial and momentum width ultracold Bose-Einstein condensates (BEC) or even delta-kick collimated (DKC) atomic ensembles are very well suited for high precision atom interferometer and measure, for example, inertial forces with high accuracy. We generate such an ensemble in a miniaturized atom-chip setup, where BEC generation and DKC can be performed in a fast and reliable way. Using the chip as a retroreflector we have realized the first atom-chip-based gravimeter. All atom-optical operations including detection take place inside a volume of a one centimeter cube. In order to investigate new geometries we studied symmetric double Bragg diffraction as well as the coherent acceleration of atoms with Bloch oscillations. By combining both techniques we developed a novel relaunch mechanism, which we use to span a fountain geometry within our gravimeter. The relaunch increases the free fall time and, thus, enhances the device’s sensitivity. Additionally, we employ these techniques to implement symmetric scalable large momentum beam splitters.

1 This work is supported by the CRC 1128 geo-Q and the DLR with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) due to an enactment of the German Bundestag under Grant No. DLR 50WM1552-1557 (QUANTUS-IV-Fallturm).

K1.00004 Towards enhanced gravimetry with an optical cavity, MARIO GONZALEZ, MA SOLEDAD BILLION, ALEJANDRA LOPEZ-VAZQUEZ, GEORGINA OLIVARES-RENTERIA, JOHN FRANCO-VILLAFANE, EDUARDO GOMEZ, Univ Autonoma de SLP — Gravimetry uses Ramsey’s separate field method with Raman transitions to accurately measure gravitational forces. Each atom interferes only with itself in the traditional gravimetry, giving an uncertainty that decreases as N^{-1/2} with N the number of atoms. An improved signal would be obtained using particles with higher mass. Our goal is to achieve collective interferometry, so that all atoms contribute coherently to the signal giving a better scaling of the uncertainty (as N^{-1}). The present work gives a detailed description of the new atomic trap for collective interferometry in our laboratory. The vacuum system consists of a metal chamber with multiple windows for optical access connected to a combination of sorption and ion pumps. We use reentrant windows to avoid eddy currents generated by abrupt changes in the current of the coils. The optical components are mounted directly on the vacuum chamber using a cage system and we send the light through optical fibers. We monitor the atoms with a double relay imaging system to suppress background light. All the system is mounted in a passive isolation system to minimize vibrations.

1 CONACYT

K1.00005 Low phase noise scheme for gravimetry — MARIO GONZALEZ, NIEVES ARIAS, VAHIDE ABEDIYE, EDUARDO GOMEZ, Physics Institute. Universidad Autonoma de San Luis Potosi — The Raman beams required for atomic gravimetry involve two phase locked beams with different frequency. The traditional method uses two independent lasers with an optical phase lock loop to keep a fixed phase relation between them. Alternatively one can use a phase modulator to produce the required beams that are automatically phase locked. This method gives a simple system with a phase noise limited by the quality of the microwave synthesizer. Here, two Raman pairs are produced and they interfere with each other. We show that by using a calcite crystal we can change the relative polarization of the carrier and the sidebands. The destructive interference that appears in co-propagating Raman transitions is transformed into constructive interference with this method. We split the carrier and sidebands taking advantage of their different polarization and we send them in opposite directions to excite counter-propagating Raman transitions. By dialing the correct frequency we can select a particular direction for the momentum transfer.

1 Funding from CONACYT
K1.00006 Design of an optical cavity for gravimetry1, M.S. BILLION REYES, Physics Institute, Universidad Autònoma de San Luis Potosí, A. LOPEZ-VAZQUEZ, W. M. PIMENTA, M. A. GONZÁLEZ, J. A. FRANCO-VILLAFANE, E. GOMEZ, Physics Institute, Universidad Autònoma de San Luis Potosí — Atomic interferometry is a widely used method to perform precision measurements of accelerations. We enhance the interferometric signal by adding an optical cavity around the free-falling atoms inside of a vacuum chamber. We use a bow-tie configuration to support a traveling wave and avoid spatial fluctuations in the light shift. To induce collective behavior (entangled state), we design the optical cavity with a cooperativity factor higher than one. We present the characterization of an optical cavity with a non-confocal arrangement so that we can excite transverse modes independently or simultaneously. We describe our progress to achieve a transverse mode closer to a flat-top and a cavity design that fits our geometrical restrictions.

1Funding from CONACyT

K1.00007 Versatile Atom Interferometer using a Single Diode Laser, XUEJIAN WU, FEI ZI, RYAN BIOLTTA, JORDAN DUDLEY, HOLGER MUELLER, University of California, Berkeley — Light-pulse atom interferometry has been applied to measure gravity, Newton’s gravitational constant and the fine structure constant with high precision. Miniature and transportable atom interferometers would lend more agility and practical applications in geodesy, geophysics, and mineral exploration. Here, we present a single-diode laser-based atom interferometer for measuring gravity by use of a simplified laser system and a pyramid-based magneto-optical trap. The laser system contains only a single distributed feedback laser. Both the repumping frequency and the Raman frequencies are generated from a fiber electro-optical modulator, and the Raman pulses are produced by acousto-optical modulators. In order to eliminate the AC Stark shift and balance the Rabi frequency and the single photon scattering, we choose a single photon detuning of 150 MHz red detuned from $F = 4\rightarrow F^\prime = 5$ of cesium D$_2$ transition. In the experiment, we capture 0.4 million atoms at 2 µK from the background vapor and achieve fringes with good visibility as the Raman pulse separation time is as long as tens of milliseconds in the Mach-Zehnder geometry. Additionally, multiple-axis measurement including three-axis acceleration and three-axis rotation is also possible in our atom interferometer with irradiating Raman pulses toward individual pyramid faces. Being simple, robust and multiple-axis capable, our versatile atom interferometer can be used for inertial sensing out of laboratory.

K1.00008 Theoretical analysis of atom interferometry using a modulated laser, JOHN ALEXANDER FRANCO VILLAFANE, GEORGÍNA OLIVARES, YASSER JERONIMO MORENO, EDUARDO GOMEZ, Physics Institute, Universidad Autònoma de San Luis Potosí — The widely used technique in atom interferometry, the precision measurements are highly limited by the phase noise between the lasers involved in the Raman transition. To overcome this limitation atom interferometry using modulated Raman laser has been demonstrated experimentally recently in both counter- and co-propagating beams configuration. The theoretical analysis of this technique is far from being well understood. In this work, we will present an overview of the main challenges in the theoretical analysis of an atom interferometer using a modulated Raman laser. Some analytical solutions in limit cases are presented in counterpropagation configuration.

K1.00009 Lukewarm lithium recoil interferometer, ERIC COPENHAVER, KAYLEIGH CASSELLA, BRIAN ESTEY, UC Berkeley, YANYING FENG, Tsinghua University, CHEN LAI, UC San Diego, MILLER HOLGER, UC Berkeley — We demonstrate recoil-sensitive atom interferometry with laser-cooled lithium-7 at 50 times the recoil temperature. The large bandwidth of 160-ns beam-splitter pulses drives conjugate interferometers simultaneously with nearly equal contrast. Two-photon Raman transitions spectrally resolve the outputs, which thermally expand too quickly to be spatially resolved. Two images captured during a single exposure of a camera with slow readout detects both output ports. Optical pumping to a magnetically insensitive state using the well-resolved D$_1$ line suppresses magnetic dephasing and extends coherence time. Sensitivity comparable to interferometers utilizing large momentum transfer pulses is attainable at interrogation times on the order of 10 ms due to lithiums high recoil frequency and the increased available atom number. Vibration noise is mitigated at this time scale and is converted to amplitude noise in our detection scheme, isolating the the recoil frequency from what is conventionally phase noise. These techniques relax requirements for cooling in recoil-sensitive interferometry, broadening the choice of species to particles that remain difficult to trap and cool, like electrons.

K1.00010 Development of an Atom Interferometer Gravity Gradiometer for Earth Sciences1, AKASH RAKHOLIA, ALEX SUGARBAKER, ADAM BLACK2, AO Sense, Inc., MARK KASEVICH, Stanford University, AO Sense, Inc., BABAK SAIF, SCOTT LUTHCKE, LISA CALLAHAN, BERNARD D. SEERY, LEE FEINBERG, JOHN C. MATHER, RITVA KESKI-KUHA, NASA Goddard Space Flight Center — We report progress towards a prototype atom interferometer gravity gradiometer for Earth science studies from a satellite in low Earth orbit. The terrestrial prototype has a target sensitivity of $8 \times 10^{-22}$ E/Hz$^{1/2}$ and consists of two atom sources running simultaneous interferometers with interrogation time $T = 300$ ms and 126 kHz photon recoils, separated by a baseline of 2 m. Interferometers would lend more agility and practical applications in geodesy, navigation, and metrology. Here, we demonstrate the use of a single photon at a temperature of 3 µK. The sensitivity extrapolates to $7 \times 10^{-19}$ E/Hz$^{1/2}$ in microgravity on board a satellite. Simulations derived from this sensitivity demonstrate a monthly time-variable gravity accuracy of 1 cm equivalent water height at 200 km resolution yielding an improvement over GRACE by 1-2 orders of magnitude. A gravity gradiometer with this sensitivity would also benefit future planetary, lunar, and asteroidal missions.

1Supported by NASA’s Instrument Incubator Program (IIP)
2Currently affiliated with U.S. Naval Research Laboratory

K1.00011 A large mode optical resonator for enhanced atom interferometry1, RANJITA CHANU SAPAM, NICOLAS MIELEC, LNE-SYRTE, Observatoire de Paris, PSL Research Univ., CNRS, Sorbonne Univ., ISABELLE RIOUT, BENJAMIN CANUEL, LP2N, Université Bordeaux-IOGS-CNRS, DAVID HOLVILLE, LNE-SYRTE, Observatoire de Paris, PSL Research Univ., CNRS, Sorbonne Univ., BESS FANG, LP2N, Université Bordeaux-IOGS-CNRS, ARNAUD LANDRAGIN, REMI GEIGER, LNE-SYRTE, Observatoire de Paris, PSL Research Univ., CNRS, Sorbonne Univ. — The development of atom interferometry in the last few decades has led to high precision measurements of inertial effects and tests of fundamental physics. New methods for higher sensitivity atom interferometers (AIs) are being explored, particularly the interrogation of atoms with optical cavities. Its benefits would be higher optical power allowing large momentum transfer beam splitters, and possibly cleaner and controlled phase profiles. However high sensitivity AIs require long interrogation times, which combined with cold atom expansion, bring the challenges of large waists in cavities. We propose an optical resonator composed of a convergent lens with two flat mirrors at its focal plane. This cavity is marginally stable and exhibits half degenerate behaviour. A numerical study of its behaviour, using an ABCD transfer matrix formalism, showed that typical controllable misalignments of a few micrometres would not be critical for atom interrogation. We realise this cavity with a 200 mm lens and an 8 µm input waist and a 7 mm waist Gaussian beam inside the cavity.

1ANR-10-LABX-48-01, ANR-11-EXPQX-0028, city of Paris (HSENS-MWGRAV), CNRS GRAM, H2020 MC-Grant 660081- MWGRAV
K1.00012 Characterizing the potential profile of an atom trap using tomographic fluorescence imaging1. 

EDWARD MOAN, TANWA ARPORNTHIP, CHARLES SACKETT, UVA — We have developed a technique to fully characterize an arbitrary potential profile of an atom trap. A cold, but not condensed, atom cloud is first loaded into the trap and allowed to equilibrate. The trap is then turned off and the atoms are rapidly pumped into a dark state, such that they do not interact with light from a probe laser. A selected slice of the atom cloud is reactivated by repump light that is cylindrically focused into a light sheet with an appropriate thickness. The reactivated cross-sectional region interacts with the probe laser light to create a fluorescence image which is viewed perpendicular to the sheet. The light sheet can be translated to generate cross-section images of the cloud at different positions. Combining these cross-sections provides a full three dimensional profile of the atom cloud, much like tomographic imaging used in medical imaging. From the cloud profile the trap potential function is readily determined. We have demonstrated the technique using Rb atoms in a time-orbiting trap. We verified that the potential obtained had the correct anharmonic terms, when compared to an analysis of the trajectory of a Bose-Einstein condensate moving in the trap. The tomographic technique is both faster to acquire and in general simpler to analyze.

1 NSF, NASA

K1.00013 Correcting for time-dependent field inhomogeneities in a time orbiting potential magnetic trap1. 

ADAM FALLON, SETH BERL, CHARLES SACKETT, University of Virginia — Many experiments use a Time Orbiting Potential (TOP) magnetic trap to confine a Bose- condensate. An advantage of the TOP trap is that it is relatively insensitive to deviations and errors in the magnetic field. However, precision experiments using the trapped atoms often do require the rotating field to be well characterized. For instance, precision spectroscopy requires accurate knowledge of both the field magnitude and field direction relative to the polarization of a probe laser beam. We have developed an RF spectroscopic technique to measure the magnitude of the field at arbitrary times within the TOP trap rotation period. From the time-variation mapped out, various imperfections can be isolated and measured, including asymmetries in the applied trap field and static environmental fields. By compensating for these imperfections, field control at the 10 mG level or better is achievable, for a bias field of 10 G or more. This should help enable more precision experiments using trapped condensates, including asymmetries in the applied trap field and static environmental fields. By compensating for these imperfections, field control at the 10 mG level or better is achievable, for a bias field of 10 G or more. This should help enable more precision experiments using trapped condensates, including precision measurements of tune-out wavelengths and possibly parity-violation measurements.

1Supported by the National Science Foundation, the Jefferson Scholars Foundation, and NASA

K1.00014 Enhancing Geometric Phases Sensitivity in Atomic Coupled Ring Interferometers by Modulating Inter-Ring Distance.1. 

JOHN TOLAND, ELENI ROMANO, CUNY: LaGuardia Community College, Long Island city, New York — Previous theoretical work in the study of transmission properties of cold atoms in coupled ring waveguide structures has indicated that the sensitivity to geometrical phase shifts be greatly enhanced by increasing the number of rings in the array or by changing the relative size of the rings in an array of the coupled waveguides. The coupled ring structures in these simulations assumed zero distance between rings. Our research addresses how increasing the inter-ring distance of the chain of N rings affects the rotational sensitivity of a ring array interferometer. We determine the sensitivity of a ring array gyroscope by calculating the slopes of the transmission function with respect to phase at the sharpest transmission resonance in the transmission function. The distance between rings is parameterized as the product of the wave number k and the distance between the rings d, while the size of the rings is parameterized by the product of k and the ring circumference L. The transmission is periodic with oscillatory regions and zero transmission gap regions. Our results show that modulating the inter-ring distance near kd = 0.5π leads to sharp transmission resonances with slopes that are orders of magnitude greater than those in ring arrays with directly connected rings.

1CILES, NASA

K1.00015 Toward a precision force sensor based on Bloch oscillations of atoms in an optical lattice. 

ROBERT NIEDERRITER, CHANDLER SCHLUFF, E LIOT BOHR, ERIK SZWED, YOUNA PARK, SAMI KHAMIS, PÄUL HAMILTON, University of California - Los Angeles — Precision force sensors have potential for exploring and constraining unknown forces such as dark energy candidates [1]. We are developing a precision sensor that measures the force on ytterbium atoms optically trapped inside an optical cavity. The trapped and cooled atoms undergo Bloch oscillations which can be monitored for continuous force measurement [2]. Using trapped atoms allows long measurement times in a small volume. Continuous measurement enables detection of time-varying forces and reduces sensitivity to vibrations. The atoms for the force sensor are cooled and trapped in a two-dimensional magneto-optical trap (MOT) and loaded into a three-dimensional MOT within an optical cavity. We present progress towards the development of a precision force sensor and tests of new fundamental forces. [1] P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Müller, J. Khoury, Science 349, 849 (2015). [2] B. Prasanna Venkatesh, M. Trupke, E. A. Hinds, and D. H. J. ODell, Phys. Rev. A 80, 063834 (2009).

K1.00016 ATOMIC CLOCKS

K1.00017 A Cd+ microwave frequency standard based on dual-trap and sympathetic cooling. 

YAN ZUO, PENGFEI CHENG, XIAOLIN SUN, JIANWEI ZHANG, LIJUN WANG, Tsinghua Univ, JOINT INSTITUTE FOR MEASUREMENT SCIENCE TEAM — The passive microwave atomic clocks are studied widely, and the frequency stability of the state-of-the-art ones are close to the quantum projection noise limit. Most of those frequency standards work in pulse mode, which means that there exits dead time in each lock cycle due to states initialization and detection, laser cooling. High frequency fluctuations of the local oscillator (LO) are down-converted to the feedback loop to degrade the frequency stability, namely, Dick effect. The microwave frequency standard based on laser-cooled 113Cd+ ions in our laboratory has similar issue. Although it achieved the frequency stability to 6e-13 τ−1/2, it is far from the limit of theoretical performance. Analyses show that the Dick effect and RF heating are the two main limitations. Thus, we propose and design a new scheme to overcome these two limits by sympathetic cooling and interleaving lock. The 23Mg+ ions cooled by 280nm laser are used to sympathetically cool the 113Cd+ ions via Coulomb interaction to decrease the RF heating in ion traps. Meanwhile, two ion clouds in two identical ion traps are interrogated alternatively to lock the same LO to estimate dead time. The new scheme could improve the performance of the microwave atomic clocks greatly.
uncertainty of the ytterbium optical lattice clock at the $10^{-17}$ level significantly reduces the deleterious aliasing process which limits most optical clocks. By further decreasing the technical noise, it should be possible to develop optical clocks to be trapped at ultracold temperatures. The resulting technical simplicity makes atoms with narrow two-photon transitions attractive candidates for such secondary standards are needed in order to form clock ensembles. Ideally such secondary standards will offer enhanced robustness, portability and high accuracy and stability. We will present our efforts to develop a strontium optical clock testbed at JPL, aimed towards extending the exceptional performance demonstrated by OCs from state-of-the-art laboratory designs to a transportable instrument that can fit within the space power constraints of e.g. a single express rack onboard the International Space Station. The overall technology will find applications for future fundamental physics research, both on ground and in space, precision time keeping, and NASA/JPL time and frequency test capabilities.

**References**


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**K1.00018 Properties of Lu\(^{2+}\) ion for the atomic clock development**

M. S. SAFRONOVA, University of Delaware and JQI, NIST and the University of Maryland, W. R. JOHNSON, University of Notre Dame, U. I. SAFRONOVA, University of Nevada, Reno — Significant bottleneck for further improvement of trapped ion clock accuracy arises from relatively low stability achievable with a single ion. A solution was proposed [1] that may allow to overcome this hurdle via the use of large ion crystals with a special scheme to cancel the effects of micromotion. The crucial condition for the implementation of such a scheme is the negative value of the scalar polarizability difference for the clock transition. Doubly ionized lutetium satisfies such a condition, and a potentially promising candidate for multi-ion clock development [2]. In this work, we study relevant parameters of Lu\(^{2+}\), including transition matrix elements, lifetimes, polarizabilities, hyperfine constants and the blackbody radiation shift of the potential clock transition [3].


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**K1.00019 Updates on the NIST ytterbium optical lattice clock**

XIAOGANG ZHANG, ROGER BROWN, National Institute of Standards and Technology, MARCO SCHIOPPO, Institut fur Experimentalphysik, Heinrich-Heine-Universitat Dusseldorf, KYLE BELOY, WILLIAM MCGREW, ROBERT FASANO, DANIELE NICOLODI, HOLLY LEOPARDI, TARA FORTIER, ANDREW LUDLOW, National Institute of Standards and Technology — We present a summary of recent developments in an optical lattice clock based on ultracold ytterbium. By combining two lattice-trapped cold-atom systems to realize continuous laser interrogation, we demonstrate an optical clock with a fractional frequency instability of $6 \times 10^{-17}$ for an averaging time 1 s. The continuous laser interrogation scheme effectively eliminates the deleterious aliasing process which limits most optical clocks. By further decreasing the technical noise, it should be possible to realize quantum-limited stability due to quantum projection noise. We also characterize important systematic effects influencing the frequency uncertainty of the ytterbium optical lattice clock at the $10^{-18}$ level. Recent experimental studies of high-order lattice Stark shifts, including higher multipolarizabilities from magnetic dipole and electric quadrupole as well as hyperpolarizability, will be reported, together with DC Stark effects, background gas shifts, residual Doppler effects, and more.

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**K1.00020 Optical Atomic Clock for Fundamental Physics and Precision Metrology in Space**

JASON WILLIAMS, THANH LE, SASCHA KULAS, NAN YU, Jet Propulsion Laboratory, California Institute of Technology — The maturity of optical atomic clocks (OC), which operate at optical frequencies for higher quality-factor as compared to their microwave counterparts, has rapidly progressed to the point where lab-based systems now outperform the record cesium clocks by orders of magnitude in both accuracy and stability. We will present our efforts to develop a strontium optical clock testbed at JPL, aimed towards extending the exceptional performance demonstrated by OCs from state-of-the-art laboratory designs to a transportable instrument that can fit within the space power constraints of e.g. a single express rack onboard the International Space Station. The overall technology will find applications for future fundamental physics research, both on ground and in space, precision time keeping, and NASA/JPL time and frequency test capabilities.

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**K1.00021 Frequency stability measurement of pulsed superradiance from strontium**

MATTHEW NORCIA, JULIA CLINE, JOHN ROBINSON, JUN YE, JAMES THOMPSON, JILA, University of Colorado Boulder — Superradiant laser light from an ultra-narrow optical transition holds promise as a next-generation of active frequency references. We have recently demonstrated pulsed lasing on the milliHertz linewidth clock transition in strontium. Here, we present the first frequency comparisons between such a superradiant source and a state of the art stable laser system. We characterize the stability of the superradiant system, and demonstrate a reduction in sensitivity to cavity frequency fluctuations of nearly five orders of magnitude compared to a conventional laser.

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**K1.00022 A Fermi-degenerate three-dimensional optical lattice clock**

AKIHISA GOBAN, SARA CAMPBELL, ROSS HUTSON, JILA, CU Boulder, G. EDWARD MARTI, JILA, NIST, CU Boulder, LINDSAY SONDERHOUSE, JOHN ROBINSON, CU, Boulder, WEI ZHANG, JUN YE, JILA, NIST, CU Boulder — The pursuit of better atomic clocks has advanced many research areas, providing better quantum state control, tighter limits on fundamental constant variation, and improved tests of relativity. Recent progress in optical lattice clock to clock accuracy of $2 \times 10^{-18}$ has benefited from the understanding of atomic interactions. Also the precision of clock spectroscopy has been applied to explore many-body interactions including SU(N) symmetry. In our previous 1D optical lattice, atomic interactions cause suppression and broadening of the atomic resonance, limiting the clock stability. To overcome this limitation, we demonstrate a scalable solution that takes advantage of the high density of a degenerate Fermi gas in a three-dimensional optical lattice to protect against on-site interaction shifts. Using an ultrastable laser, we achieve an unprecedented level of atom-light coherence, reaching a spectroscopic quality factor $5 \times 10^{15}$. We investigate clock systematics unique to this design; on-site interactions are resolved so that their contribution to clock shifts is orders of magnitude suppressed compared to the 1D optical lattice experiments. Also, we measure the combined scalar and tensor magic wavelengths for state-independent trapping along all three lattice axes.

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**K1.00023 A clock transition in a solid-state system**

G. J. A. EDGE, S. POTNIS, A. C. VUTHA, University of Toronto — With the impending redefinition of the SI second based on optical frequency standards, new secondary frequency standards are needed in order to form clock ensembles. Ideally such secondary standards will offer enhanced robustness, portability and high signal-to-noise ratio (SNR), to enable comparison to be made against primary standards. A clock based on a narrow optical transition, in atoms that are doped into a solid-state host, offers the experimental simplicity and large SNR to satisfy these requirements. The intra-configuration $^7F_0 \rightarrow ^7D_0$ transition, in Sm\(^{2+}\) ions doped into a host crystal, is an attractive candidate for such secondary standards due to its low susceptibility to perturbations from the crystal environment. We present results from the interrogation of this clock transition with a narrow linewidth laser.

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**K1.00024 A compact apparatus for a two-photon optical clock**

S. POTNIS, S. JACKSON, A. C. VUTHA, University of Toronto — The Doppler- and recoil-free nature of two-photon transitions eliminates the need for atoms in optical lattice to be trapped at ultracold temperatures. The resulting technical simplicity makes atoms with narrow two-photon transitions attractive candidates for portable optical frequency standards. We report on progress towards the construction of a two-photon optical clock based on the 915 nm $4s^2 1S_0 \rightarrow 4s3d^4 D_2$ transition in calcium atoms. We demonstrate laser cooling of calcium in a compact and portable apparatus, and report on the performance of two narrow-linewidth 915 nm lasers.
Finally, we will present LIF spectroscopy of ThF for the efficient production of ThF$^+$ electric dipole moment (eEDM) using trapped HfF.

We recently completed a first measurement of the electrons, WILLIAM B. CAIRNCROSS, DANIEL N. GRESH, YAN ZHOU, KIA BOON NG, et al. (2016) [1].

Current results and future directions for an electron electric dipole moment search using molecular ions, WILLIAM B. CAIRNCROSS, DANIEL N. GRESH, YAN ZHOU, KIA BOON NG, et al. (2016) [1].

Improvements to the YbF electron electric dipole moment experiment, B. E. SAUER, J. M. RABEY, J. A. DEVLIN, M. R. TARBU TT, C. J. HO, E. A. HINDS, Imperial College London — The standard model of particle physics predicts that the permanent electric dipole moment (EDM) of the electron is very nearly zero. Many extensions to the standard model predict an electron EDM just below current experimental limits. We are currently working to improve the sensitivity of the Imperial College YbF experiment [1]. We have implemented combined laser-radiofrequency pumping techniques which both increase the number of molecules which participate in the EDM experiment and also increase the probability of detection. Combined, these techniques give nearly two orders of magnitude increase in the experimental sensitivity. At this enhanced sensitivity magnetic effects which were negligible become important. We have developed a new way to construct the electrodes for electric field plates which minimizes the effect of magnetic Johnson noise [1].

Design and Operation of the ATRAP Low-Inductance Ioffe Trap, ERIC TARDIFF, CHRISTOPHER HAMLEY, NATHAN JONES, CHANSHYAMBAHI KHATRI, GERALD GABRIELSE, COLE MEISENHELDER, THARON MORRISON, Harvard University, SIU AU LEE, CORY RASOR, SAMUEL RONALD, DYLAN YOST, Colorado State University, BARTOSZ GLOWACZ, MARCIN ZIELINSKI, Jagiellonian University, DIETER GRZONKA, Forschungzentrum Juelich, DANIEL ZAMBRANO, Northwestern University, OLG A ANDRIEYEVSKA, ERIC HESSELS, TAYLOR SKINNER, CODY STORRY, York University — The ATRAP experiment aims to perform Lyman alpha cooling and 1S-2S spectroscopy of trapped antihydrogen atoms for a precision test of CPT symmetry [1].
K1.00031 Constructing a Laser Stabilization System for a Parity Non-Conservation Experiment with Francium1, A.C. DEHART, GERALD GWINNER, MICHAEL KOSSIN, Univ of Manitoba, JOHN BEHR, ALEXANDRE GORELOV, MUKUT KALITA, MATTHEW PEARSON, TRIUMF, SETH AUBIN, C. of William and Mary, EDUARDO GOMEZ GARCIA, Instituto de Fisica, UASLP, LUIS OROZCO, QJI, Physics, U. of Maryland & NIST — We are developing an experiment at TRIUMF to test the Standard model at low energies by measuring Parity Non-Conservation (PNC) effects in francium. Current efforts include preparations to study the 7s – 8s electric dipole (E1) forbidden transition in francium at 507 nm under the influence of an electric field. Fr has no stable isotope; therefore to frequency-stabilize our laser at 507 nm, we are developing a laser stabilization system by using the Pound-Drever-Hall technique with a Fabry-Perot cavity made of Ultra Low Expansion Glass (ULE) as our stable frequency reference. The system will stabilize a 1014 nm laser, which will be frequency doubled to 507 nm, before sending the light to our cold and trapped francium sample. We will report on our recent experiences with the laser stabilization system.

K1.00032 Progress Towards an Order of Magnitude Improvement on the Measurement of the Electron Electric Dipole Moment1, DANIEL ANG, Harvard University, DAVID DEMILLE, Yale University, JOHN DOYLE, GERALD GABRIELSE, JONATHAN HAEFNER, Harvard University, ZACK LASNER, Yale University, COLE MEISENHELDER, CRISTIAN PANDA, Harvard University, ADAM WEST, Yale University, ELIZABETH WEST, Harvard University — The search for the electron electric dipole moment (eEDM) is a powerful probe of fundamental physics beyond the Standard Model. In 2014, the first generation of the ACME experiment set the most stringent upper limit on the eEDM of |d_e| < 1 x 10^{-30} e·cm by means of measuring spin precession in a beam of thorium monoxide (Science 343 (2014), 269-272). Since then, we have implemented various improvements, such as STIRAP preparation of the experimental H state, rotational cooling, optimized apparatus geometry, and enhanced detection efficiency, boosting our signal by a factor of about 400. We have also devised means to reduce the leading systematics we found in the Generation I experiment. We describe the recent progress in taking data using our Generation II apparatus and our ongoing efforts to investigate various systematics.

K1.00033 Future Improvements to the ACME Electric Dipole Moment Experiment1, JONATHAN HAEFNER, DANIEL ANG, JACOB BARON, Harvard University, DAVID DEMILLE, Yale University, JOHN DOYLE, GERALD GABRIELSE, NICHOLAS HUTZLER, Harvard University, ZACK LASNER, Yale University, COLE MEISENHELDER, CRISTIAN PANDA, Harvard University, ADAM WEST, Yale University, ELIZABETH WEST, Harvard University, ACME COLLABORATION — In 2014, the ACME collaboration set a new upper bound on the electric dipole moment of the electron using beams of cold ThO. We discuss studies into further improvements to the ACME experiment, with the eventual goal of sensitivity at the 10^{-30} e·cm level, a factor of 100 smaller than the first generation experiment. Methods focus primarily on improving statistics, and include the use of an electrostatic or magnetic molecular beam focusing lens, optical cycling to improve detection, and the use of a new thermochemical beam source to increase molecule number.

K1.00034 FLOQUENT PHYSICS —

K1.00035 A graph-theoretical representation of multiphoton resonance processes in artificial atoms, HOSSEIN Z. JOOYA, SHIH-I CHU, University of Kansas, UNIVERSITY OF KANSAS TEAM — We propose a graph-theoretical formalism to study generic circuit quantum electrodynamics systems consisting of a two level qubit coupled with a single-mode resonator in arbitrary coupling strength regimes beyond rotating-wave approximation. We define colored-weighted graphs, and introduce different production rules between them to investigate the dynamics of superconducting qubits in transverse, longitudinal, and bidirectional coupling schemes. The intuitive and predictive picture provided by this method, and the simplicity of the mathematical construction, are demonstrated with some numerical studies of the multiphoton resonance processes and quantum interference phenomena for the superconducting qubit systems driven by intense ac fields.

K1.00036 Direct Observation of Topological Invariants using Quantum Walks, VINAY RAMASESH, EMMANUEL FLURIN, SHAY HACohen-GOURGY, LEIGH MARTIN, IRFAN SIDDIQI, NORMAN YAO, Department of Physics, UC Berkeley — Quantum walks are generalizations of the classical random walk in which the walking particle is endowed with an internal degree of freedom and can exist on a superposition of lattice sites. Initially investigated as a possible replacement for classical random walks in randomized algorithms, quantum walks have since found numerous applications, including the possibility of performing universal quantum computation and simulating interacting systems. More recently, it was realized that quantum walks also possess topological properties. Like spin-orbit coupled Hamiltonians in condensed matter physics, the effective band-structures corresponding to quantum walks feature topological invariants robust to local deformations.

K1.00037 Investigation of a driven fermionic system and detecting chiral edge modes in an optical lattice, FREDERIK GRG, MICHAEL MESSEr, GREGOR JOTZU, KILIaN SANDBHOLZER, RMI DESBUQUOIS, Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland, NATHAN GOLDMAN, CENOLI, Facult des Sciences, Universit Libre de Bruxelles (U.L.B.), B-1050 Brussels, Belgium, TILMAN ESSLINGER, Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland — Periodically driven systems of ultracold fermions in optical lattices allow to implement a large variety of effective Hamiltonians through Floquet engineering. An important question is whether this method can be extended to interacting systems. We investigate driven two-body systems in an array of double wells and measure the double occupancy and the spin-spin correlator in the large frequency limit and when driving resonantly to an energy scale of the underlying static Hamiltonian. We analyze whether the emerging states of the driven system can be adiabatically connected to states in the unshaken lattice. In addition, we measure the amplitude of the micromotion which describes the short time dynamics of the system and compare it directly to theory. In another context we propose a method to create topological interfaces and detect chiral edge modes in a two dimensional optical lattice. We illustrate this through an optical lattice realization of the Haldane model for cold atoms, where an additional spatially-varying lattice potential induces distinct topological phases in separated regions of space.

1Supported by NSERC, NRC/TRIUMF, DOE, NSF, CONACYT, Fulbright, and U. of Manitoba

1We would like to thank the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST) for funding our experiment.
K1.00038 Discrete time-crystalline order in black diamond, HENG YUN ZHOU, SOONWON CHOI, JOONHEE CHOI, RENATE LANDIG, GEORG KUCSKO, Harvard University. JUNICHI ISOYA, University of Tsukuba, FEDOR JELEZKO, Ulm University, SHINOBU ONODA, Takasaki Advanced Radiation Research Institute, HITOSHI SUMIYA, Sumitomo Electric Industries Ltd., VEDIKA KHEMANI, Harvard University, CURT VON KEYSERLINGK, Princeton University, NORMAN Y. YAO, University of California Berkeley, EUGENE DEMLER, MIKHAIL D. LUKIN, Harvard University — The interplay of periodic driving, disorder, and strong interactions has recently been predicted to result in exotic “time-crystalline” phases, which spontaneously break the discrete time-translation symmetry of the underlying drive. Here, we report the experimental observation of such discrete time-crystalline order in a driven, disordered ensemble of $10^6$ dipolar spin impurities in diamond at room temperature. We observe long-lived temporal correlations at integer multiples of the fundamental driving period, experimentally identify the phase boundary and find that the temporal order is protected by strong interactions; this order is remarkably stable against perturbations, even in the presence of slow thermalization. Our work opens the door to exploring dynamical phases of matter and controlling interacting, disordered many-body systems.

K1.00039 Demonstration of the Kibble-Zurek mechanism in a non-equilibrium phase transition, YOGESH S. PATIL, HIL F. H. CHEUNG, ADITYA G. DATE, MUKUND VENGALATORE, Cornell University — We describe the experimental realization of a driven-dissipative phase transition (DPT) in a mechanical parametric amplifier and demonstrate key signatures of a critical point in the system, where the susceptibilities and relaxation time scales diverge and coincide with the spontaneous breaking of symmetry and the emergence of macroscopic order. While these observations are reminiscent of equilibrium phase transitions, it is presently an open question whether such DPTs are amenable to the conventional Landau-Ginsburg-Wilson paradigm that relies on concepts of scale invariance and universality — Indeed, recent theoretical work has predicted that DPTs can exhibit phenomenology that departs from these conventional paradigms [1]. By quenching the system past the critical point, we measure the dynamics of the emergent ordered phase and its departure from adiabaticity, and find that our measurements are in excellent agreement with the Kibble-Zurek hypothesis. In addition to validating the KZ mechanism in a DPT for the first time, we also uniquely show that the measured critical exponents accurately reflect the interplay between the intrinsic coherent dynamics and the environmental correlations, with a clear departure from mean field exponents in the case of non-Markovian system-bath interactions. We also discuss how the techniques of reservoir engineering and the imposition of artificial environmental correlations can result in the stabilization of novel many-body quantum phases and exotic non-equilibrium states of matter. [1] L. M. Sieberer et al., Phys. Rev. Lett. 110, 195301.

K1.00040 Long-range Prethermal Time Crystals, FRANCISCO MACHADO, GREGORY D. MEYER, University of California - Berkeley, DOMINIC ELSE, University of California - Santa Barbara, CHRISTOPHER OULUND, University of California - Berkeley, CHETAN NAYAK, Station Q - Microsoft Research, University of California - Santa Barbara, NORMAN Y. YAO, University of California - Berkeley — Driven quantum systems have recently enabled the realization of a discrete time crystal — an intrinsically out-of-equilibrium phase of matter. One strategy to prevent the drive-induced, runaway heating of the time crystal is the presence of strong disorder leading to many-body localization (MBL). A more elegant, disorder-less approach is simply to work in the prethermal regime where time crystalline order can persist to exponentially long times. One key difference between prethermal and MBL time crystals is that the former is prohibited from existing in one dimensional systems with short-range interactions. In this work, we demonstrate that long-range interactions can stabilize a one dimensional prethermal time crystal. By numerically studying the pre-thermal regime, we find evidence for a phase transition out of the time crystal as a function of increasing energy density. Finally, generalizations of previous analytical bounds for the heating time-scale of driven quantum systems to long-range interactions will also be discussed.

K1.00041 SYNTHETIC GAUGE FIELDS AND SPIN-ORBIT COUPLING IN COLD GASES —

K1.00042 Spin-orbit coupling in ultracold Fermi gases of $^{173}$Yb atoms, BO SONG, CHENG-DONG HE, ELNUR HAJIYEV, ZEJIAN REN, BOJEONG SEO, GEYUE CAI, DOVRAN AMANOV, SHANCHAO ZHANG, GYU-BOO NG JO, Hong Kong Univ of Sci & Tech — Synthetic spin-orbit coupling (SOC) in cold atoms opens an intriguing new way to probe nontrivial topological orders beyond natural conditions. Here, we report the realization of the SOC physics both in a bulk system and in an optical lattice. First, we demonstrate two hallmarks induced from SOC in a bulk system, spin dephasing in the Rabi oscillation and asymmetric atomic distribution in the momentum space respectively. Then we describe the observation of non-trivial spin textures and the determination of the topological phase transition in a spin-dependent optical lattice dressed by the periodic Raman field. Furthermore, we discuss the quench dynamics between topological and trivial states by suddenly changing the band topology. Our work paves a new way to study non-equilibrium topological states in a controlled manner.

1Supported by Croucher Foundation and Research Grants Council (RGC) of Hong Kong (Project ECS26300014, GRF16300215, GRF16311516, and Croucher Innovation grants).

K1.00043 Few-body bound states near free-space $p$-wave resonances in the presence of single-particle spin-orbit coupling terms, D. BLUME, Q. GUAN, Washington State University — Ultracold atom systems provide unique opportunities for studying extremely weakly-bound two- and few-body states. Theoretically, many aspects of such bound states have been explored successfully using zero-range $s$-wave contact interactions. Experimentally, bound state spectra have been deduced using radio-frequency spectroscopy. This work considers weakly-bound two- and few-body states in the vicinity of two-body free-space $p$-wave scattering resonances in the presence of spin-orbit coupling. While it has been shown previously that the single-particle spin-orbit coupling terms have a profound effect on the two- and three-body bound state energies for $s$-wave interacting systems, the interplay between two-body $p$-wave interactions and single-particle spin-orbit coupling terms is much less studied. This contribution discusses our implementation of the explicitly correlated Gaussian basis set expansion approach and the dependence of the resulting two- and few-body energy spectra on the free-space scattering volume, the two-body effective range, and the spin-orbit coupling parameters such as the Raman coupling strength and the detuning.

1Supported by the NSF is gratefully acknowledged.
K1.00044 New forms of spin-orbit coupling in a strontium optical lattice clock1. MICHAEL PERLIN, ARGHAVAN SAFAVI-NAINI, JILA, ROEE OZERI, Weizmann Institute of Science, ANÁ MARIA REY, JILA — Ultracold atomic systems allow for the simulation of a variety of condensed matter phenomena, including spin-orbit coupling (SOC), a key ingredient behind recently discovered topological insulators and a path for the realization of topological superfluids. While many experimental efforts have used alkali atoms to engineer SOC via Raman transitions, undesirable heating mechanisms have limited the observation of many-body phenomena manifest at long timescales. Alkaline earth atoms (AEA) have been recently shown to be a potentially better platform for the implementation of SOC due to their reduced sensitivity to spontaneous emission [1,2,3]. While previous work has used electronic clock states as a pseudo-spin degree of freedom, we consider the effects of clock side-band transitions. We discuss the richer SOC dynamics which emerges as a result of this extension, and present methods to probe these dynamics in current AEA optical lattice clocks. [1] Galitski, V. and Spielman, I.B., “Spin-orbit coupling in quantum gases.” Nature 494.7435 (2013): 49-54. [2] Kolkowitz, S., et al. “Spin-orbit-coupled fermions in an optical lattice clock.” Nature (2016). [3] Wall, M.L., et al. “Synthetic spin-orbit coupling in an optical lattice clock.” Physical review letters 116.3 (2016): 035301.

1AFOSR, NSF-PF and DARPA

K1.00045 Scattering resonances in a low-dimensional Rashba-Dresselhaus spin-orbit coupled quantum gas5. SU-JU WANG, D. BLUME, Department of Physics and Astronomy Washington State University — Confined-momentum resonances allow for the tuning of the effective one-dimensional coupling constant. When the scattering state associated with the ground transverse mode is brought into resonance with the bound state attached to the energetically excited transverse modes, the atoms interact through an infinitely strong repulsion. This provides a route to realize the Tonks-Girardeau gas. On the other hand, the realization of synthetic gauge fields in cold atomic systems has attracted a lot of attention. For instance, bound-state formation is found to be significantly modified in the presence of spin-orbit coupling in three dimensions. This motivates us to study ultracold collisions between two Rashba-Dresselhaus spin-orbit coupled atoms in a quasi-one-dimensional geometry. We develop a multi-channel scattering formalism that accounts for the external transverse confinement and the spin-orbit coupling terms. The interplay between these two single-particle terms is shown to give rise to new scattering resonances. In particular, it is analyzed what happens when the scattering energy crosses the various scattering thresholds that arise from the single-particle confinement and the spin-orbit coupling.

1Support by the NSF is gratefully acknowledged.

K1.00046 Microscopy of the interacting Harper-Hofstadter model in the few-body limit1, M. ERIC TAI, ALEXANDER LUKIN, MATTHEW RISPOLI, ROBERT SCHITTKO, TIM MENKE, DAN BORGNIA, Harvard University, PHILIPP PREISS, Universität Heidelberg, FABIAN GRUSDT, ADAM KAUFMAN, MARKUS GREINER, Harvard University — The interplay of magnetic fields and interacting particles can lead to exotic phases of matter exhibiting topological order and high degrees of spatial entanglement. While these phases were discovered in a solid-state setting, recent techniques have enabled the realization of gauge fields in systems of ultracold neutral atoms, offering a new experimental paradigm for studying these novel states of matter. This complementary platform holds promise for exploring exotic physics in fractional quantum Hall systems due to the microscopic manipulation and precision possible in cold atom systems. However, these experiments thus far have mostly explored the regime of weak interactions. Here, we show how strong interactions can modify the propagation of particles in a $2 \times N$, real-space ladder governed by the Harper-Hofstadter model. We observe inter-particle interactions affect the populating of chiral bands, giving rise to chiral dynamics whose multi-particle correlations indicate both bound and free-particle character. The novel form of interaction-induced chirality observed in these experiments demonstrates the essential ingredients for future investigations of highly entangled topological phases of many-body systems.

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K1.00047 Studies of dressed states with coupling between spin and orbital-angular-momentum in a Bose condensate 1, YU-JU LIN, HONG-REN CHEN, PAK-KONG CHEN, KUAN-YU LIN, HUNG-JI WEI, NENG-CHUN CHIU, Institute of Atomic and Molecular Sciences, Academia Sinica — We Raman-couple bare spin states of a Bose condensate with a transfer of orbital-angular-momentum (OAM), where one of the Raman beams is a Laguerre Gaussian beam. The dressed spin state in such systems is a superposition state consisting of bare spin states with different OAM. We characterize the spin texture, relevant gauge potentials and lifetime of these dressed states; it is studied in both trap geometries of harmonic potentials and ring-shaped potentials.

K1.00048 Observation of the supersolid stripe phase in spin-orbit coupled Bose-Einstein condensates1, JUNRU LI, JEONGWON LEE, WUJIE HUANG, SEAN BURCHESKY, BORIS SHTEYNAS, FURKAN TOP, ALAN JAMISON, WOLFGANG KETTERLE, Massachusetts Inst of Tech-MIT — Supersolidity combines the property of superfluid flow with long-range spatial periodicity of solids and has not been observed since predicted in condensed matter systems. The concept of supersolidity was then generalized to include other superfluid systems which break continuous translational symmetry. Bose-Einstein condensates with spin-orbit coupling are predicted to possess a stripe phase with supersolid properties. Here we report the first observation of the predicted density modulation of the stripe phase using Bragg reflection — the evidence for spontaneous long-range order in one direction while maintaining a sharp momentum distribution — the hallmark of superfluid Bose-Einstein condensates. In our system, the spin-orbit coupling was realized in an optical superlattice as described in [1]. Briefly two lowest bands in the superlattice were used as pseudospins and a Raman process was implemented to provide coupling between pseudospin and momentum. Our work establishes a system with unique continuous symmetry breaking properties, associated Goldstone modes and superfluid behavior. References: [1] J. Li et. al PRL 117.185301 [2] J. Li et. al arXiv:1610.08194

1We acknowledge the support from the NSF through the Center for Ultracold Atoms and by award 1506369, from ARO-MURI Non-equilibrium Many-body Dynamics (grant W911NF-14-1-0003) and from AFOSR-MURI Quantum Phases of Matter (grant FA9550-14-1-0005)

K1.00049 NONLINEAR DYNAMICS AND OUT OF EQUILIBRIUM TRAPPED GASES —
K1.00050 One-body density-matrix characterization of many-body localization, FABIAN HEIDRICH-MEISNER, LMU Munich, Germany, SOUMYA BERÁ, MPI PKS Dresden, Germany, THOMAS MARTYNEC, TU Berlin, Germany, HENNING SCHOMERUS, Lancaster University, UK, JENS BARDARSON, MPI PKS Dresden, Germany — We present a comprehensive analysis of the one-body density matrix (OPDM) in a system of interacting fermions in the presence of disorder in a one-dimensional lattice. We show that the eigenstates of the OPDM are localized/delocalized in the many-body localized (MBL)/ergodic phase while the eigenvalues exhibit a characteristic discontinuity in MBL phase reminiscent of the momentum distribution function of a zero-temperature Fermi-liquid [1]. Based on these results, we discuss the connection of OPDM eigenstates to quasi-particle-like integrals of motion in the MBL phase [2]. [1] Bera et al. Phys. Rev. Lett. 115, 046603 (2015) [2] Bera et al. arXiv:1611.01687.

K1.00051 Measuring commutator square in nuclear spin systems, XUAN WEI, Massachusetts Inst of Tech-MIT, CHANDRAKAR RANJANATHAN, Dartmouth College, PAOLA CAPPELLARO, Massachusetts Inst of Tech-MIT — Out-of-time ordered correlations (OTOC) have recently received much attention due to their unique ability to probe information scrambling in many-body quantum systems. As a result OTOC have been fruitfully applied to the study of quantum chaos, many-body localization, and quantum phase transitions. We provide experimental measurements of the commutator square, akin to OTOC, in a disordered interacting spin chain at effectively infinite temperature. We observe a slow growth of the commutator square consistent with slow information scrambling in disordered systems. We also measure the commutator square in a system exhibiting a phase transition; we observe the commutator square to grow the fastest near the critical point.

K1.00052 Quantum dynamics of dynamically unstable, integrable few-mode systems, RANCHU MATHEW, University of Maryland, EITE TIESINGA, University of Maryland and National Institute of Standards and Technology — Recently, quenches in isolated ultra-cold atomic quantum systems have become a subject of intense study. We consider quantum few-mode systems that are integrable in their classical mean-field limit and become dynamically unstable after a quench of a system parameter. Specifically, we study the cases of a Bose-Einstein condensate (BEC) in a double-well potential and of an antiferromagnetic $\mathbf{F} = 1$ spinor BEC constrained to a chain at a finite temperature. After the quench within the truncated Wigner approximation and find that due to phase-space mixing the systems relax to a steady state. Using action-angle formalism and guided by insights from the related pendulum system, we obtain analytical expressions for the time evolution of expectation values of observables and their long-time values. We also study the full quantum dynamics of the systems. Comparing their results with the TWA results, we find agreement in the long-time expectation value of the observables. The relaxation time scales, however, are different.

K1.00053 Modulational instability and its role in the formation of matter-wave soliton trains, DE LUO, JASON H. V. NGUYEN, RANDALL G. HULET, Department of Physics and Astronomy, Rice University — Modulational instability (MI) is a process by which perturbations at a critical wavelength in a waveform grow exponentially due to the interplay between a focusing nonlinearity and dispersion. The break-up of the waveform can lead to the formation of soliton trains. It was observed that matter-wave soliton trains form from a Bose-Einstein condensate, after an interaction quench from a repulsive to an attractive nonlinearity[1]. An alternating phase structure was inferred from the dynamics of the soliton train, in which adjacent solitons repel one another. The mechanism by which the phase structure develops remains unclear. In this work, we examine the role of MI in the formation of the matter-wave soliton trains. We confirm that MI correctly predicts the number of solitons and the time-scale of the formation process. With real-time imaging, we provide evidence that the soliton train is born with an alternating phase structure, rather than evolving into one.

1Work supported by the NSF, ONR, an ARO MURI grant, and the Welch Foundation.

K1.00054 Superradiance and dynamical instability in an illuminated BEC, WILLIAM LUNDEN, JESSE AMATO-GRILL, IVANA DIMITROVA, NIKLAS JEPSEN, WOLFGANG KETTERLE, MIT — An elongated, trapped Bose-Einstein condensate illuminated by an off-resonant laser beam has been used as a platform to observe superradiant Rayleigh scattering for almost two decades. We now consider the case of an elongated BEC illuminated by a pair of non-interfering, off-resonant lasers, and explore the dynamics of the coupled light-matter system in the short-time regime (i.e., times on the order of the inverse of the single-photon recoil frequency). In particular, we look for signatures of a proposed dynamical instability in the coupled system which spontaneously breaks the translational symmetry of both the BEC density and the total light field’s intensity profile along the long axis of the trap. We also explore the relative roles of the spontaneous light force and the dipole force in both superradiance and this dynamical instability.

K1.00055 Influence of system-bath interactions on driven-dissipative phase transitions, HIL F H CHEUNG, YOGESH S PATIL, MUKUND VENGALATTOR, Cornell University — A wide range of non-equilibrium systems exhibit signatures of critical behavior and phase transitions such as critical slowing down, divergent correlation lengths and susceptibilities. Such signatures are coincident with the emergence of macroscopic phases due to the interplay between the coherent system dynamics and dissipation to the environment. In contrast to equilibrium physical systems, the physical mechanisms that give rise to this order involve both the system and the environment. Due to the different origins of these mechanisms, such driven-dissipative transitions can exhibit dynamical phase transitions where the critical behavior lies beyond the conventional universality classes of equilibrium phase transitions [1]. We describe such a driven-dissipative phase transition in a parametric oscillator-amplifier system and demonstrate that the system exhibits key signatures of a continuous phase transition, including a spontaneously broken symmetry and the emergence of goldstone modes. In contrast to an equilibrium phase transition, we show that the phase diagram and emergent phases crucially depend on the environmental correlations and that as such, can be modified by the imposition of correlations beyond the Markovian regime. We also discuss the extension of this description of universal behavior near criticality in driven-dissipative phase transitions to lower dimensions. [1] L. M. Sieberer et al., Phys. Rev. Lett. 110, 195301.

K1.00056 The Kibble-Zurek mechanism in phase transitions of non-equilibrium systems, HIL F H CHEUNG, YOGESH S PATIL, ADITYA G DATE, MUKUND VENGALATTOR, Cornell University — We experimentally realize a driven-dissipative phase transition using a mechanical parametric amplifier to demonstrate key signatures of a second order phase transition, including a point where the susceptibilities and relaxation time scales diverge, and where the system exhibits a spontaneous breaking of symmetry. Though reminiscent of conventional equilibrium phase transitions, it is unclear if such driven-dissipative phase transitions are amenable to the conventional Landau-Ginsburg-Wilson paradigm, which relies on concepts of scale invariance and universality, and recent work has shown that such phase transitions can indeed lie beyond such conventional universality classes [1]. By quenching the system past the critical point, we investigate the dynamics of the emergent ordered phase and find that our measurements are in excellent agreement with the Kibble-Zurek mechanism. In addition to verifying the Kibble-Zurek hypothesis in driven-dissipative phase transitions for the first time, we also demonstrate that the measured critical exponents accurately reflect the interplay between intrinsic coherent dynamics and environmental correlations, showing a clear departure from mean field exponents in the case of non-Markovian system-bath interactions. We further discuss how reservoir engineering and the imposition of artificial environmental correlations can result in the stabilization of novel many-body quantum phases and aid in the creation of exotic non-equilibrium states of matter. [1] L. M. Sieberer et al., Phys. Rev. Lett. 110, 195301.
Designing an optical lattice trap for ions

MATT GRAU, CHRISTOPH FISCHER, OLIVER WIPFLI, JONATHAN HOME, ETH Zurich — Ions trapped in an optical lattice have the potential to realize interesting two and three-dimensional geometries with long range, tunable spin-spin couplings with application to quantum simulation of many-body spin Hamiltonians. For 2D lattices, we employ an approach based on the recursive calculation of the Green's functions for two interacting particles. This work was funded by NSERC of Canada.
K1.00064 Cold interactions and chemical reactions of linear polyatomic anions with alkali-metal and alkaline-earth-metal atoms, MICHAL TOMZA, Univ of Warsaw — We consider collisional studies of linear polyatomic ions immersed in ultracold atomic gases and investigate the intermolecular interactions and chemical reactions of several molecular anions (OH−, CN−, NCO−, C2H−, C3H−) with alkali-metal (Li, Na, K, Rb, Cs) and alkaline-earth-metal (Mg, Ca, Sr, Ba) atoms. State-of-the-art ab initio techniques are applied to compute the potential energy surfaces (PESs) for these systems. The coupled cluster method restricted to single, double, and noniterative triple excitations, CCSD(T), is employed and the scalar relativistic effects in heavier metal atoms are included within the small-core energy-consistent pseudopotentials. The leading long-range isotropic and anisotropic induction and dispersion interaction coefficients are obtained within the perturbation theory. The PESs are characterized in detail and their universal similarities typical for systems dominated by the induction interaction are discussed. The possible channels of chemical reactions and their control are analyzed based on the energetics of reactants. The present study of the electronic structure is the first step towards the evaluation of prospects for sympathetic cooling and controlled chemistry of linear polyatomic ions with ultracold atoms.

K1.00065 Manifestations of dipolar collisions in thermal and BEC gases of dysprosium, YIJUN TANG, Stanford University, ANDREW SYKES, LPTMS, CNRS, Univ.Paris Sud, Universit Paris-Saclay, NATHANIEL BURDICK, Stanford University, DMITRY S. PETROV, LPTMS, CNRS, Univ.Paris Sud, Universit Paris-Saclay, BENJAMIN LEV, Stanford University — Ultracold and quantum gases of dysprosium provide the opportunity to explore the physics of strongly dipolar gases. In this talk, we report on two recent experiments that highlight this physics. The first is a direct measurement of collisions between two Bose-Einstein condensates with strong dipolar interactions. A collision halo corresponding to the two-body differential scattering cross section is observed. The results demonstrate a novel regime of quantum scattering, relevant to dipolar interactions, in which a large number of angular momentum states become coupled during the collision. We perform Monte-Carlo simulations to provide a detailed comparison between theoretical two-body cross sections and the experimental observations. The second is a measurement of the anisotropic expansion of ultracold bosonic dysprosium gases at temperatures above quantum degeneracy. We develop a theory to express the post-expansion aspect ratio in terms of temperature and microscopic collisional properties by incorporating Hartree-Fock mean-field interactions, hydrodynamic effects, and Bose-enhancement factors. Our results extend the utility of expansion imaging by providing accurate thermometry for dipolar thermal Bose gases.

K1.00066 A quantum gas microscope for highly dipolar atoms, SUSANNAH DICKERSON, ANNE HEBERT, AARON KRAHN, GREGORY PHELPS, MARKUS GREINER, Harvard University — Highly dipolar atoms present an exciting opportunity to extend previous quantum gas microscope (QGM) experiments to more complex systems influenced by long range, anisotropic interactions. With its large dipole moment, numerous isotopes, and rich Feshbach spectrum, is an excellent element for such research. We present on current progress toward the construction of a QGM for ultracold erbium atoms in an optical lattice. We discuss technical features including the novel reflective imaging system and the optical lattice expandable in all three dimensions. We also discuss proposed avenues for research including studies of magnetism, the Einstein-de Haas effect, and quantum phase transitions with fractional filling factors.

K1.00067 Retardation effects in induced atomic dipole-dipole interactions, SEAN GRAHAM, JEFFREY MCGUIRK, Simon Fraser University — We present mean-field calculations of azimuthally averaged retarded dipole-dipole interactions in a Bose-Einstein condensate induced by a laser, at both long and short wavelengths. Our calculations demonstrate that dipole-dipole interactions become significantly stronger at shorter wavelengths, by as much as 30-fold, due to retardation effects. This enhancement along with the inclusion of the dynamic polarizability, indicate a method of inducing long-range interatomic interactions in neutral atom condensates at significantly lower intensities than previously realized.

K1.00068 Dipolar droplets in bosonic erbium quantum fluids.1, LAURIANNE CHOMAZ, SIMON BAIER, DANIEL PETTER, GIULIA FARAO’NI, JAN-HENDRIK BECHER, RICK VAN BIJNEN, MANFRED J. MARK, FRANCESCA FERLAINO, University of Innsbruck — Due to their large magnetic moment and exotic electronic configuration, atoms of the lanthanide family, such as dysprosium (Dy) and erbium (Er), are an ideal platform for exploring the competition between inter-particle interactions of different origins and behaviors. Recently, a novel phase diagram of damped gas Carnot has been observed in a ultracold gas of bosonic Dy when changing the ratio of the contact and dipole-dipole interactions and setting the mean-field interactions to slightly attractive. This has been attributed to the distinct, non-vanishing, beyond-mean-field effects in dipolar gases when the mean interaction cancels. Here we report on the investigation of droplet physics in fluids of bosonic Er. By precise control of the scattering length a, we quantitatively probe the Bose-Einstein condensate (BEC)-to-droplet phase transition and the rich underlying dynamics. In a prolate geometry, we observe a crossover from a BEC to a single macro-droplet, prove the suppression role of quantum fluctuations and characterize the special dynamical properties of the droplet. In an oblate geometry, we observe the formation of assemblies of tinier droplets arranged in a chain and explore the special state dynamics following a quench of a, marked by successive merging and reformation events.

1L.C. is supported within the Marie Curie Individual Fellowship DIPPHASE No. 706809 of the European Commission.

K1.00069 Thermodynamics and Magnetism of the Fermi-Hubbard Hamiltonian 2D-3D Crossover, RICK MUKHERJEE, Rice University, THEREZA PAIVA, Instituto de Fisica, Universidade Federal do Rio de Janeiro, RICHARD T. SCALETTAR, University of California, Davis, RANDALL G. HULET, KADEN R. A. HAZZARD, Rice university — To observe antiferromagnetism with fermionic ultracold atoms in optical lattices is one of the major ongoing pursuits in cold atoms. Atoms in anisotropic lattices are an interesting place to explore anti-ferromagnetic (AF) order in ultracold systems. We investigate the possibility of enhancing magnetic order by using anisotropy, specifically in a cubic lattice with tunneling stronger along two directions than in the third, which intercalates between the 2D and isotropic 3D regimes. Using determinant Quantum Monte Carlo methods, we calculate the real space spin-spin correlations and the corresponding magnetic structure factor as a function of temperature and anisotropy for the model at half filling. Similar to the 1D-3D crossover, we find enhanced magnetic structure due to anisotropy for some interaction strengths. Although the long-ranged magnetic order never exceeds that of the isotropic system at the optimal interaction strength, the correlations become anisotropic, which can lead to enhanced short-ranged correlations along certain directions.

K1.00070 COLD RYDBERG GASES AND PLASMAS —

K1.00071 Probing inter-atomic correlations using excitation to high Rydberg states1, JOVICA STANOJEVIC, ROBIN CÔTÉ, Department of Physics, University of Connecticut, Storrs — We study potential surfaces of a Rydberg atom interacting with several ground-state atoms of the same or different species than the Rydberg atom. The energy of the Rydberg atom depends measurably on the positions of the ground-state atoms and the Rydberg state. It has been demonstrated recently that these potentials support molecular bound states. Our goal is to utilize these potential surfaces for various nl states as means to probe correlations between ground-state atoms.

1This work is partially funded by the PIF program of the National Science Foundation grant number PHY-1415560.
K1.00072 Measurement of $nD$ Rydberg-ground molecules in Rb. JAMIE MACLENNAN, GEORG RAITHEL, University of Michigan — We experimentally measure the energies of several Rydberg-ground molecular bond states in Rb($nD + 5S_{1/2}$), including vibrationally excited states. Because these molecular states arise from the scattering interaction of a Rydberg electron with a ground-state atom, their measurement allows an estimate of scattering lengths. Photoassociation out of an optical dipole trap facilitates our observation of molecules of relatively low principal quantum numbers, leading to good resolution of the bound-energy measurements. The study further addresses hyperfine-mixed singlet-triplet states.

K1.00073 Adiabatic preparation of Rydberg crystals in a cold lattice gas: Influence of atomic relaxations. DAVID PETROSYAN, Inst of Elec Structure & Laser, FORTH, Greece, KLAUS MOLMER, Department of Physics and Astronomy, Aarhus University, Denmark, MICHAEL FLEISCHHAUER, Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Germany — Strong, long-range interactions between atoms in high-lying Rydberg states make them attractive systems for the studies of ordered phases and phase transitions of interacting many-body systems. Different approaches have been explored, both theoretically and experimentally, for the preparation of crystalline order of Rydberg excitations in spatially-extended ensembles of cold atoms. These include direct (near-)resonant laser excitation of interacting Rydberg states in a lattice gas, and adiabatic preparation of crystalline phases of Rydberg excitations in a one-dimensional optical lattice by adiabatic frequency sweep of the excitation laser. We show, however, that taking into account realistic relaxation processes affecting the atoms severely complicates the prospects of attaining sizable crystals of Rydberg excitations in laser-driven atomic media. Our many-body simulations well reproduce the experimental observations [Schauf et al., Science 347, 1455 (2015)] of spatial ordering of Rydberg excitations in driven dissipative lattice gases, as well as highly sub-Poissonian probability distribution of the excitation number. We find that the excitations essentially form liquid rather than crystal phases with long-range order.

K1.00074 Effect of atomic motion on Rydberg blockade in a hot atomic beam1. S. YOSHIDA, J. BURGDÖRFER, Vienna University of Technology, X. ZHANG, F. B. DUNNING, Rice University — The dipole blockade of very-high-$n$ ($n \sim 300$) strontium 5s$n^f$ $^1F_3$ Rydberg atoms in a hot atomic beam is studied. For such high $n$, the blockade radius ($\sim 0.1$mm) can exceed the linear dimensions of the excitation volume. Rydberg atoms formed inside the excitation volume can, upon leaving the region, continue to suppress excitation until they have moved further away than the blockade radius. Moreover, the high density of states near the $F$-states originating from strong coupling to nearby high-$L$ states results in a small but finite probability for excitation of $n^1F_3$ atom pairs at small internuclear separations below the blockade radius. We suggest a theoretical model to study the time evolution of the average Rydberg number and the Mandel Q parameter revealing the correlation in many-body excitation in a time resolved manner. The results will be compared with measured data.

1Research supported by the NSF, the Robert A. Welch Foundation, and the FWF (Austria).

K1.00075 Towards Rydberg dressing of a lithium Fermi gas. ELMER GUARDADO-SANCHEZ, PETER SCHAUSS, DEBAYAN MITRA, PETER BROWN, WASÉEM BAKR, Princeton University — One attractive route towards finite-range interactions in ultracold gases is off-resonant coupling to Rydberg states, the so-called Rydberg dressing. Lithium is an interesting candidate due to its light mass and therefore fast dynamics. We report on the progress of Rydberg spectroscopy of lithium $p$-states with an ultra-violet laser at 230nm. We achieve narrow linewidth UV-light of up to 80mW by frequency-quadrupling of an amplified diode laser at 920nm locked to a ULE cavity. As a first step we implemented a V-type spectroscopy in a lithium cell and afterwards we plan to perform high-resolution loss spectroscopy in our quantum gas microscope setup. The long-term goal is a Fermi gas with tunable finite-range interactions under the microscope.

K1.00076 Toward Probing Many-Body Correlations in Ultracold Gases using Ultralong-Range Rydberg Molecules1. J. D. WHALEN, R. DING, F. CAMARGO, F. B. DUNNING, T. C. KIL-LIAN, Rice University — Experimental techniques such as photoassociation spectroscopy and, more recently, quantum gas microscopes have been developed to probe correlations between atoms in ultracold quantum systems. These techniques have been remarkably successful at measuring correlations at very short ranges, $r < 200 \text{ a}_{0}$, and at ranges of the order of an optical lattice site, $r > 5000 \text{ a}_{0}$. However, many physical systems such as halo dimers, Efimov trimers, Cooper pairs, etc. express correlations in a more intermediate regime. We propose a new method of probing this intermediate regime using photoassociation of ultralong-range Rydberg molecules. Excitation to well localized dimer states of vanishing principal quantum number ($20 < n < 100$) will provide a tunable probe of interparticle correlations and direct measurement of the two-body correlation function $g^{(2)}(r)$. We present an experimental proposal and preliminary results using this technique to measure the two-body wavefunction of a strongly interacting gas of $^{84}$Sr and $^{88}$Sr.

1Research supported by the AFOSR, NSF, Robert A Welch Foundation, and The Rice Dean’s Fund

K1.00077 Symmetry-protected collisions between strongly interacting photons. TRAVIS NICHOLSON, Massachusetts Institute of Technology, JEFF THOMPSON1, Harvard University, QIUYU LIANG, SERGIO CANTU, Massachusetts Institute of Technology, ADITYA VENKATRAMANI, SOONWON CHOI, Harvard University, DANIEL VISCOR, THOMAS POHL, Max Planck Institute for the Physics of Complex Systems, MIKHAIL LUKIN, Harvard University, VLADAN VULETIC, Massachusetts Institute of Technology — Realizing robust quantum phenomena in strongly interacting systems is one of the central challenges in modern physical science. Here, using coherent coupling between light and Rydberg excitations in an ultracold atomic gas, we demonstrate a controlled and coherent state exchange collision between two strongly interacting photons. The collision is accompanied by a $\pi/2$ phase shift, which is robust in that the value of the shift is determined by the interaction symmetry rather than the precise experimental parameters, and in that it occurs under conditions where photon absorption is minimal. The measured phase shift of 0.48(5)$\pi$ is in excellent agreement with a theoretical model. These observations open a route to realizing robust single-photon switches and all-optical quantum logic gates, and to exploring novel quantum many-body phenomena with strongly interacting photons.

1Current affiliation: Princeton University

K1.00078 Spatial and Temporal Correlations in a Cold-Atom Rydberg-EIT System, MICHAEL VIRAY, STEPHANIE MILLER, GEORG RAITHEL, University of Michigan — We investigate spatial and temporal second-order correlation functions, $g''((2)) (r)$ and $g''((2)) (r)$, of cold rubidium-87 Rydberg atoms in a Rydberg-electromagnetically-induced-transparency (Rydberg-EIT) medium. To measure the spatial correlations, Rydberg atoms are field-ionized, and the resulting ion positions are recorded and processed to yield the spatial correlation function. For the temporal correlations in the Rydberg-EIT medium, the photon timing of the probe beam is recorded with a single photon counting module, and temporal correlations are extracted. We present preliminary results of these measurements and look at relations between the two correlation functions.
K1.00079 Ultracold neutral plasma heating due to resonance excitation. ADAM DODSON, QUINTON MCKNIGHT, TUCKER SPRENKLE, SCOTT BERGESON, Brigham Young University — We report electron heating measurements in an expanding ultracold neutral calcium plasma. The plasma is formed by resonantly ionizing calcium atoms in a magneto-optical trap. The 397 nm resonance transition is excited at intensities ranging from 0.2 to 10 times the saturation intensity. We observe an increasing plasma expansion rate due to more rapid electron heating as the intensity of the 397 nm excitation increases. We discuss possible implications for laser-cooling the ions in this ultracold neutral plasma environment.

1Supported in part by National Science Foundation grant PHY-1404488

K1.00080 Experimental optimization of directed field ionization. ZHIMIN CHERYL LIU, VINCENT C. GREGORICI, Bryn Mawr College, THOMAS J. CARROLL, Ursinus College, MICHAEL W. NOEL, Bryn Mawr College — We report on the development of an apparatus for the study of quantum dynamics of Rydberg atoms of potassium. Samples of Rydberg atoms at 1 mK and present calculated lifetimes of the relevant states in different temperature regimes.

This work was supported by the National Science Foundation under Grants No. 1607335 and No. 1607377.

K1.00081 Directed Field Ionization: A Genetic Algorithm for Evolving Electric Field Pulses. XINYUE KANG, ZOE A. ROWLEY, THOMAS J. CARROLL, Ursinus College, MICHAEL W. NOEL, Bryn Mawr College — When an ionizing electric field pulse is applied to a Rydberg atom, the electron’s amplitude traverses many avoided crossings among the Stark levels as the field increases. The resulting superposition determines the shape of the time resolved field ionization spectrum at a detector. An engineered electric field pulse that sweeps back and forth through avoided crossings can control the phase evolution so as to determine the electron’s path through the Stark map. In the region of $n=35$ in rubidium there are hundreds of potential avoided crossings; this yields a large space of possible pulses. We use a genetic algorithm to search this space and evolve electric field pulses to direct the ionization of the Rydberg electron in rubidium. We present the algorithm along with a comparison of simulated and experimental results.

This work was supported by the National Science Foundation under Grants No. 1607335 and No. 1607377 and used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number OCI-1053575.

K1.00082 Blackbody effects in high-precision microwave spectroscopy with circular Rydberg atoms. STEPHEN DIORIO, ANDIRA RAMOS, KAITLIN MOORE, GEORG RAITHAL, University of Michigan — Rydberg atoms experience a shift in transition frequencies and a shortening of lifetimes due to blackbody radiation (BBR). In a proposed Rydberg-constant measurement (RCM), which hopes to contribute to solving the “proton radius puzzle” [Bermu, Pohl, Sci. Am. 310, 32 (2014)], circular Rydberg atoms are used. This work requires a careful examination of BBR effects. Typically, approximations are made to account for BBR effects, however, since BBR at room temperature matches the frequency range of our transitions, we follow the exact procedure outlined by Farley and Wing [Farley, Wing, Phys. Rev. A, 23, 2937 (1981)] to calculate these shifts. We present calculations for BBR shifts in different temperature regimes and show that these calculated shifts converge and do not necessitate the consideration of continuum transitions. We also present calculated lifetimes of the relevant states in different temperature regimes.

K1.00083 An ultracold potassium Rydberg source for experiments in quantum optics and many-body physics. CHARLES CONOVER, PAMELA DUPRE, AI PHUONG TONG, CARLVIN SANON, KEVIN CLARKE, BRIAN DOOLITTLE, STEPHEN LOURIA, PHILIP ADAMSON, Colby College Department of Physics and Astronomy — We report on the development of an apparatus for the study of quantum dynamics of Rydberg atoms of potassium. Samples of Rydberg atoms at 1 mK and varying density are excited in a magneto-optical trap of $10^{-3}$ K-39 atoms. The atoms are excited to Rydberg states in a steps from 4s to 5p and from 5p to $n s$ and $n d$ states using stabilized external-cavity diode lasers at 405 nm and 980 nm. Selective field ionization and detection with microchannel plates provides a platform for spectroscopic measurements in potassium, exploration of multiphoton processes, and experiments on cold atom collisions.

This research was supported by the National Science Foundation under Grant PHY-1126599.

K1.00084 A Rydberg/cavity QED apparatus for exploring polariton blockade. ALEXANDROS GEORGAKOPOULOS, ALBERT RYOO, NINGUAN JIA, NATHAN SCHINE, Univ of Chicago, ARIEL SOMMER, MIT, JONATHAN SIMON, Univ of Chicago — In this work, we present the technical advances that have enabled us to explore Rydberg-mediated Interactions between resonator photons. In particular, we describe an exotic resonator geometry that enables us to maintain the small mode waist essential for exploring blockade physics, while keeping all material surfaces nearly a full cm away from the electric-field sensitive Rydbergs. We achieve strong fields stable at the 10mV/cm level over a day, in spite of the presence of a hight-voltage piezo actuator to stabilize the resonator length to the few angstrom level. This enables us to employ 87Rb Rydbergs in the n=1215 quantum state, with a DC polarizability of nearly 24GHz/(v/cm)^2, for our cavity Rydberg EIT experiments, thereby reaching the blocked regime, indicating strong interactions between individual photons. We will also explore prospects for pushing these experiments into a multimode regime where dissipative manybody pumping will allow us to explore crystals and topological fluids of photons.

K1.00085 DEGENERATE FERMI GASES

K1.00086 Towards ultracold mixtures of lithium and strontium atoms. XIAOBIN MA, ZHUXIONG YE, LIYANG XIE, XIANGLIANG LI, State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, LI YOU, MENG KHOON TEE, State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University; Collaborative Innovation Center of Quantum Matter — Both lithium and strontium come with bosonic and fermionic isotopes, which will enable many possibilities for rich inter-species interaction dominated mixture physics, and facilitate systematic investigations of impurity and disorder related many body quantum models. Progress towards a new experimental setup aimed at realizing degenerate mixtures of lithium and strontium atoms will be presented.
K1.00087 Transport of ultracold atoms through a quantum point contact . SAMUEL HUSLER, MARTIN LEBRAT, DOMINIK HUSMANN, LAURA CORMAN, SEBASTIAN KRINNER, ETH Zürich, CHARLES GRENIER, ENS Lyon, JEAN-PHILIPPE BRANTUT, EPFL Lausanne, TILMAN ESSLINGER, ETH Zürich — We explore transport of neutral particles through a quantum point contact with tunable interactions. The contact is optically imprinted onto the center of a cigar-shaped cloud of fermionic lithium 6 atoms connected to macroscopic reservoirs on each side. We create a particle, spin or temperature bias between the reservoirs and measure the induced conductance. At weak attractive interactions we observe quantized particle conductance at multiples of 1/h, an upper bound for Fermi liquid reservoirs. Upon increasing attraction the plateaus continuously increase to non-universal values as high as 4/h before the gas becomes superfluid. At stronger interactions, the plateaus in the particle conductance disappear while spin transport is suppressed, signaling the emergence of superfluid pairing. The anomalous quantization challenges a Fermi liquid description of the normal phase, shedding new light on the strongly attractive gas. Complementary to particle and spin transport we study the thermoelectric response to a temperature gradient between the reservoirs. We observe that resonant interactions strongly modify the particle and energy evolution compared to the weakly attractive case.

K1.00088 New apparatus for the production of Fermi-Fermi mixtures of Dy and K , MARIAN KREYER, CORNELIS RAVENBERGEN, SŁAWA TZANOWA, ELISA SOAVE, ALEXANDER WERLBERGER, VINCENT CORRE, EMIL KIRILOV, RUDOLF GRRIMM, Institute for Quantum Optics and Quantum Information, Austrian Academy of Science, and Institute for Experimental Physics, University of Innsbruck — We have developed a new apparatus for the production of Fermi-Fermi mixtures of dysprosium and potassium. An atomic beam of dysprosium is produced in a high-temperature effusion oven and decelerated with a Zeeman slower. The atoms are then trapped by a narrow-line magneto-optical trap (MOT) operating on the 626 nm intercombination transition. Potassium atoms are first trapped with a 2D+ MOT, which produces a beam of slow atoms, and then transferred to the 3D MOT in the main chamber. We have so far achieved MOTs of bosonic 39K and 164Dy, and fermionic 40K and 161Dy, as well as the first double MOT of Dy and K. Our laser systems are based on infrared fiber lasers, which provide Dy light via sum frequency generation and K light via frequency-doubling, respectively. This brings the advantages of high stability, narrow linewidths and high beam quality, as well as the possibility to supply repumping light for potassium via sideband modulation. Further laser systems will enable narrow-line cooling for Dy as well as gray-molasses cooling for K.


1We acknowledge support from National Science Foundation Grant No. DMR-1151717.

K1.00090 Fermi Gas Microscopy of Potassium , FUDONG WANG, RHYS ANDERSON, PEIHANG XU, VIJIN VENU, GRAHAM J. A. EDGE, STEFAN TROTZY, JOSEPH H. THYWISSEN, Department of Physics, University of Toronto — Quantum gas microscopes offer a unique and direct view on strongly correlated atoms in optical lattices. Optical imaging with single-site resolution is a local probe, when the system size is large, and especially when motional states of atoms are restricted to the lowest band of the lattice. We present the current performance of our Fermi gas microscopy imaging 40K atoms trapped in an optical lattice through a 200-micron-thick sapphire window. In-situ fluorescence imaging relies on continuous laser cooling to pin atoms to a single site during imaging. We have extended our original approach of electromagnetically-induced-transparency (EIT) cooling by combining it with simultaneous Raman sideband cooling (RSC). This method shows an improved performance over a "pure EIT" cooling scheme. We describe the principle behind this method, show new images, and discuss measurements in progress.

K1.00091 Probing and studying homogeneous atomic Fermi gases . ZHENJIE YAN, BISWAROOP MUKHERJEE, PARTH PATEL, ĀIRILĀ SHAFFER-MOÅG, CEDRIC WILSON, RICHARD FLETCHER, Massachusetts Institute of Technology, ZORAN HADZIBABIC, Cavendish Laboratory, University of Cambridge, TARIK YEFSAH, LKB, CNRS, ENS-PSL Research University, UPMC-Sorbonne Universités and Collège de France, JULIAN STRUCK, MARTIN ZWIERLEIN, Massachusetts Institute of Technology — We create and study homogeneous Fermi gases of ultracold atoms in uniform trapping potentials. The homogeneity of the gas enables the measurement of momentum distributions without density averaging. For the non-interacting Fermi gas, we observe the emergence of the Fermi surface and the saturated occupation of one particle per momentum state. For thermodynamic measurements, we convert the uniform trap into a hybrid potential that is harmonic in one dimension and uniform in the other two. The spatially resolved compressibility reveals the superfluid transition in a spin-balanced Fermi gas, saturation in a fully polarized Fermi gas, and strong attraction in the polaronic regime of a partially polarized Fermi gas. In addition, we present results on the temperature dependence of the contact of the unitary Fermi gas measured with radio-frequency spectroscopy.

K1.00092 QUANTUM INFORMATION –

K1.00093 Towards quantum information transport through a classical conductor . DA AN, HARTMUT HAEFFNER, MAYA LEWIN-BERLIN, ERIK URBAN, Univ of California - Berkeley — Establishing quantum links between separately trapped ions is a significant step towards scalable trapped ion quantum computation. Here, we present our design, simulation, and ongoing implementation of a novel surface ion trap for studying quantum correlations between separate trapping sights through an ordinary conducting wire. This is a challenging task since the thermal noise in the wire is much greater than the motional ion energy, but as long as the decoherence sources are minimized, we can achieve quantum coupling through the wire. We also include intermediate steps towards this goal, such as characterizing the stability of our novel trap, which has variable trapping height, and establishing a classical link through the wire. This technology may lead to quantum computation with mixed ion species, sympathetic cooling of ion species that cannot be co-trapped, and hybrid quantum devices that couple ion based qubits with superconducting qubits.
Gate operation, in some cases entirely preventing the ideal π to that obtained for a similar atom in a chiral waveguide configuration. We also show that the initial pulse shape has a significant effect on the pulse off of a three-level atom in the V configuration contained within a cavity. Our solution utilizes a full multimode treatment of the quantized basis states.

K1.00095 Investigating phonon-mediated interactions with polar molecules1. JOHN SOUS, KIRK MADISON, MONA BERCILLI, Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1, ROMAN KREMS, Department of Chemistry, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1 — We show that an ensemble of polar molecules in an optical lattice realizes the Peierls polaron model for hard-core particles/pseudospins. We analyze the quasiparticle spectrum in the one-particle subspace, the two-particle subspace and at finite concentrations. We derive an effective model that describes the low-energy behavior of the system. We show that the Hamiltonian includes phonon-mediated repulsions and phonon-mediated “pair-hopping” terms which move the particle pair as a whole. We show that microwave excitations of the system exhibit signatures of these interactions. These results pave the way for the experimental observation of phonon-mediated repulsion.

1This work was supported by NSERC of Canada and the Stewart Blusson Quantum Matter Institute.

K1.00096 Simulation of Quantum Many-Body Dynamics for Generic Strongly-Interacting Systems, GREGORY MEYER, FRANCISCO MACHADO, NORMAN YAO, University of California – Berkeley — Recent experimental advances have enabled the bottom-up assembly of complex, strongly interacting quantum many-body systems from individual atoms, ions, molecules and photons. These advances open the door to studying dynamics in isolated quantum systems as well as the possibility of realizing novel out-of-equilibrium phases of matter. Numerical studies provide insight into these systems; however, computational time and memory usage limit common numerical methods such as exact diagonalization to relatively small Hilbert spaces of dimension \( \sim 10^3 \). Here we present progress toward a new software package for dynamical time evolution of large generic quantum systems on massively parallel computing architectures. By projecting large sparse Hamiltonians into a much smaller Krylov subspace, we are able to compute the evolution of strongly interacting systems with Hilbert space dimension nearing \( 10^5 \). We discuss and benchmark different design implementations, such as matrix-free methods and GPU based calculations, using both pre-thermal time crystals and the Sachdev-Ye-Kitaev model as examples. We also include a simple symbolic language to describe generic Hamiltonians, allowing simulation of diverse quantum systems without any modification of the underlying C and Fortran code.

K1.00097 Quantum simulation using photons and room temperature atoms1. CONNOR GOHAM, MEHDI NAMAZI, EDEN FIGUEROA, State Univ of NY- Stony Brook — Recent proposals show that Electromagnetically Induced Transparency (EIT) using quantized light fields and atoms can be a promising and alternative approach for quantum simulation [1,2]. In our experiment we generate a dark state polariton (DSP) through the storage of a pulse of light in a room temperature vapor and retrieve it using a multi-lambda scheme including the D1 and D2 lines of rubidium 87 atoms [3]. By applying a position dependent magnetic field during retrieval we have engineered the resultant coupled DSPs to follow a nonlinear Dirac Hamiltonian analogous to the Jackiw-Rebbi model describing a Dirac field with spatially variable mass. [1] Scientific Reports, 4:6110 2014. [2] Phys. Rev. Lett., 105:173603 2010. [3] Nature Communications, 5:5542 2014.

1The work was supported by the US-Navy Office of Naval Research, grant number N00141410801, the National Science Foundation, grant number PHY-1404398 and the Simons Foundation, grant number SBF241180. B.

K1.00098 A Raman phase gate for \(^{87}\)Rb Bose–Einstein Condensates, JOSEPH D. MURPHREE, MAITREYI JAYASEELAN, JUSTIN T. SCHULTZ, NICHOLAS P. BIGELOW, University of Rochester — Bose–Einstein condensates (BECs) are of interest for use in quantum information and quantum computing due to their macroscopic dimensions and long coherence lifetimes. This requires the realization of quantum gates in BECs, and phase gates are an important first step. We use a coherent Raman process to implement a phase gate on a \(^{87}\)Rb BEC. This process is capable of effecting a spatially varying, arbitrary rotation on the Bloch sphere in the pseudo-spin-1/2 space created from two spin sublevels. We first use a set of Raman pulses to create a full-Bloch BEC, a spin texture on the cloud which includes every state on the Bloch sphere. A second set of Raman pulses introduces a phase shift between the spin components, applying a phase gate to every possible superposition of states simultaneously. The amount and spatial uniformity of the added phase is then measured using atom-optic polarimetry. Using structured or singular Raman beams with this technique could enable the study of quantum gates with Laguerre–Gaussian basis states.

K1.00099 A Multimode Analysis of an Atom-Cavity System as a Controlled Phase Gate, WILLIAM KONYK, JULIO GEA-BANACLOCHE, Univ of Arkansas-Fayetteville — We study the scattering of a single- and two-photon pulse off of a three-level atom in the V configuration contained within a cavity. Our solution utilizes a full multimode treatment of the quantized electric field and leads to analytic results for common input pulses. We use this solution to analyze the system’s ability to act as a conditional phase gate between two photons for various choices of couplings and detunings. We find that the maximum success probability is nearly identical to that obtained for a similar atom in a chiral waveguide configuration. We also show that the initial pulse shape has a significant effect on the gate operation, in some cases entirely preventing the ideal \( \pi \) phase shift between the two photons for any choice of parameters.
process has allowed us to laser cool rare, naturally-occurring barium isotopes $^{132} \text{Ba}$, heating and cooling along with mass filtering to produce isotopically pure chains of any naturally-occurring barium isotope. This purification by thermal ionization from a platinum ribbon. We experimentally demonstrate the isotopic purification of large numbers of barium ions using laser light. Furthermore, background-free qubit readout, where the readout is insensitive to laser scatter, is possible in the use of high-power lasers, low-loss fibers, high quantum efficiency detectors, and other optical technologies developed for visible wavelength nuclear spin 1/2, allowing for a robust hyperfine qubit with simple state preparation and readout. The existence of long-lived metastable D-states of the P$_1$ with adjustable mean kinetic energy by combining a surface ionization source and ion optics. HUDSON, Univ of California - Los Angeles — 133 Ba$^+$: a new qubit. JUSTIN CHRISTENSEN, DAVID HUCUL, WESLEY CAMPBELL, ERIC HUDSON, Univ of California - Los Angeles — 131 Ba$^+$ combines many of the advantages of commonly used trapped ion qubits. 131 Ba$^+$ has a nuclear spin 1/2, allowing for a robust hyperfine qubit with simple state preparation and readout. The existence of long-lived metastable D-states and a lack of low-lying F-states simplifies shielding, which will allow high fidelity state detection. The visible wavelength optical transitions enable the use of high-power lasers, low-loss fibers, high quantum efficiency detectors, and other optical technologies developed for visible wavelength light. Furthermore, background-free qubit readout, where the readout is insensitive to laser scatter, is possible in 133 Ba$^+$, and simplifies its use in small ion traps and the study of ions near surfaces. We report progress on realizing this qubit. We load barium ions into an ion trap using thermal ionization from a platinum ribbon. We experimentally demonstrate the isotopic purification of large numbers of barium ions using laser heating and cooling along with mass filtering to produce isotopically pure chains of any naturally-occurring barium isotope. This purification process has allowed us to laser cool rare, naturally-occurring barium isotopes $^{132} \text{Ba}$ and $^{130} \text{Ba}$, and we report the isotope shifts from $^{138} \text{Ba}$ of the P$_{1/2}$ to D$_{3/2}$ transitions near 650 nm for the first time. In addition, we have developed an ion gun to produce high luminosity ion beams with adjustable mean kinetic energy by combining a surface ionization source and ion optics.

K1.00103 Nondestructive fluorescence detection of hyperfine states of Rb using an EMCCD camera MINHO KWON, MATTHEW EBERT, CHRISTOPHER YOUNG, THAD WALKER, MARK SAFFMAN, Univ of Wisconsin, Madison — We demonstrate a method to non-destructively differentiate two hyperfine ground states of trapped neutral $^{87}$ Rb atoms, with an EMCCD camera. The semi-closed cycling transition limits the number of photons that atoms can scatter before their internal state changes. We utilize circularly polarized probe light and strictly controlled quantization axis to fully close the transition. This enables us to collect sufficient photons for a measurement while preserving the internal state. In our proof of principle experiments up to five trap sites are interrogated in parallel. A few ms of readout time and scalability of the method allow significant speed ups in quantum information experiments with neutral atoms. We also report progress toward Rydberg-mediated gate experiments using ensembles.

K1.00104 Absolute Calibration of Analog Photodiodes with Correlated Twin Beams from Four-wave Mixing MENG-CHANG WU, BRIAN ANDERSON, BONNIE SCHMITTBERGER, Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, College Park, MD 20742, USA, ALAN MIGDALL, PAUL LETT, Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, Gaithersburg, MD 20899, USA — Quantum-correlated twin beams are a promising source for absolute calibration of analog photodiodes over a large frequency range. In our experiment, we make two-mode squeezed light with four-wave mixing in a double-lambda scheme in a warm Rb vapor. At least -5 dB of intensity-difference squeezing in the measurement frequencies range of 100Hz to a few megahertz is obtained routinely. One of the correlated twin beams is detected by a first uncalibrated detector and this provides a reference for signals at a second uncalibrated detector. Fluctuations in one detector should be mirrored in the other, and any inefficiency of the photodiodes, or losses in the optical path for the twin beams will reduce the degree of their correlation. We can obtain the quantum efficiency of both analog photodiodes in the test by measuring the correlation functions of twin beams and having good loss measurements for all of the optical paths. We measure the losses of every optical element and the loss from the Rb atoms in the source. The main contributions to the uncertainties of the calibration are from the loss measurements.

K1.00105 Visible-Wavelength Multi-Species Trapped-Ion Quantum Logic COLIN BRUZEWICZ, ROBERT MCCONNELL, JONATHON SEDLACEK, JULES STUART, JOHN CHIAPERINI, JEREMY SAGE, MIT Lincoln Laboratory — Large-scale quantum information processing using trapped ions will likely utilize multiple atomic species to permit sympathetic cooling of shared ion motion and to facilitate quantum state measurement without decohering unmeasured qubits. Using the techniques of quantum logic spectroscopy, we demonstrate state transfer and subsequent readout using a memory (Ca$^{+}$) and auxiliary (Sr$^{+}$) ion in a surface-electrode ion trap. This method obviates the need for fluorescence detection of the memory ion, massively reducing the amount of resonant scattered light as a source of decoherence in other nearby memory ions. Further, the necessary lasers for manipulation of Ca$^{+}$ and Sr$^{+}$ are all in the visible and near-infrared portion of the spectrum and may permit the use of integrated photonic waveguides to route light throughout a trap array without the need for free-space optics.
K1.00106 Implementation of a Single-Shot Displacement Receiver for Quaternary Phase-Shift-Keyed Coherent States. MATTHEW DIMARIO, FRANCISCO BECERRA, RICHARD JACKSON, ZEKE CARRASCO, EQuIC—University of New Mexico — Non-Gaussian receivers that achieve discrimination errors below the Quantum Noise Limit (QNL) are an important tool in communication and quantum information. Discrimination of coherent states of light with zero probability of error is fundamentally impossible due to their intrinsic overlap. Therefore, the goal is to design and demonstrate strategies that minimize the probability of error and outperform a perfect heterodyne measurement working at the QNL, while being compatible with current communication technologies. We experimentally implement a strategy proposed in PRA 86, 042328 (2012) to discriminate between quaternary phase-shift keyed (QPSK) coherent states below the QNL that is based on simultaneously testing multiple hypotheses within a single-shot measurement. The receiver uses displacement operations and single photon counting without the need for any feedback operations and thus it is compatible with current high-bandwidth communications. In our demonstration we use optimized displacement operations to minimize the probability of error in a polarization based set-up. Our investigations allow us to identify how the critical parameters, such as visibility of the displacements with current high-bandwidth communications. In our demonstration we use optimized displacement operations to minimize the probability of error in a polarization based set-up. Our investigations allow us to identify how the critical parameters, such as visibility of the displacements, influence the error probability as well as what is required to out-perform a heterodyne measurement under realistic noise and loss.

K1.00107 Improvement in T2* via Cancellation of Spin Bath Induced Dephasing in Solid-State Spins. ERIK BAUCH, CONNOR HART, Harvard Univ, JENNIFER SCHLOSS, Massachusetts Institute of Tech, MATTHEW TURNER, Harvard Univ, JOHN BARRY, RONALD L. WALSWORTH, Smithsonian Center for Astrophysics — In measurements using ensembles of nitrogen vacancy (NV) centers in diamond, the magnetic field sensitivity can be improved by increasing the NV spin dephasing time, T2*. For NV ensembles, T2* is limited by dephasing arising from variations in the local environment sensed by individual NVs, such as applied magnetic fields, noise induced by other nearby spins, and strain. Here, we describe a systematic study of parameters influencing the NV ensemble T2*, and efforts to mitigate sources of inhomogeneity with demonstrated T2* improvements exceeding one order of magnitude.

K1.00108 Linear optical quantum metrology with single photons — Experimental errors, resource counting, and quantum Cramer-Rao bounds. NICHOLAS STUDER, Louisiana State University, JONATHAN OLSON, Harvard University, KEITH MOTES, Macquarie University, PATRICK BIRCHALL, University of Bristol, MARGARITE LABORDE, TODD MOULDER, Louisiana State University, PETER ROHDE, University of Technology Sydney, JONATHAN DOWLING, Louisiana State University — Quantum number-path entanglement is a resource for super-sensitive quantum metrology and in particular provides for sub-shotnoise or even Heisenberg-limited sensitivity. However, such number-path entanglement has thought to have been resource intensive to create in the first place — typically requiring either very strong nonlinearities, or nondeterministic preparation schemes with feed-forward, which are difficult to implement. Recently we showed that number-path entanglement from a BOSONSAMPLING inspired interferometer can be used to beat the shot-noise limit. In this work, we compare and contrast different interferometric schemes, discuss resource counting, calculate exact quantum Cramer-Rao bounds, and study details of experimental errors.


K1.00110 QUANTUM/COHERENT CONTROL –

K1.00111 Preparation of Vibrationally Excited H₂ in a Coherent Superposition of M-States Using Stark Induced Adiabatic Raman Passage (SARP) 1. NANDINI MUKHERJEE, WENRUI DONG, WILLIAM PERREAULT, RICHARD ZARE, Stanford Univ — We prepare a large ensemble of rovibrationally excited (M and J = +2) H₂ molecules in a coherent superposition of M-states using Stark-induced adiabatic Raman passage (SARP) with linearly polarized single mode pump (532 nm) and Stokes (699 nm) laser pulses of duration 6 ns and 4 ns. A bi-axial superposition state, |v> = 1/√2 [ |v = 1, J = 2, M = -2>, |v = 1, J = 2, M = +2> ], is prepared using SARP with a sequence of a pump laser pulse partially overlapping with a cross polarized Stokes laser pulse co-propagating along the quantization z-axis. The degree of phase coherence is measured by recording interference fringes in the ion signal produced using the O(2) line of 2+1 resonance enhanced multiphoton ionization (REMPI) from the rovibrationally excited (v = 1, J = 2) level as a function of REMPI laser polarization angle. The ion signal is measured using a time-of-flight mass spectrometer. Nearly 60% population transfer from H₂ (v = 0, J = 0) ground state to the superposition state in H₂ (v = 1, J = 2) is measured from the depletion of Q(0) REMPI signal of the (v = 0, J = 0) ground state. The M-state superposition behaves much like a multi-slit interferometer where the number of slits, i.e. the number of M-states, and their separations, i.e. the relative phase, can be varied experimentally. 1This work has been supported by the U.S. Army Research Office
K1.00112 Raman transition at motional sideband for a trapped ion using co-propagating pulsed lasers and a high NA lens. 
YEONG-DAE KWON, Quantum Tech. Lab., SK Telecom, SEOKJUN HONG, MINJAE LEE, DONGIL DAN CHO, ASRI/ISRC and Department of Electrical and Computer Engineering, Seoul National University, TAEHYUN KIM, Quantum Tech. Lab., SK Telecom — A pulsed laser is a great tool for coherent control of qubits based on trapped ions. Unlike microwave, it allows addressing individual ions among the string of ions stored in the same trap, and the high instantaneous power of the pulsed laser enables faster and more stable qubit operations [1]. The pulsed laser can also play a crucial role in the cooling process, as a two-photon Raman process allows transitions between different motional states of an ion, which makes the sideband cooling possible [2]. Generally, however, for such a transition to occur, two beams traveling in different directions are needed to impart a sufficient momentum kick to the ion. In this research, we show that co-propagating pulsed lasers are also capable of driving such inter-motional-state transitions as long as they reach the ion through a high NA lens, from which the beams gain the extra momentum difference. Such a scheme can vastly simplify the optical setup, since the active matching and stabilization of the path lengths of the two pulsed lasers are no longer required when the lasers co-propagate. [1] D. Hayes et al., Phys. Rev. Lett. 104, 140501 (2010). [2] C. Monroe et al., Phys. Rev. Lett. 75, 4011 (1995).

1This work was supported by ICT R&D program of MSIP/IITP. [10043464 ,Development of quantum repeater technology for the application to communication systems]

K1.00113 Electron spin control and spin-libration coupling of a levitated nanodiamond. 
THAI HOANG, Purdue University, YUE MA, Tsinghua University, JONGHOON AHN, JAEOOON BANG, FRANCIS ROBICHEAUX, Purdue University, MING GONG, University of Science and Technology of China, ZHANG-QI YIN, Tsinghua University, TONGCANG LI, Purdue University — Hybrid spin-mechanical systems have great potentials in sensing, macroscopic quantum mechanics, and quantum information science. Recently, we optically levitated a nanodiamond and demonstrated electron spin control of its built-in nitrogen-vacancy (NV) centers in vacuum. We also observed the libration (torsional vibration) of a nanodiamond trapped by a linearly polarized laser beam in vacuum. We propose to achieve strong coupling between the electron spin of a NV center and the libration of a levitated nanodiamond with a uniform magnetic field. With a uniform magnetic field, multiple spins can couple to the torsional vibration at the same time. We propose to use this strong coupling to realize the Lipkin-Meshkov-Glick (LMG) model and generate rotational superposition states.

This work is supported by the National Science Foundation under grant no.1555035-PHY.

K1.00114 Analysis of decoherence mechanisms in a single-atom quantum memory. 
MATTHIAS KOERBER, STEFAN LANGENFELD, OLIVIER MORIN, ANDREAS NEUZNER, STEPHAN RITTER, GERHARD REMPE, Max Planck Institute for Quantum Optics, Hans-Kopfermann Str. 1, 85748 Garching — While photons are ideal for the transmission of quantum information, they require dedicated memories for long-term storage. The challenge for such a photonic quantum memory is the combination of an efficient light-matter interface with a low-decoherence encoding. To increase the time before the quantum information is lost, a thorough analysis of the relevant decoherence mechanisms is indispensable. Our optical quantum memory consists of a single rubidium atom trapped in a two dimensional optical lattice in a high-finesse Fabry-Perot-type optical resonator. The qubit is initially stored in a superposition of Zeeman states, making magnetic field fluctuations the dominant source of decoherence. The impact to this type of noise is greatly reduced by transferring the qubit into a subspace less susceptible to magnetic field fluctuations. In this configuration, the achievable coherence times are no longer limited by those fluctuations, but decoherence mechanisms induced by the trapping beams pose a new limit. We will discuss the origin and magnitude of the relevant effects and strategies for possible resolutions.

K1.00115 Decoherence and electric field noise analysis of nitrogen vacancy center diamonds due to the surface charge fluctuations and lattice strain. 
DEBORAH SANTAMORE, Delaware State University — We theoretically investigate the decoherence mechanisms due to the electric field noise in nitrogen vacancy (NV) center diamonds. The noise is caused by both the surface charge fluctuations and strain due to surface contaminants and bulk impurities. The system is modeled with nitrogen impurities in diamond and hydrogen surface terminations with water. We obtain the equations of motion, calculate the electric field fluctuations, and analyze noise. We find that the surface effect is greater than lattice distortion by the bulk impurity substitution. We also discuss how to minimize the noise. Finally, we examine lattice distortion and stability of NV centers under high pressure.

1NSF: DMR-1505641

K1.00116 Manipulating trapped ions with ultrafast laser pulses to generate mesoscopic states and entanglement. 
STEVEN MOSES, DAVID WONG-CAMPOS, KALE JOHNSON, JONATHAN MIZRAHI, CHRISTOPHER MONROE, Joint Quantum Institute and University of Maryland Department of Physics, College Park, Maryland 20742 — The main requirements for a viable quantum computing platform include robustness to external perturbations and logical operations faster than the system’s decoherence time. Trapped ions have met these requirements while maintaining high operation fidelities. Although extensive work has been done in the resolved sideband regime, ultrafast quantum state control promises an improvement to both clock speeds and scalability. Here we demonstrate the use of ultrafast laser pulses for generating high fidelity spin-dependent momentum kicks (SDKs) in $^{171}$Yb$^+$ ions. These SDKs are the building blocks used to create mesoscopic superpositions, or Schrödinger cat states, of motional states that enable sensing of thermal states up to room temperature. More recently, we have used a sequence of SDKs on two ions to realize a novel phase gate, which operates independent of temperature and is scalable to large system sizes.

1This work is supported by the ARO and the NSF Physics Frontier Center at JQI.

K1.00117 Quantum many-body control beyond the adiabatic regime. 
YOGESH S PATIL, HIL F H CHEUNG, Cornell University, ADITYA G DATE, California Institute of Technology, MUKUND VENGALATTORE, Cornell University — We demonstrate the optomechanical realization of a non-equilibrium heat engine in a system out-of-equilibrium with its environment. We investigate the limits on the work-extraction efficiency in such non-equilibrium systems which violate adiabaticity or indeed even the fluctuation-dissipation theorem. We discuss how such protocols can potentially be used to relate microscopic non-equilibrium equalities to macroscopic thermodynamic quantities and to shed light on the microscopic basis of thermodynamics. Furthermore, we describe how feedback and continuous measurements can be used to coax out-of-equilibrium quantum systems into novel correlated many-body quantum states. As an example of the power of such non-equilibrium processes, we demonstrate a dramatic increase in the squeezing achieved using a non-equilibrium transient protocol.
K1.00118 Atomic excitation probability for Fock and coherent-state pulses: asymptotic results. HEMLIN SWARAN RAG, JULIO GEA-BANACLOCHE, Univ of Arkansas-Fayetteville — For a two-level atom in a cavity or waveguide, interacting with a single-photon pulse, the excitation probability $P_n$ can never equal one unless the pulse shape is the exact time-reverse of the spontaneous decay. For pulses with the “wrong” shape, we investigate (following the work of Wang et al.

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K1.00119 \text{ Two qubit gate operation using the frequency encoding technique}^1. \text{ JUNGHYUN LEE, KEIGO ARAI, Masaoye Ishida, RIKO WATANABE, Harvard-Smithsonian Center for Astrophysics, ERIK BAUMANN, EMMA ROSENFIELD, Harvard University, RONALD WALTHOUR, Harvard-Smithsonian Center for Astrophysics — Nitrogen-vacancy (NV) color centers in diamond are good candidates for realizing a scalable spin coupled system. For a simple two NV electronic spin interacting system, two qubit gate operations can be realized through the spin dipolar interaction. With two NV electronic spins separated by about 10 nm, and by manipulating an applied magnetic field gradient and a Rabi driving field, we outline how the spin dipolar interaction can be controlled to create different types of two qubit gate operations. Furthermore, we outlook how this two electronic spin qubit system can act as a channel for entangling two nitrogen nuclear spins adjacent to each NV electronic spins.}

\[1^1\text{ILJU Foundation}\]

K1.00120 Are strategies in physics discrete? A remote controlled investigation. ROBERT HECK, JACOB F. SHERSON, Department of Physics and Astronomy, Aarhus University. WWW.SCIENCEATHOME.ORG TEAM AND PLAYERS TEAM — In science, strategies are formulated based on observations, calculations, or physical insight. For any given physical process, often several distinct strategies are identified. Are these truly distinct or simply low dimensional representations of a high dimensional continuum of solutions? Our online citizen science platform www.scienceathome.org used by more than 150,000 people recently enabled finding solutions to fast, 1D single atom transport [Nature2016]. Surprisingly, player trajectories bunched into discrete solution strategies (clans) yielding clear, distinct physical insight. Introducing the multi-dimensional vector in the direction of other local maxima we locate narrow, high-yield “bridges” connecting the clans. This demonstrates for this problem that a continuum of solutions with no clear physical interpretation does in fact exist. Next, four distinct strategies for creating Bose-Einstein condensates were investigated experimentally: hybrid and crossed dipole trap configurations in combination with either large volume or dimple loading from a magnetic trap. We find that although each conventional strategy appears locally optimal, “bridges” can be identified. In a novel approach, the problem was gamified allowing 750 citizen scientists to contribute to the experimental optimization yielding nearly a factor two improvement in atom number.

K1.00121 Toward Nanoscale Magnetometry of Van der Waals Heterostructures using Nitrogen-Vacancy Centers in Diamond. THOMAS MITTIGA, SATCHER HSIEH, CHONG ZU, CHENHAO JIN, JONGHWAN KIM, BRYCE KOBRIN, FENG WANG, NORMAN YAO, Univ of California - Berkeley — Two-dimensional layered heterostructures remain at the forefront of materials research and are promising candidates from the perspective of both fundamental science and technological advancement. They can exhibit a rich array of magnetic phenomena, with recent experiments in transition metal dichalcogenides (TMD) demonstrating long-lived spin relaxation and coherence times. We present first steps toward a wide-field confocal microscope aimed at probing the excited and defect-based magnetism of such materials. By observing the quenching of fluorescence from single Nitrogen-Vacancy centers of predetermined depths, we measure the transition dipole moment of the TMD and characterize this as a function of layer number. We also describe recent progress toward the imaging of magnetic defects and evaluate the feasibility of using this scheme to probe coupled spin and valley dynamics.

K1.00122 Synthetic clock states generated in a Bose-Einstein condensate via continuous dynamical decoupling. NATHAN LUNDBLAD, Bates College, DIMITRIOS TRYPOGORIOS, ANA VALDES-CURIEL, ERIN MARSHALL, University of Maryland, College Park, IAN SPIELMAN, University of Maryland, College Park NIST — Radiofrequency- or microwave-dressed states have been used in NV centers and ion-trap experiments to have becoherence times, shielding qubits from magnetic field noise through a process known as continuous dynamical decoupling (1). Such field-insensitive dressed states, as applied in the context of ultracold neutral atoms, have applications related to the creation of novel phases of spin-orbit-coupled quantum matter (2). We present observations of such a protected dressed-state system in a Bose-Einstein condensate, including measurements of the degree of coherence on rf coupling strength, and estimates of residual field sensitivities.


K1.00123 NONLINEAR OPTICS

K1.00124 ABSTRACT WITHDRAWN

K1.00125 Rotational Doppler effect in third-harmonic generation from spinning molecules. ILYA SH. AVERBUKH, Weizmann Institute of Science, Rehovot, Israel, J. ZYSS, Laboratoire de Photonique Quantique et Moléculaire, Ecole Normale Supérieure de Cachan, France, A. MILNER, V. MILNER, Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada, E. PROST, E. HERTZ, F. BILLARD, B. LAVOREL, O. FAUCHER, Laboratoire Interdisciplinaire CARNOT de Bourgogne, UMR 6303 CNRS-Université Bourgogne Franche-Comté, Dijon, France — The angular Doppler effect results from interaction of a rotating body with a circularly-polarized (CP) light. In linear optics, it was first evidenced by observing the frequency shift imparted to a CP light transmitted through a mechanically rotated wave plate [Opt. Commun., 31, 1 (1979)], and more recently, demonstrated in our experiments with fast spinning molecules [Nat Photon. 7, 711 (2013); Phys.Rev.Lett. 112, 113004 (2014); Phys.Rev.Lett. 114, 103001 (2015)]. We present here the first observation of the nonlinear rotational Doppler shift in the frequency of optical harmonic generated in fast rotating molecules. Conservation of energy and angular momentum in the light-molecule interaction suggests four different kinds of nonlinear shifts depending on the mutual handedness of the circularly polarized fundamental and harmonic fields, as well as the handedness of the molecular rotation. All four types of the frequency shifts were observed in our experiments on third-harmonic generation in a gas of fast spinning $O_2$ molecules [Phys. Rev. A 94, 051402(R) (2016)].
K1.00126 Rotational cavity optomechanics. WYATT WETZEL, B. RODENBURG, B. EK, Rochester Inst of Tech, A. K. JHA, Indian Inst of Tech, M. BHATTACHARYA, Rochester Inst of Tech — We consider optomechanics based on the exchange of orbital angular momentum between light and matter. Specifically we consider a nanoparticle levitated in an optical ring trap in a cavity. The motion of this particle is probed by an angular lattice created by two co-propagating beams carrying equal but opposite angular momenta. First we consider the case where the lattice is weak, so the nanoparticle can execute complete rotations about the cavity axis. We establish analytically the existence of a linear regime where accurate Doppler velocimetry can be performed on the nanoparticle, and also describe numerically the dynamics in the nonlinear regime where the velocimetry is no longer accurate. Second, we consider the case where the lattice is strong and the nanoparticle executes torsional motion about the cavity axis. We find the presence of an external torque introduces an instability, but can also be used to tune continuously the linear optomechanical coupling whose strength can be measured by homodyning the cavity output field. This research was supported by the National Science Foundation (NSF) (1454931), the Office of Naval Research (N00014-14-1-0803), and the Research Corporation for Science Advancement (20066).

K1.00127 Electromagnetically Induced Transparency in a Double-Lambda System. SAESUN KIM, ALBERTO MARINO, University of Oklahoma — Electromagnetically induced transparency (EIT) is a well-known phenomenon due in part to its application to quantum devices such as quantum gate and quantum gates. Commonly, EIT is modeled with three-level lambda configurations due to the simplicity of the calculation; however, even all of the D1 transitions in alkali atoms have four hyperfine levels. As a result, it is necessary to consider the effect of two excited states whose frequency separation is smaller or of the order of the Doppler broadening when working with atomic vapors. We model the atomic system as a double-lambda system and analytically calculate its response using the density matrix formalism under the assumption of a weak probe field and taking Doppler broadening into account. We show that the presence of the fourth level leads to an additional term in the susceptibility compared to two independent three-level lambda systems. This extra interference term leads to an enhancement of EIT and electromagnetically induced absorption (EIA) and under certain conditions to an additional absorption in-between the two upper levels. Finally, we measure the transmission spectrum through a $^{85}\text{Rb}$ vapor cell and show that it agrees with the theoretical calculations.

1Work supported by a grant from the AFOSR (FA9550-15-1-0402)

K1.00128 Harmonic generation with an ultra-strongly coupled cavity polariton. MICHAEL CRESCIMANNO, Dept. of Physics and Astron., Youngstown State University, KENNETH SINGER, BIN LIU, MICHAEL MCMASTERS, Case Western Reserve University — The large dipole density in a new class of glassy organic dyes results in ultrastrong exciton-cavity field coupling leading to polariton splittings of over an eV. We describe the theoretical model and experimental protocol used to understand third harmonic generation (THG) in this system. We quantify the THG enhancement at the polariton branches through its dependence on coupling, cavity-exciton detuning and cavity finesse.

K1.00129 Current studies and improvements on a single frequency blue source generated by second harmonic from IR. ALI KHADEMIAN, SAI LAKSHMAN JAMANI, MATTHEW TRUSCOTT, ANOOJA JAYARAJ, DAVID SHINER, University of North Texas — We have reported 81.5% efficiency in generating ~500 mW of blue at 486 nm by second harmonic generation (SHG) from the IR, using a periodically poled Lithium Tantalate (PPSLT) crystal. Initially a total cavity loss of 0.65% was observed. We developed techniques for careful measurement of individual losses such as scattering and absorption in the crystal and mirrors, polarization misalignment caused by the crystal and back reflection from the periodically poled boundaries of crystal. We have replaced the crystal with a tilted periodically poled crystal. This eliminated the reflection loss, but scattering in the crystal, we speculate from the MgO doping, is still causing enough feedback to destabilize the IR source. We are also replacing cavity mirrors with ultra-low loss sputtered mirrors to minimize their contribution to loss. Crystal lifetime at different blue power levels is being investigated. In our setup a mixed signal processor (MSP) is used for cavity locking and temperature stabilizing. Once MSP is programmed by a computer interface, it can be installed inside the cavity housing, making the laser source standalone and self-sufficient. We have been able to stabilize and lock the laser cavity length, the temperature of the IR laser source, the temperature of fiber Bragg grating (FBG), and the temperature of the nonlinear crystal using the MSP, matching the performance of high end commercial fiber temperature controllers and lock-in amplifiers. Our recent progress and improvements will be presented.

1This work is supported by NSF award # 1404498.

K1.00130 ULTRA FAST —

K1.00131 A superradiant laser integrated in a hollow-core photonic-crystal fiber. FERESHTEH RAJABI, University of Western Ontario, TAEHYUN YOON, JEREMY FLANNERY, SREESH VENUTURUMILLI, MICHAL BAJSY, Institute for Quantum Computing. University of Waterloo — Superradiant lasers exhibit a high spectral purity characterized by a frequency linewidth thousand times less than that of a conventional laser. This characteristic of superradiant laser, which is due to collective effects arising in the dipole ensemble forming the gain medium, makes it an excellent candidate for high-precision metrology applications. Additionally, superradiant lasers are an interesting platform to study strongly-correlated systems. We propose a fiber-integrated superradiant laser consisting of an ensemble of cold Cs atoms coupled to a single mode of radiation field in a Fabry-Perot cavity formed in a hollow-core photonic crystal fiber (HCPF). The Cs atoms, initially cooled using a magneto-optical trap (MOT), are guided and confined inside a short piece of HCPF with a magic-wavelength dipole trap. The Fabry-Perot cavity is integrated into the fiber using photonic-crystal slabs acting as mirrors, which are attached to the ends of the fiber piece. A small number of photons can synchronize atomic dipoles inside the cavity and result in superradiance, while a steady-state superradiance can be achieved by re-populating the atomic excited state at a proper rate.

K1.00132 A fiber-coupled incoherent light source for ultra-precise optical trapping. TIM MENKE, ROBERT SCHITTOK, ANTON MAZURENKO, M. ERIC TAI, ALEXANDER LUKIN, MATTHEW RISPOLI, ADAM M. KAUFMAN, MARKUS GREINER, Harvard University — The ability to engineer arbitrary optical potentials using spatial light modulation has been enabled by repeated optical feedback, which can lead to superradiance, while a steady-state superradiance can be achieved by re-populating the atomic excited state with light. We have reported 81.5% efficiency in generating ~500 mW of blue at 486 nm by second harmonic generation (SHG) from the IR, using a periodically poled Lithium Tantalate (PPSLT) crystal. Initially a total cavity loss of 0.65% was observed. We developed techniques for careful measurement of individual losses such as scattering and absorption in the crystal and mirrors, polarization misalignment caused by the crystal and back reflection from the periodically poled boundaries of crystal. We have replaced the crystal with a tilted periodically poled crystal. This eliminated the reflection loss, but scattering in the crystal, we speculate from the MgO doping, is still causing enough feedback to destabilize the IR source. We are also replacing cavity mirrors with ultra-low loss sputtered mirrors to minimize their contribution to loss. Crystal lifetime at different blue power levels is being investigated. In our setup a mixed signal processor (MSP) is used for cavity locking and temperature stabilizing. Once MSP is programmed by a computer interface, it can be installed inside the cavity housing, making the laser source standalone and self-sufficient. We have been able to stabilize and lock the laser cavity length, the temperature of the IR laser source, the temperature of fiber Bragg grating (FBG), and the temperature of the nonlinear crystal using the MSP, matching the performance of high end commercial fiber temperature controllers and lock-in amplifiers. Our recent progress and improvements will be presented.

1This work is supported by NSF award # 1404498.
K1.00133 High-repetition-rate setup for pump-probe time-resolved XUV-IR experiments employing ion and electron momentum imaging1, SHAHAN PATHAK, SEYYED JAVAD ROBATJAZI, PEARSON WRIGHT LEE, KANAKA RAJU PANDIRI, DANIEL ROLLES, ARTEM RUĐENKO, Kansas State University — J.R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan KS, USA We report on the development of a versatile experimental setup for XUV-IR pump-probe experiments using a 10 kHz high-harmonic generation (HHG) source and two different charged-particle momentum imaging spectrometers. The HHG source, based on a commercial KM Labs eXtreme Ultraviolet Ultrafast Source, is capable of delivering XUV radiation of less than 30 fs pulse duration in the photon energy range of 17 eV to 100 eV. It can be coupled either to a conventional velocity map imaging (VMI) setup with an atomic, molecular, or nanoparticle target; or to a novel double-sided VMI spectrometer equipped with two delay-line detectors for coincidence studies. An overview of the setup and results of first pump-probe experiments including studies of two-color double ionization of Xe and time-resolved dynamics of photoionized CO2 molecule will be presented.

1This project is supported in part by National Science Foundation (NSF-EPSCOR) Award No. IIA-1430493 and in part by the Chemical science, Geosciences, and Bio-Science division, Office of Basic Energy Science, Office of science, U.S. Department of Energy. K

K1.00134 Filming nuclear dynamics of iodine using x-ray diffraction at the LCLS, MATTHEW WARE, Stanford University, SLAC, and PULSE Institute, ADI NATAN, SLAC and PULSE Institute, JAMES GLOWNIA, SLAC and LCLS, JAMES CRYAN, SLAC and PULSE Institute, PHIL BUCKSBAUM, Stanford University, SLAC, and PULSE Institute — We will provide an overview of our analysis of the nuclear dynamics of iodine. At the LCLS, we pumped a gas cell of iodine with a weak 520 nm, 50 fs pulse, and the nuclear dynamics are then probed with 9 keV, 40 fs x-rays with variable time delay. This allows us to simultaneously image nuclear wavepackets on the dissociating A state, on the bound B state, and even Raman wavepackets in the ground electronic state. We will explain at length how we isolate each of these signals using a Legendre decomposition of our x-ray data and the selection rules for each of the transitions. Likewise, we will discuss how we convert the x-ray diffraction patterns into real-space movies of the nuclear dynamics.

K1.00135 Multiphoton Double Ionization of H2, Y. LI, M. S. PINDZOLA, Auburn University, J. P. COLGAN, Los Alamos National Laboratory — Multiphoton double ionization probabilities for H2 are calculated using a time-dependent close-coupling method. Total double ionization probabilities are calculated for 2, 3, and 4 photon absorption in the energy range from 10 eV to 50 eV. Single and triple differential probabilities are calculated at photon energies where the total ionization probability is near a maximum.

1 Research supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Atomic, Molecular, and Optical Science Program. Use of LCLS supported under DOE Contract No. DE-AC02-76SF00515

K1.00136 TIME-RESOLVED MOLECULAR DYNAMICS AND FEMTOCHEMISTRY —

K1.00137 Vibrational relaxation of hot carriers in C60 molecules, MOHAMMED MADJET, QEERI, Hamad Bin Khalifa University, Doha, Qatar, HIMADRI CHAKRABORTY, Northwest Missouri State University, Maryville, USA — Electron-photon coupling in molecular systems is at the heart of several important physical phenomena, including the mobility of carriers in organic electronic devices [1]. Following the optical absorption, the vibrational relaxation of excited (hot) electrons and holes to the fullerene band-edges driven by electron-phonon coupling, known as the hot carrier thermalization process, is of particular fundamental interest [2]. Using the non-adiabatic molecular dynamical methodology (PYXAID + Quantum Espresso) based on density functional approach [3], we have performed a simulation of vibronic relaxations of hot carriers in C60. Time-dependent population decays and transfers in the femtosecond scale from various excited states to the states at the band-edge are calculated to study the details of this relaxation process. [1] Coropceanu et al, Chem. Rev. 107, 926 (2007); [2] Ross et al, Nature Materials 8, 208 (2009); [3] Madjet et al, Phys. Chem. Chem. Phys. 18, 5219 (2016).

1This work was supported by the U.S. National Science Foundation.

K1.00138 Modeling Quantum Dynamics in Multidimensional Systems, KYLE LISS, Dickinson College, THOMAS WEINACHT, Stony Brook University, BRETT PEARSON, Dickinson College — Coupling between different degrees-of-freedom is an inherent aspect of dynamics in multidimensional quantum systems. As experiments and theory begin to tackle larger molecular structures and environments, models that account for vibrational and/or electronic couplings are essential for interpretation. Relevant processes include intramolecular vibrational relaxation, conical intersections, and system-bath coupling. We describe a set of simulations designed to model coupling processes in multidimensional molecular systems, focusing on models that provide insight and allow visualization of the dynamics. Undergraduates carried out much of the work as part of a senior research project. In addition to the pedagogical value, the simulations allow for comparison between both explicit and implicit treatments of a system’s many degrees-of-freedom.

K1.00139 Ultrafast photo-dissociation imaged with femtosecond gas electron diffraction1, KYLE WILKIN, Univ of Nebraska - Lincoln, JIE YANG, RYAN COFFEE, JAMES CRYAN, SLAC National Laboratory, MARKUS CUEHR, Univ of Potsdam, KAREEM HEGAZY, RENKAI LI, MICHAEL MINITTI, SLAC National Laboratory, PEDRO NUNES, Univ of York, XIAOZHE SHEN, THOMAS WOLF, XIJIE WANG, SLAC National Laboratory, MARTIN CENTURION, Univ of Nebraska - Lincoln — We examine dynamics of single photon excitation in C2F5I2 molecules in the gaseous state using Ultrafast Electron Diffraction (UED). The experiments were performed at SLAC National Laboratory using the MeV gun with sub-200 fs resolution. With UED we can observe dynamics of the molecule with sub-Angstrom resolution. This allows us to view the transient state C2F5I + I before the molecule fully dissociates to C2F5 + 2I. We report on any dynamics observed in the transient state. We also report on differences in the rise time of the dynamics when comparing sub-sections of dissociation patterns both parallel and orthogonal to the polarization of the pump laser.

1This work was supported by the AMOS program in the Chemical Sciences, Geosciences, and Biosciences Division, Basic Energy Sciences, Office of Science, U.S. Department of Energy under Award Number: DE-SC0014170.
K1.00140 Non-Born-Oppenheimer dynamics in small molecules - connecting experiment and theory . KIRK A LARSEN, ELIO G CHAMPENOIS, University of California, Berkeley and Lawrence Berkeley National Laboratory, LOREN GREENMAN, Lawrence Berkeley National Laboratory, C WILLIAM MCCURDY, University of California, Davis and Lawrence Berkeley National Laboratory, THORSTEN WEBER, DANIEL S SLAUGHTER, Lawrence Berkeley National Laboratory — A femtosecond pulse of VUV light can coherently excite a wavepacket in a molecule that then evolves on an excited state potential energy surface (PES). This can lead to non-Born-Oppenheimer dynamics via the coupling of electronic and nuclear degrees of freedom near conical intersections of PESs. Even for molecular systems comprised of just a few atoms, its PESs exist in a highly dimensional space. This can make interpreting time-resolved VUV/XUV pump-probe experiments very challenging, as it can be difficult to ascertain which dimensions of the PESs play central roles in driving the quantum dynamics. Here, I present preliminary results from time-resolved VUV pump-probe electron and ion momentum imaging experiments on simple polyatomic molecules, such as NH₃, using a high harmonic generation light source, and discuss the use of parallelized ab initio time-independent molecular electronic structure calculations to give insight into the results of these experiments. 

In certain cases, even for molecules with highly dimensional PESs, time-independent theory can elucidate observed wavepacket motion. I will also present time-dependent dynamics calculations and discuss the strengths and weaknesses of these approaches to understanding the results of our experiments.

K1.00141 Ultrafast Polarization Spectroscopy in Polyatomic Molecules . RICHARD THURSTON, NIRANJAN SHIVARAM, ELIO CHAMPENOIS, SAID BAKHTI, PAVAN MUDDUKRISHNA, ALI BELKACEM, Chemical Sciences Division, Lawrence Berkeley National Laboratory — Polarization spectroscopy has been used in the past to study dynamics in solid, liquid and gas phase systems on picosecond and femtosecond time scales. In polarization spectroscopy, two laser pulses (drive and probe) with a relative polarization of 45 degrees, interact with the medium being probed. Due to the third order non-linear polarization induced in the medium a signal with a polarization orthogonal to the probe is generated along the probe direction. This signal measured after a crossed polarizer is directly related to the induced birefringence and dichroism in the medium. Here, we present preliminary measurements in ultraviolet grade fused silica and discuss our model to obtain the ultrafast electronic response of the medium. We then discuss the extension of this method to study ultrafast dynamics in polyatomic molecular systems using multiple pulses.

K1.00142 Measuring attosecond time-delays between dissociating vibrational states of D₂⁺ using a two-color laser field¹. T. SEVERT, BEN BERRY, M. ZOHRABI, PEYMAN FEIZOLLAH, BETHANY JOCHIM, KANAKA RAJU P., J. MCKENNA, B. Gaire, K. D. CARNES, G. S. J. ARMSTRONG, D. URSPREY, J. V. HERNANDEZ, F. ANIS, B. D. ESRY, I. BEN-ITZHAK, J.R. Macdonald Laboratory, Physics Department, Kansas State University, Manhattan, KS 66506, USA — There is considerable interest in studying attosecond time-delays in the photodissociation of neighboring electronic states of atomic and more complex targets. The underlying assumption of that work is that electron dynamics are responsible for such short delays, since they match the natural electronic timescale. Recent theoretical work has shown that the two-color dissociation probability of adjacent vibrational states in the HeH⁺ molecule exhibit time-delays of tens of attoseconds. Since electronic excitation is negligible in HeH⁺ for the considered laser parameters, this demonstrates that attosecond delays occur for purely nuclear motion. Here, we present an analogous experiment on a D₂⁺ ion beam, where attosecond time-delays are observed using an intense two-color (800/400-nm) laser field. In the two-color field, interfering pathways ending in opposite parity states result in a spatial asymmetry with respect to the laser polarization. By comparing the phase shifts of the spatial asymmetry parameter between the v = 7 and v = 8 vibrational states of the 1σ₉⁺, we observe a 53-as delay.

¹Supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy.

K1.00143 Time-resolved electron and ion imaging to investigate ultrafast structural dynamics in gas-phase halomethane molecules¹. F. ZIAEE, A. RUDENKO, D. ROLLES, IRLML, Kansas State University, E. SAVELYEV, C. BOMME, R. BOLL, B. MANSCHWETUS, B. ERK, S. TRIPPEL, J. WIESE, KIRK A LARSEN, ELIO G CHAMPENOIS, University of California, Berkeley and Lawrence Berkeley National Laboratory, John Hopkins University, MD, 21218-9483, USA — We investigate structural dynamics in halomethane molecules (CH₃I, CH₃Br and CH₃Cl) within a UV pump-IR probe scheme, in which the UV pulse initiates a photodissociation reaction, and the delayed IR-probe pulse ionizes the molecule. The produced electrons and ions are imaged by a double-sided velocity map imaging (VMI) spectrometer. Delay-dependent yields and momentum distributions of ionic fragments are recorded with the PImMS camera [1]. Simultaneously, angle-resolved electron spectra are recorded on the other side of the spectrometer. We observe large changes in the yield and kinetic energy of various fragment ions along with subtler changes in the electron spectrum, from which we extract dissociation dynamics of the molecule information. [1] K. Amini et al., Rev. Sci. Instrum. 86, 103113 (2015)

¹This project is supported by the DOE, Office of Science, Division of Chemical, Geological, and Biological Sciences.

K1.00144 Femtosecond Time-Resolved Photoelectron Imaging of Excited Doped Helium Nanodroplets . CATHERINE SALADRIGAS, CAMILA BACCELLAR, STEPHEN R. LEONE, DANIEL M. NEUMARK, University of California Berkeley, OLIVER GESSNER, Lawrence Berkeley National Lab — Helium nanodroplets are excellent matrices for high resolution spectroscopy for the study of ultrafast chemistry. The droplets are very transparent with any atomic or molecular dopant. Electronically excited droplets, however, can strongly interact with dopants through a variety of relaxation mechanisms. Previously, these host-dopant interactions were studied in the energy domain, revealing Penning ionization processes enabled by energy transfer between the droplet host and atomic dopants. Using femtosecond time-resolved XUV photoelectron imaging, we plan to perform complementary experiments in the time domain to gain deeper insight into the timescales of energy transfer processes and how they compete with internal droplet relaxation. First experiments will be performed using noble gas dopants, such as Kr and Ne, which will be compared to previous energy-domain studies. Femtosecond XUV pulses produced by high harmonic generation will be used to excite the droplets, IR and near-UV light will be used to monitor the relaxation dynamics. Using velocity map imaging, both photoelectron kinetic energies and angular distributions will be recorded as a function of time. Preliminary results and proposed experiments will be presented.

K1.00145 ION-ATOM, ION-ION COLLISIONS –
**K1.00146 Thin film deposition using rarefied gas jet**. DR. SAHADEV PRADHAN, Department of Chemical Engineering, Indian Institute of Science, Bangalore-560 012, India — The rarefied gas jet of aluminium is studied at Mach number $Ma = (U_J / \sqrt{kb T_J} / m)$ in the range $0.1<Ma<2$, and Knudsen number $Kn = (1 / \sqrt{kb T^2}) n_d d_H$ in the range $0.01<Kn<15$, using two-dimensional (2D) direct simulation Monte Carlo (DSMC) simulations, to understand the flow phenomena and deposition mechanisms in a physical vapor deposition (PVD) process for the development of the highly oriented pure metallic aluminium thin film with uniform thickness and strong adhesion on the surface of the substrate in the form of ionic plasma, so that the substrate can be protected from corrosion and oxidation and thereby enhance the lifetime and safety, and to introduce the desired surface properties for a given application. Here, $U_J$ is the characteristic dimension, $U_J$ and $T_J$ are the jet velocity and temperature, $n_d$ is the number density of the jet, $m$ is the molecular mass and diameter, and $kb$ is the Boltzmann constant. An important finding is that the capture width (cross-section of the gas jet deposited on the substrate) is symmetric around the centerline of the substrate, and decreases with increased Mach number due to an increase in the momentum of the gas molecules. DSMC simulation results reveals that at low Knudsen number ($Kn = 0.01$; shorter mean free paths), the atoms experience more collisions, which direct them toward the substrate. However, the atoms also move with lower momentum at low Mach number, which allows scattering collisions to rapidly direct the atoms to the substrate.

**K1.00147 Positronium formation from C$_60$**. PAUL-ANTOINE HERVIEUX, Universite de Strasbourg, CNRS, Institut de Physique et Chimie des Materiaux de Strasbourg, France, ANZUMAAN CHAKRABORTY, HIMADRI CHAKRABORTY, Northwest Missouri State University, Maryville, USA — Due to the dominant electron capture by positrons from the molecular shell and the spatial dephasing across the shell-width, a powerful diffraction effect universally underlies the positronium (Ps) formation from C$_60$. This results into trains of resonances in the Ps formation cross section as a function of the positron beam energy [1], producing structures in recoil momenta in analogy with classical single-slit diffraction fringes in the configuration space. C$_60$ is modeled by a jellium-based local-density approximation (LDA) method [2] and the Ps formation is treated by the continuum distorted-wave final-state (CDW-FS) approximation [3]. The work may motivate application of the Ps formation spectroscopy to gas-phase nanoparticles and also the access target-level- and Ps-level-differential measurements. [1] Hervieux et al (submitted), arXiv:1610.00335 [physics.atm-clus]; [2] Choi et al (submitted), arXiv:1610.00346 [physics.atm-clus]; [3] Fojon et al, Phys. Rev. A 54, 4923 (1996)

1This work was supported by the U.S. National Science Foundation.

**K1.00148 Vortices for Ps formation in positron-hydrogen collisions**. S. J. WARD, University of North Texas, P. VAN REETH, University College London, ALBANDARI W. ALROWAILY, University of North Texas — We have found two deep minima in the differential cross section for Ps formation in positron-hydrogen collisions in the Ore Gap. Each minimum has been shown to correspond to a vortex in the velocity field associated with the scattering amplitude. The velocity field rotates about the position where the real and imaginary parts of the scattering amplitude are zero. For the first time, we have verified that the magnitude of the circulation [1] is $2\pi/M$, where $M$ is the mass of the outgoing Ps. [1] Iwo Bialynicki-Birula, Zofia Bialynicka-Birula, and Cezary Sliwa, Phys. Rev. A 61, 032110 (2000).

1Home Institution: Princess Nourah bint Abdulrahman University

**K1.00149 Spectral Resolution of Resonant Positron-Molecule Annihilation due to Multimodes**. J. R. DANIELSON, M. R. NATISIN, C. M. SURKOV, University of California, San Diego — The annihilation spectra of positrons on molecules, as a function of incident positron energy, are typically dominated by relatively sharp features that have been identified as vibrational Feshbach resonances (VFR) mediated by fundamental vibrations. The theory of Gribakin and Lee is successful in describing the annihilation spectra for selected small molecules where the annihilation is dominated by a small number of dipole-allowed modes. However, in most molecules, these sharp peaks ride on a broad background of enhanced annihilation. There is indirect evidence that this effect is due to a dense set of combination and overtone resonances. An extension of the Gribakin-Lee theory can be used to describe VFR’s due to these multimodes, where the important effect of multiple decay channels is also included. Prospects for resolving these features using a new high-resolution positron beam will be discussed.

1Work supported by NSF grant PHY-1401794.
2G. F. Gribakin, J. A. Young, C. M. Surkko, Rev. Mod. Phys. 82, 2557 (2010).

**K1.00150 Computation of Electron Impact Ionization Cross sections of Iron Hydrogen Clusters – Relevance in Fusion Plasmas**. UMANG PATEL, Gandhinagar Institute of Technology, K N JOSHIPURA, Retired Professor, S P University — Plasma-wall interaction (PWI) is one of the key issues in nuclear fusion research. In nuclear fusion devices, such as the JET tokamak or the ITER, first-wall materials will be directly exposed to plasma components. Erosion of first-wall materials is a consequence of the impact of hydrogen and its isotopes as main constituents of the hot plasma. Besides the formation of gas-phase atomic species in various charge states, di- and polyatomic molecular species are expected to be formed via PWI processes. These compounds may profoundly disturb the fusion plasma, may lead to unfavorable re-deposition of materials and composites in other areas of the vessel. Interaction between atoms, molecules as well transport of impurities are of interest for modelling of fusion plasma. $Q_{ion}$ by electron impact are such process also important in low temperature plasma processing, astrophysics etc. We reported electron impact $Q_{ion}$ for iron hydrogen clusters, FeH$_n$ ($n = 1$ to $10$) from ionization threshold to 2000eV. A semi empirical approach called Complex Scattering Potential – Ionization Contribution (CSP-ic) has been employed for the reported calculation. In context of fusion relevant species $Q_{ion}$ were reported for beryllium and its hydrides, tungsten and its oxides and cluster of beryllium-tungsten by Huber et al. Iron hydrogen clusters are another such species whose $Q_{ion}$ were calculated through DM and BEB formalisms, same has been compared with present calculations. U. R. Patel et al., J. Chem. Phys. 140 (2014) 44302 2S. E. Huber et al, Eur. Phys. J. D. 70 (2016) 182
K1.00151 Quantum Chemistry and Non-equilibrium Thermodynamics in an Atom-Ion Hybrid Trap, MICHAEL MILLS, PRATEEK PURI, STEVEN SCHOWALTER, ALEX DUNNING, CHRISTIAN SCHNEIDER, ERIC HUDSON, Univ of California - Los Angeles — In this presentation we describe work conducted with the MOTion trap - a hybrid atom-ion trap consisting of a linear quadrupole ion trap (LQT) and a co-located magneto-optical trap (MOT). With the long interrogation times associated with the ion trap and precisely tunable entrance channels of both the atom and ion via laser excitation, the MOTion trap is a convenient platform for the study of quantum state resolvable cold chemistry. We describe a recent study of excited state chemistry between cold Ca atoms and the BaOCH3+ molecular ion, which has resulted in the product BaOCa+, the first observed mixed hypermetallic alkaline earth oxide molecule. Further, due to the complexity of ion-ion heating within an LQT and micromotion interruption collisions, there remain many open questions about the thermodynamics of these systems as well an experimental effort confirming one of the more interesting hallmarks of this model, the bifurcation in steady state energy of ions immersed in an ultracold gas.

K1.00152 Effect of viscosity on propagation of MHD waves in astrophysical plasma, ALEMAYEHU CHERKOS, Addis Ababa University, SOLOMON COLLABORATION — We determine the general dispersion relation for the propagation of magnetohydrodynamic (MHD) waves in an astrophysical plasma by considering the effect of viscosity with an anisotropic pressure tensor. Basic MHD equations have been derived and linearized by the method of perturbation to develop the general form of the dispersion relation equation. Our result indicates that an astrophysical plasma with an anisotropic pressure tensor is stable in the presence of viscosity and a strong magnetic field at considerable wavelength.

K1.00153 Electron transfer, ionization, and excitation in collisions between protons and the ions F8+ and Ne10+, THOMAS WINTER, Retired — Coupled-state cross sections are being determined for electron transfer, ionization, and excitation in collisions between keV-energy protons and the hydrogenic ions F8+ and Ne10+ initially in the ground state, extending earlier works on the less highly charged target ions He+, Li2+, Be3+, B4+, and C5+, and work reported at the 2016 DAMOP meeting on the target ions N2+ and O3+. As in the more recent works, a basis of 60 Sturmians on each center is being used, and in a second calculation, a basis of 280 Sturmians on the target nucleus and a single ls function on the proton is being used. The extent to which high-energy scaling rules with target nuclear charge Z are valid is being examined further for transfer to the ground state, total transfer, and ionization, as well as for excitation and individual-state processes at intermediate energies near where the cross sections peak, and at lower energies.

K1.00154 Towards Laser Controlled Generation of Rydberg State, One-Electron Ions, JOAN DREILING, National Institute of Standards and Technology, AUNG NAING, University of Delaware, JOSEPH TAN, National Institute of Standards and Technology — We report on progress towards the goal of producing hydrogen-like ions in Rydberg states for laser spectroscopy measurements of fundamental constants [1]. Fully stripped neon atoms (Ne10+) are produced in an electron beam ion trap (EBIT). These bare nuclei are extracted via a beamline from the EBIT into a second apparatus where they are captured at low energy in a unitary Penning trap [2]. The second apparatus has a cross-beam configuration, with a perpendicular beam of laser excited Rb atoms intersecting the ion beam at the Penning trap. While stored in the trap, the ions can interact with the Rb and, through charge exchange interactions, the bare nuclei can capture one or more electrons from the Rb. The charge states of the stored ions can then be analyzed by dumping the ions from the trap to a time-of-flight (TOF) detector [2]. To achieve an enhanced electron capture due to the laser excitation, initial studies compare the charge exchange rates in the TOF data for ground state Rb and for laser excited Rb. [1] U.D. Jentschura et al., Phys. Rev. Lett. 100, 160404 (2008). [2] S.F. Hoogerheide et al., Atoms 3, 367 (2015).

K1.00155 Radiative collisional processes for atoms and ions, J.F. BABB, ITAMP, Harvard-Smithsonian CFA, B. M. MCLAUGHLIN, Queen's U. Belfast — We describe theoretical studies of radiative collisional processes between atoms and ions. The cross sections and rate coefficients for the radiative charge transfer process between a carbon atom and a helium ion (CHe+) [1] and between other atom-ion pairs are calculated. The radiative association process is investigated for a carbon atom and a proton (C+H+) and for other atom-ion systems. Applications of the results are discussed. [1] J.F. Babb and B. M. McLaughlin, J. Phys. B 50 (2017), 044003.

K1.00156 Quantum-State-Resolved Ion-Molecule Chemistry, TIANGANG YANG, GARY CHEN, ERIC HUDSON, WESLEY CAMPBELL, Univ of California - Los Angeles, WESLEY CAMPBELL TEAM — We are working towards a new platform for quantum-state-resolved ion-molecule chemistry by utilizing a combination of cryogenic buffer gas cooling, laser-cooled ion sympathetic cooling, and integrated mass spectrometry in an RF Paul trap. Cold molecular species produced in a cryogenic buffer gas beam collide with target atomic carbon ions in an linear quadrupole trap. Ion imaging and time of flight mass spectrometry are then used to observe the resulting reaction rates and products. We can utilize the precision control over quantum states allowed by this neutral-plus-ion chemistry environment (N+ICE) to resolve state-resolved quantum chemical reactions without high-density molecular sample production; proposed extensions suggest true state-to-state chemistry is possible in this system. We report progress towards cold carbon and water chemistry, including co-trapping and sympathetic cooling of carbon ions with laser-cooled beryllium ions.

1Supported in part by the NSF

1US Air Force Office of Scientific Research BRI program
K1.00157 Fully differential study on projectile coherence effects in ionization of helium by protons1, SACHIN SHARMA, T-ARTHANAYAKA, B.R LAMICHHANE, Missouri Univ of Sci & Tech, A HASAN, Dept of Physics, UAE Univ, AI Ain, Abu Dhabi, UAE, S BORBLY, F IRAI-SZAB, L NAGY, Faculty of Physics, Babes-Bolyai Univ, Romania, MICHAEL SCHULZ, Missouri Univ of Sci & Tech — Atomic-fragmentation experiments have played a crucial role in our understanding of the dynamic few-body processes. Despite incredible progress in the field, puzzling discrepancies between theory and experimental still exist for some very fundamental collision systems e.g. single ionization of He by 100 MeV/a.m.u C6+ ions. In recent years, a possible explanation for these discrepancies has been explored through various experimental studies on “Projectile Coherence Effects” (PCE). Here, we present a fully differential study on single ionization of helium by 75 keV protons. FDCS were measured for two different transverse projectile coherence lengths i.e. 1 a.u. and 3.5 a.u. Substantial differences between the FDCS were observed, once again signifying pronounced PCE. The FDCS for the large PCL contain an interference term due to a coherent superposition of different impact parameters that are leading to the same scattering angles, which is suppressed for the small PCL. The experimental data have been qualitatively well reproduced by a non-perturbative ab initio time-dependent model, which treats the projectile coherence properties in terms of a wave-packet.

1 NSF

K1.00158 ELECTRON-ATOM COLLISIONS —

K1.00159 Analytic descriptions of ultracold electron-atom collisions1, BO GAO, University of Toledo, ALEX DALGARNO, ITAMP — From the quantum defect theory (QDT) and the multichannel quantum defect theory (MQDT) for an attractive polarization potential, we derive both a QDT expansion and a MQDT expansion, that together provide analytic descriptions of low-energy electron collisions with atoms in a ground 1S or a ground 2S state. The expansions are accurate over an energy range from the zero kelvin to hundreds of kelvins, and include effects of hyperfine structure if it is present in cases of 2S atoms. Results for electron-hydrogen hyperfine-changing collisions are presented as an example.

1 Supported by NSF

K1.00160 Free-free experiments in potassium: the search for dressed-atom effects1, C.M. WEAVER, B.N. KIM, N.L.S. MARTIN, University of Kentucky, B.A. DEHARAK, Illinois Wesleyan University — The absorption or emission of radiation during the collision of charged particles with atoms and molecules is investigated in the so-called free-free experiments. Up to now almost all such experiments have been in agreement with a simple theory which assumes that the interaction of the radiation with the atom itself has no effect on the scattering process. Very recently the first experiments to observe the unambiguous breakdown of this assumption have been carried out in xenon by Morimoto, Kanya, and Yamanouchi. An estimate of the dressing of the target by the radiation’s electric field may be made in terms of the electric dipole polarizability of the target. The effects in Xe were extremely difficult to measure because they occur at very small scattering angles. We have begun to carry out experiments in potassium which has a polarizability an order of magnitude larger than Xe. Estimates show that the dressing effects in potassium should be observed at scattering angles easily accessible to experiments, and without the need for complicated corrections.

1 This work was supported by the National Science Foundation under grants Nos. PHY-1607140 (NLSM), PHY-1402899 (BAdH)

K1.00161 Comprehensive out-of-plane (e,2e) measurements on He autoionizing levels1, N.L.S. MARTIN, B.N. KIM, C.M. WEAVER, University of Kentucky, B.A. DEHARAK, Illinois Wesleyan University, O. ZAT-SARINNY, K. BARTSCHAT, Drake University — We report out-of-scattering-plane (e,2e) measurements on helium 21S/22S autoionizing levels for 80, 100, 120, 150, and 488 eV incident electron energies, and scattering angles 60°, 90°, 120°, 180° and 360°, respectively. The kinematics are similar in all cases: ejected electrons are detected in a plane that contains the momentum transfer direction and is perpendicular to the scattering plane, and the momentum transfer is 2.1 a.u. The results are presented as (e,2e) angular distributions energy-integrated over each level, and are compared with our second-order theory calculated for 488 eV incident electron energy, as well as predictions based on a fully non-perturbative close-coupling model. At all energies except 80 eV, the shapes of the angular distributions, and the recoil peak intensities, are in excellent agreement with the 488 eV results for all three autoionizing levels. The reasons why this is so, for incident energies that vary by almost a factor of five, is at present unclear.

1 This work was supported by the National Science Foundation under grants Nos. PHY-0855040, PHY-1607140 (NLSM), PHY-1402899 (BAdH), PHY-1403245 (KB), and PHY-1520970 (OZ & KB)

K1.00162 Spin entanglement in elastic electron scattering from quasi-one electron atoms.1, SAMANTHA FONSECA DOS SANTOS, KLAUS BARTSCHAT, Drake University — We have extended our work on e-Li collisions [1] to investigate low-energy elastic electron collisions with atomic hydrogen and other alkali targets (Na,K,Rb). These systems have been suggested for the possibility of continuously varying the degree of entanglement between the elastically scattered projectile and the valence electron [2,3]. In order to estimate how well such a scheme may work in practice, we carried out overview calculations for energies between 0 and 10 eV and the full range of scattering angles (0° – 180°). In addition to the relative exchange symmetry parameter that characterizes the entanglement, we present the differential cross section in order to estimate whether the count rates in the most interesting energy-angle regimes are sufficient to make such experiments feasible in practice. [1] K. Bartschat and S. Fonseca dos Santos, arXiv:1611.06180. [2] K. Blum and B. Lohmann, Phys. Rev. Lett. 116 (2016) 033201. [3] B. Lohmann, K. Blum, and B. Langer, Phys. Rev. A 94 (2016) 032331.

1 Work supported by the NSF under PHY-1403245.
K1.00163 Benchmark calculations for electron-impact excitation of Mg$^{4+}$. 1. KEDONG WANG, Henan Normal University, LUIS FERNÁNDEZ-MENCHERO, OLEG ZATSARINNY, KLAUS BARTSCHAT, Drake University — There are major discrepancies between recent B-spline R-matrix (BSR) [1] and Dirac Atomic R-matrix Code (DARC) [2] calculations regarding electron-impact excitation rates for transitions in Mg$^{4+}$. To identify possible reasons for these discrepancies and to estimate the accuracy of the various results, we carried out independent BSR calculations with the same 86 target states as in the previous calculations, but with a more accurate representation of the target structure. We find close agreement with the results given in [2] for the majority of transitions. The remaining discrepancies in the collision strengths are mostly due to the different structure description, specifically the inclusion of correlation effects, and the likely occurrence of pseudoresonances in the DARC calculations. To further check the convergence of the predictions, we carried out even more extensive calculations by coupling 316 states of Mg$^{4+}$. Extending the close-coupling expansion results in major corrections for transitions involving the high-lying states and allows us to assess the likely uncertainties in the existing datasets. [1] K. M. Aggarwal and F. P. Keenan, Can. J. Phys. 95 (2017) 9. [2] S. S. Tayal and A. M. Sossnah, Astron. Astroph. 574 (2015) A87.

1Work supported by the NSF under PHY-1403245 and XSEDE-090031.

K1.00164 Novel mechanism for creating long-lived metastable atomic negative ions1, ALFRED MZEZANE, ZINEB FELFLI, Clark Atlanta University — A novel mechanism is proposed for creating long-lived metastable atomic negative ions in complex atoms, such as the lanthanides. It exploits the orbital collapse of the 5d orbital in Gd ($Z=64$) into the 4f orbital of Tb ($Z=65$). In the region of collapse the properties of the 5d and 4f orbitals are quite sensitive to the changes in the effective potential. Consequently the collapse phenomenon impacts the core-polarization interaction significantly in the relevant atom, namely Tb inducing a new excited Tb-anion. The mechanism is demonstrated in the lanthanide atoms Tb and Dy through the appearance of long-lived Tband Dyanions in the Regge pole calculated electron elastic total cross sections. Ground and long-lived metastable negative ion formation occurs at the second Ramsauer - Townsend minima.

1This work was supported by U.S. DOE, Basic Energy Sciences, Office of Energy Research

K1.00165 Monitoring GaAs photocathode heat cleaning temperature1, NATHAN CLAYBURN, University of Nebraska- Lincoln, KENNETH TRANTHAM, University of Nebraska- Kearney, MATTHEW DUNN, TIMOTHY GAY, University of Nebraska- Lincoln — A GaAs photocathode must be cleaned. This is most commonly done by ohmic, radiative, or electron bombardment heating. We report a new technique to monitor the temperature of heated GaAs photocathodes by observation with a camera. The method is robust and yields the same temperatures for different GaAs samples heated using different methods in different mounting configurations.

1Funded by NSF PHY-1505794


1BCS thanks NNSA for partial supports

K1.00167 Dielectronic Recombination of Si-Like Ions and the Low-temperature S$^{2+}$ Orion Nebula Abundance Conundrum. JAGJIT KAUR, THOMAS GORCZYCA, Western Michigan University, NIGEL BADWELL, University of Strathclyde — We describe detailed calculations for the dielectronic recombination (DR) of the Si-like isoelectronic sequence. Our theoretical methodology begins with the perturbative, multi-configurational Breit-Pauli code AUTOSTRUCTURE for efficient yet comprehensive calculations along the entire sequence. We have also investigated, using more sophisticated R-matrix and multi-configuration Hartree-Fock (MCHF) approaches, the low-energy DR resonances. The resultant DR rate coefficients at lower temperatures are extremely sensitive to the theoretically-predicted near-threshold resonance energy positions. This problem is especially acute for near-neutral Si-like ions, including the uncertainties in the S$^{2+}$ DR rate coefficient, an important parameter in astrophysical plasma models for the sulfur ionization balance in the Orion nebula. The computed DR rate coefficients comprise part of the assembly of the DR data base required in the modeling of dynamic finite density plasmas.

K1.00168 Doubly excited states of atomic negative ions. MATTHEW EILES, CHRIS GREENE, Purdue University Department of Physics and Astronomy — Doubly excited states of negative ions reveal the intricate details of electron correlations and depend sensitively on the structure of the excited atomic state. In hydrogen, the degenerate states of the excited atom form a permanent dipole, leading to the dipole series of doubly excited resonances. In other species, the non-degenerate excited states instead form induced dipole potentials, but for higher partial waves their increasingly small energy splittings can lead to both polarization terms in the asymptotic potentials. We theoretically investigate the high partial wave cross sections measured recently using the eigenchannel R-Matrix method to understand the role of these potentials in the observed photodetachment cross sections. We also explore the interactions between a doubly excited hydrogen negative ion and a neutral atom, using analogies to Rydberg molecules. Just as a Rydberg electron can bind to an atom within its large ($R \sim n^2$) orbit, the outer electron of a doubly excited H- ion can also bind to an atom in its exponential orbit, $R \sim \exp(n)$. We use the Fermi pseudopotential to investigate the possibility of forming exotic molecules.

2Lindahl et al. PRL 108, 033004 (2012)

K1.00169 SPECTROSCOPY, LIFETIMES, OSCILLATOR STRENGTHS –
K1.00170 Laser Spectroscopy of \(^{176}\)Lu\(^{+}\). RATTAKORN KAERUAM, ARJAN ROY, KYLE ARNOLD, MURRAY BARRETT, Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, 117543 Singapore — Singly ionized lutetium \(^{176}\)Lu\(^{+}\) possesses low-lying metastable D levels where the corresponding decay channels have been proposed as promising optical clock transitions. Here we report laser spectroscopy of the \(3\, D_{1}, 3\, D_{2}, 3\, P_{0}, \) and \(3\, P_{1}\) levels relative to the \(1\, S_{0}\) ground state. The hyperfine structure for each level, the allowed E1 transitions for detection and cooling, and clock transitions are all determined. These measurements provide a useful reference for establishing optical clock operation with this ion.

K1.00171 Relativistic many-body calculation of energies, multipole transition rates, and lifetimes in molybdenum ions. DADONG HUANG, Z. ZUHRIANDA, University of Delaware, M. S. SAFRONOVA, University of Delaware and JQI, NISTand the University of Maryland, U. I. SAFRONOVA, University of Nevada, Reno — Accurate calculations of atomic properties for systems with 3\(d^n\) valence configurations are complicated by strong correlation corrections. In this work, we apply the relativistic hybrid approach that combines the configuration interaction and the coupled cluster methods to this problem. We chose molybdenum ions with two, three, and four valence electrons as testing cases. The \(4d^{4}, 4d^{5}5s, 4d^{6}5d, 4d^{6}6s\) even-parity states and the \(4d^{5}5p\) and \(4d^{2}5d5p\) odd-parity states are considered for Zr-like Mo\(^{2+}\). The \(4d^{4}\) and \(4d^{2}5p\) states are considered for Y-like Mo\(^{3+}\), and \(4d^{2}, 4d5s, 4d5d,\) and \(4d5p\) states are considered for Sr-like Mo\(^{4+}\). Energy levels, multipole (E1, M1, and E2) matrix elements, and lifetimes are evaluated for all three ions. The energy results are compared with the experimental values for benchmark tests of the method performance for these configurations.

K1.00172 Photoelectron Angular Distributions of RotationallyResolved Autoionizing States of Molecular Nitrogen. ALEXANDER M. CHARTRAND, Bryn Mawr College, UGO JACOVIELLA, ETH Zrich, DAVID M. P. HOLLAND, STFC Daresbury Laboratory, BERENGER GANS, CNRS, Univ. Paris-Sud, and Universit Paris-Saclay, STEPHEN T. PRATT, Argonne National Laboratory, LAURENT NAHON, GUSTAVO A. GARCIA, Synchrotron Soleil, XIAOFENG TANG, Chinese Academy of Sciences, ELIZABETH F. MCCORMACK, Bryn Mawr College — Rotationally resolved excitation of \(N\,^2\Sigma\,^+\) just above the ionization threshold allowed the recording of photoelectron angular distributions (PADs) for selected autoionizing levels of the \((X\,^1\Sigma\,^+\to \Sigma\,^+\) \(v = 2\) and \((X\,^1\Sigma\,^+\to \Sigma\,^+\) \(v = 1\) Rydberg states. Because the direct ionization continuum is weak compared to the autoionizing resonances, the PADs can be predicted using simplified formulae based on the work of Raoult et al. [J. Chem. Phys. 77, 599 (1980)]. The observed PADs are generally in good agreement with these predictions. Photoelectron angular distributions were also recorded for individual rotational levels of the \(b' \Sigma\,^+\), \(v = 42\) and 43 states, and for two complex resonances arising from the interactions between the \(b'\) state and Rydberg states converging to the \(X\,^1\Sigma\,^+, A\,^1\Sigma\,^+,\) and \(B\,^1\Sigma\,^+\) states of the ion. The analysis of these PADs is more complex and is still underway.

K1.00173 Lifetimes and Oscillator Strengths for Ultraviolet Transitions in Ge \(\text{II}\). NEGAR HEIDARIAN, RICHARD E. IRVING, STEVEN R. FEDERMAN, DAVID G. ELLIS, SONG CHENG, LARRY J. CURTIS, Univ of Toledo — Better understanding of the atomic structure for atomic ions requires experimental measurements for lifetimes and oscillator strengths which also serve as a test for theoretical calculations. Furthermore, interpreting astronomical observations of atomic ions requires knowledge of their oscillator strengths and transition probabilities. We present the results of lifetime measurements with beam-foc technique performed with the Toledo Heavy-Ion Accelerator on levels of interest in Ge \(\text{II}\) producing transitions to the ground term at 1237.1 Å and 1261.9 Å (4\(s^{2}4d\,^2\Sigma\,^+\)\(2\,D_{3/2}\) and 4\(s^{2}4d\,^2\Sigma\,^+\)\(2\,D_{3/2}\), respectively). Oscillator strengths are derived from the lifetimes, and our experimental results are compared with our MCDHF\(^{2}\) calculations using the development version of the GRASP2K package as well as the latest calculations done by others. We also provide an overall comparison of our studies on the ns\(2\,nd\,^2\Sigma\,^+\)D and nsnp\(2\,\Sigma\,^+\)D terms in three elements of group IV of the periodic table, namely Pb \(\text{II}\), Sn \(\text{II}\), and Ge \(\text{II}\).

K1.00174 Relativistic many-body calculation of energies, multipole transition rates, and lifetimes of tungsten ions. U. I. SAFRONOVA, University of Nevada, Reno, M. S. SAFRONOVA; University of Delaware and JQI, NIST and the University of Maryland, N. NAKAMURA, The University of Electro-Communications, Japan — Atomic properties of Cd-like W\(^{26+}\), In-like W\(^{25+}\), and Sn-like W\(^{24+}\) ions are evaluated using a relativistic CI+all-order approach that combines configuration interaction and the coupled-cluster methods. The energies, transition rates, and lifetimes of low-lying levels are calculated and compared with available theoretical and experimental values. The magnetic-dipole transition rates are calculated to determine the branching ratios and lifetimes for the \(4f^{3}\) states in W\(^{25+}\) and for the \(4f^{4}\) in W\(^{24+}\) ions. We also evaluated the atomic properties of these ions using the Hebrew University Lawrence Livermore Atomic (HULLAC) code and demonstrated higher accuracy of the wavelength values obtained using the CI+all-order approach.

K1.00175 Hyperfine Structure of the B State and Predictions of Optical Clocking Behavior of the X-B transition in TIF\(^{1}\). ERIC NORGARD, EUSTACE EDWARDS, DANIELL MCCROR, MATTHEW STEINECKER, DAVID DEMILLE, Yale University, SHAH ALAM, STEPHEN PECK, NEHA WADIA, LARRY HUNTER, Amherst College — The rotational and hyperfine spectrum of the \(X\,^1\Sigma\,^+\to \Sigma\,^+\) transition in TIF molecules was measured using laser excitation and detection of the resulting fluorescence from a molecular beam. Rotational and hyperfine constants are obtained from a least-squares analysis. The large magnetic hyperfine interaction of the Tl nuclear spin leads to significant mixing of the lowest \(B\,^1\Sigma\,^+\) rotational levels. Updated, more precise measurements of the \(B \to X\) vibrational branching fractions are also presented. The combined rovibrational branching fractions allow for the prediction of the number of photons that can be scattered in a given TIF optical cycling scheme, which will be critical knowledge for the CeNTREX collaboration’s upcoming precision measurement of the Schiff Moment of the Tl nucleus using TIF.

\(^{1}\)Templeton Foundation, Heising Simons Foundation
K1.00176 Analysis of monochromatic and quasi-monochromatic X-ray sources in imaging and therapy , MAXIMILLIAN WESTPHAL, The Ohio State University, SARA LIM, Medical College of Wisconsin, SULTANA NAHAR, CHRISTOPHER ORBAN, ANIL PRADHAN, The Ohio State University — We studied biomedical imaging and therapeutic applications of recently developed quasi-monochromatic and monochromatic X-ray sources [1]. Using the Monte Carlo code GEANT4, we found that the quasi-monochromatic 65 keV Gaussian X-ray spectrum created by inverse Compton scattering with relativistic electron beams were capable of producing better image contrast with less radiation compared to conventional 120 kV broadband CT scans [3]. We also explored possible experimental detection of theoretically predicted Kα resonance fluorescence in high-Z elements [2] using the European Synchrotron Research Facility with a tungsten (Z = 74) target. In addition, we studied a newly developed quasi-monochromatic source generated by converting broadband X-rays to monochromatic Kα and Kβ X-rays with a zirconium target (Z = 40). We will further study how these Kα and Kβ dominated spectra can be implemented in conjunction with nanoparticles for targeted therapy.


Acknowledgement: Ohio Supercomputer Center, Columbus, OH

K1.00177 Experimental Potential Energy Curve for the 43Π Electronic State of NaCs , ANDREW STEELEY, HANNA COOPER, HAREEM ZAIN, CIARA WHIPP, CARL FAUST, Susquehanna Univ, ANDREW KORTYNA, JILA, University of Colorado, JOHN HUENNEKENS, Lehigh University — We present results from experimental studies of the 43Π electronic state of the NaCs molecule. This electronic state is interesting in that its potential energy curve likely exhibits a double minimum. As a result, interference effects are observed in the resolved bound-free fluorescence spectra. The optical-optical double resonance method was used to obtain Doppler-free excitation spectra for the 43Π state. This dataset of measured level energies was expanded largely by observing fluorescence from levels populated by collisions. To aid in level assignments, simulations of resolved bound-free fluorescence spectra were calculated using the BCONT program (R. J. Le Roy, University of Waterloo). Spectroscopic constants were determined to summarize data belonging to inner well, outer well, and above barrier regions of the electronic state. Current work focuses on using the IPA method to construct an experimental potential energy curve.

1Work supported by NSF and Susquehanna University

K1.00178 Study of electron correlations in Helium double Rydberg wave packets , XIAO WANG, FRANCIS ROBICHEAUX, Purdue Univ — The correlation between two bound electrons as a three-body Coulomb problem remains an interesting topic. We have performed fully quantum and classical calculations on a Helium atom with two excited Rydberg wave packets. Changing the central energies and the energy widths of the wave packets may lead to totally different behavior of the system, such as faster autoionization rates or more stable trajectories. We also studied field-caused double ionizations of this system with THz short pulses, where the results can be used to study the wavefunction structure of the system during autoionization process.

1Department of Energy, Office of Science, Basic Energy Sciences.

K1.00179 Towards Er-K quantum gas mixtures , JACKSON ANGONGA, BRYCE GADWAY, Univ of Illinois - Urbana — We present our efforts towards developing a system that will trap and cool atomic mixtures of erbium and potassium. We highlight the first polarization spectroscopy measurements of erbium, which will be used to stabilize a 401nm laser beam, as well as progress towards laser cooling both species. The system will be used to study few- and many body physics, including collisional studies of Er-K mixtures and quantum magnetism with dipolar atoms.

K1.00180 Characterizing Radiation Trapping Effects in Precision Measurements of Atomic Excited State Lifetimes , BRIAN PATTERSON, JERRY SELL, ALINA GEARBA, JEREMIAH WELLS, DERALD MADSON, RANDY KNIZE, United States Air Force Academy, STEPHEN SPIKELMIRE, University of Indianapolis — Measurements of atomic excited state lifetimes provide a valuable test of atomic theory, allowing comparisons between experimental and theoretical transition dipole matrix elements. We previously measured the 6P1/2 state lifetime in Cs using a pulsed laser technique, achieving a precision of 0.15%. In that experiment, a single pulse from a mode-locked laser was used to excite cesium atoms in a thermal beam, and a subsequent pulse ionized the excited atoms. The ions were collected while varying the time delay between the excitation and ionization pulses. Two of the dominant systematic errors in the measurement included the effects of quantum beating and radiation trapping. We will present our recent efforts to reduce these systematic errors in lifetime measurements of the 5P1/2 state of rubidium. These efforts include using a gated CW laser to excite a single hyperfine level, greatly reducing quantum beats. We are also carrying out independent measurements of the atom beam density to better quantify the effects of radiation trapping on the measured lifetime. We use two-photon ionization of the atom beam and the known rubidium two-photon ionization cross-section to extract the rubidium density. Measurements of the Rb lifetime at various beam densities are compared to predictions of Monte Carlo calculations of the radiation trapping.


K1.00181 Anomalies in QED corrections to the 3d states of K-like ions , JONATHAN SAPIRSTEIN, University of Notre Dame, KWOK-TSANG CHENG, Lawrence Livermore National Laboratory — Higher-order QED corrections to atomic energy levels from electron correlations are typically smaller in magnitudes than the lowest-order radiative corrections. However, such is not the case for the 3d states of K-like ions, as screened QED corrections are enhanced by interactions with the 1s − 3p core electrons which have much larger one-loop self-energy and vacuum polarization corrections than the 3d valence electrons. In this work, screened vacuum polarization corrections are found to be almost two orders of magnitude larger than the lowest-order corrections for the 3d ground states of K-like krypton. Similar enhancements should exist in the self-energies of these 3d states.

1Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
A pulsed VUV laser for the search for the thorium-229 nuclear isomeric transition. CHRISTIAN SCHNEIDER, JUSTIN JEET, University of California, Los Angeles, EUGENE V. TKALYA, Lomonosov Moscow State University and Nuclear Safety Institute of Russian Academy of Science, ERIC R. HUDSON, University of California, Los Angeles — The nucleus of thorium-229 has an exceptionally low-energy isomeric transition in the vacuum-ultraviolet (VUV) spectrum around 7.8 ± 0.5 eV [1]. While inaccessible to standard nuclear physics techniques, there are various prospects for a laser-accessible nuclear transition. Our direct search for the transition uses thorium-doped crystals as samples. In a previous experiment [2] at the Advanced Light Source (ALS) synchrotron, LBNL, we were able to exclude a large portion of the transition lifetime-vs.-frequency region-of-interest (ROF) [3]. We will present the technical aspects of our ongoing efforts at UCLA, including a newly developed pulsed VUV laser system with wide tunability and VUV pulse energies up to 40 µJ/pulse, the absolute measurement of these pulse energies, and the characterization of the frequency spectrum of the pulsed laser light. A preliminary, updated exclusion region obtained with the new experimental setup will be depicted.


Testing quantum electrodynamics in the lowest singlet state of neutral beryllium-9, WILL WILLIAMS, CARSON PATTERSON, ALISHA VIRA, BRUCE HAWKINS, Smith College — We performed high precision spectroscopy on the 2s2p J=1 singlet state in neutral beryllium-9. This result serves as a test of quantum electrodynamics and as an assessment of theoretical methods used to predict the energy levels of beryllium. A frequency quadrupled titanium sapphire laser at 235 nm was used to probe a beam of atomic beryllium. The frequency was measured to high precision by stabilizing the 470 nm light out of the frequency doubler to an ultra-low expansion cavity that was calibrated using molecular tellurium lines. This experimental method allowed us to improve the precision of the energy level to which the singlet state is known by more than 3 orders of magnitude.

Optogalvanic spectroscopy of lanthanum hyperfine structure, AMANDA NELSON, JESSIE HANKES, PATRICK BANNER, STEVEN OLMSCHÉN, Denison University — Optogalvanic spectroscopy is a sensitive technique to measure optical transitions of atoms and ions produced in a high voltage discharge. Advantages of this technique include a comparatively simple optical setup and the ability to interrogate excited state transitions. Here, we use optogalvanic spectroscopy in a hollow cathode lamp to measure the hyperfine spectrum of several transitions in lanthanum. Hyperfine coefficients are determined for the corresponding energy levels and compared to available previous measurements.

Characterizing the perturbed 6snd series of Ytterbium using MW spectroscopy, FATHIMA NIYAZ, THOMAS GALLAGHER, University of Virginia — The Yb 6snd Rydberg series is perturbed weakly by a doubly excited state lying between the 6s26s and 6s27d states. We have used microwave transitions between 6sns-6s(n-1)d and 6sns-6s(n-1)s states to determine the energies of the 6snd Rydberg states of 28≤n≤40. We have analyzed the energies if the perturbed series using quantum defect theory, which allows the characterization of the perturbed series by only four parameters. The quantum defect theory model predicts the energies to the accuracy of a few MHz. We have also made lifetime measurements of the 6snd states as a consistency check of our analysis. This work has been supported by the Chemical Sciences Division of the Department of Energy.

Frequency-comb based spectroscopy of the Yb I 399 nm transition, QUINTON MCKNIGHT, Brigham Young University, MICHAELA KLEINERT, Willamette University, SCOTT BERGESON, Brigham Young University — We determine the frequency of the Yb I 399 nm using an optical frequency comb. Although this transition was measured previously using an optical transfer cavity [D. Das et al., Phys. Rev. A 72, 032506 (2005)], recent work has uncovered significant errors in that method. We compare our result with those from the literature and discuss observed differences. We verify the correctness of our method by measuring the frequencies of well-known transitions in Rb and Cs, and by demonstrating proper control of systematic errors in both laser metrology and atomic spectroscopy. We also demonstrate the effect of quantum interference due to hyperfine structure in a divalent atomic system and present isotope shift measurements for all stable isotopes.

Predicted broad resonant absorption feature in the continuum spectrum of Ho II, WERNER EISSNER, Stuttgart University, SULTANA NAHAR, Ohio State Univ - Columbus — Ho II lines are being observed in metal poor stars. Excess of Ho II lines relative to Fe-peak elements in these stars indicate enhanced neutron-capture or the rapid or r-process in contrast to typical stars. However due to high line blending, spectroscopic identification of the observed lines have been difficult. We have carried out atomic structure calculations from bound-bound and bound-free transitions in Ho II (Z=67) in relativistic Breit-Pauli approximation using the program SUPERSTRUCTURE. However, the objective is to study the features in the continuum, particularly due to strong 4d-4f transitions in 1s23p64d590595s25p664f711). We find that there are extensive number, a total of 6712, 4d-4f allowed E1 transitions which form an enhanced broad resonant structure in the energy region of 150 - 200 eV. The feature is expected to be observable in the absorption spectrum of Ho II.

Supported in part by National Science Foundation grants PHY-1404488 and PHY-1500376

Predicted broad resonant absorption feature in the continuum spectrum of Ho II, WERNER EISSNER, Stuttgart University, SULTANA NAHAR, Ohio State Univ - Columbus — Ho II lines are being observed in metal poor stars. Excess of Ho II lines relative to Fe-peak elements in these stars indicate enhanced neutron-capture or the rapid or r-process in contrast to typical stars. However due to high line blending, spectroscopic identification of the observed lines have been difficult. We have carried out atomic structure calculations from bound-bound and bound-free transitions in Ho II (Z=67) in relativistic Breit-Pauli approximation using the program SUPERSTRUCTURE. However, the objective is to study the features in the continuum, particularly due to strong 4d-4f transitions in 1s23p64d590595s25p664f711). We find that there are extensive number, a total of 6712, 4d-4f allowed E1 transitions which form an enhanced broad resonant structure in the energy region of 150 - 200 eV. The feature is expected to be observable in the absorption spectrum of Ho II.

Supported in part by National Science Foundation grants PHY-1404488 and PHY-1500376
K1.00188 Precise lifetime of the metastable $^2P_{1/2}$ state in Ar$^{9+}$ ions isolated in a Penning trap. JOSEPH TAN, NIST - Natl Inst of Stds & Tech, SAMUEL BREWER, Univ. of Maryland, College Park, MD 20742, JOAN DREILING, SHANON HOOPER, NICHOLAS GUISE, NIST - Natl Inst of Stds & Tech, AUNG NAING, Univ. of Delaware, Newark, DE 19716 — A measurement with <1% statistical uncertainty is presented for the radiative decay lifetime of the metastable $^2P_{1/2}$ state in the ground-state fine structure of fluorine-like Ar$^{9+}$ (one hole in the filled 2p subshell). The method involves the extraction of multiply-ionized Ar atoms from an electron beam ion trap (EBIT) and the capture of only Ar$^{9+}$ ions in a compact Penning trap. The $^2P_{1/2}$ state of the stored Ar$^{9+}$ ions can spontaneously decay via M1 (spin-flip) radiative transition to the ground state, with the photon emission monitored using a photomultiplier tube and a multichannel scaler. Improvements that reduced measurement uncertainty are discussed. The results are compared with theory and prior measurements.

$^1$Supported by NRC and JQI.

K1.00189 Observation and analysis of high-lying singlet gerade states of rubidium dimer. PHILLIP ARNDT, XINHUA PAN, DAVID BEECHER, MARJATTA LYYRA, ERGIN AHMED, Temple University — The structure of the excited electronic states of Rubidium dimer is important to a number of areas of research including, the production of ultracold ground state molecules, cold atom-molecule collisions, and the development of new ab-initio molecular electronic structure methods. In the experiment we used optical double resonance technique to observe large number of ro-vibrational levels of the $^5\Sigma^+_{g}$, $^6\Sigma^+_{g}$, and $^3\Pi_g$ electronic states in the 24000-26000 cm$^{-1}$ range. The Rb$_2$ molecules were initially excited from the ground $^5\Sigma^+_{g}$ state to an intermediate level of the mixed $^1\Sigma^+_{u}A^1\Pi_u$ manifold using a narrow band tunable TiSa laser. In the next step the probe laser, a narrow band dye laser tunable in the 13000-14000cm$^{-1}$ range, excited the molecules further to the target states. The resonances of the probe laser were observed by detecting the total fluorescence from the excited states to the $^3\Pi_g^+$ state in the 500nm range. Potential energy curve was constructed for each state from the term values of the observed levels.

K1.00190 Computing Rydberg Electron Transport Rates Using Periodic Orbits. SULIMON SATTARI, KEVIN MITCHEL, Univ of California - Merced — Electron transport rates in chaotic atomic systems are computable from classical periodic orbits. This technique allows for replacing a Monte Carlo simulation launching millions of orbits with a sum over tens or hundreds of properly chosen periodic orbits using a formula called the spectral determinant. A firm grasp of the structure of the periodic orbits is required to obtain accurate transport rates. We apply a technique called homotopic lobe dynamics (HLD) to understand the structure of periodic orbits to compute the ionization rate in a classically chaotic atomic system, namely the hydrogen atom in strong parallel electric and magnetic fields. HLD uses information encoded in the intersections of stable and unstable manifolds of a few orbits to compute relevant periodic orbits in the system. All unstable periodic orbits are computed up to a given period, and the ionization rate computed from periodic orbits converges exponentially to the true value as a function of the period used. Using periodic orbit continuation, the ionization rate is computed over a range of electron energy and magnetic field values. The future goal of this work is to semiclassically compute quantum resonances using periodic orbits.

Wednesday, June 7, 2017 5:30PM - 7:00PM —
Session L1 Career Skills Workshop: Achieving Your Goals Through Effective Communication 304-305 -

5:30PM L1.00001 Career Skills Workshop: Achieving Your Goals Through Effective Communication. CRYSTAL BAILEY, American Physical Society — Physics students graduate with a huge array of transferrable skills, which are extremely useful to employers (particularly in the private sector, which is the largest employment base of physicists at all degree levels). However, the key to successfully connecting with these opportunities lies in how well graduates are able to communicate their skills and abilities to potential employers. The ability to communicate effectively is a key professional skill that serves scientists in many contexts, including interviewing for jobs, applying for grants, or speaking with law and policy makers. In this interactive workshop, Crystal Bailey (Careers Program Manager at APS) and Gregory Mack (Government Relations Specialist at APS) will lead activities to help attendees achieve their goals through better communication. Topics will include writing an effective resume, interviewing for jobs, and communicating to different audiences including Congress, among others.

Wednesday, June 7, 2017 7:30PM - 8:30PM —
Session L2 Public Lecture: The Quantum Engineering Conundrum 306-307 -

7:30PM L2.00001 The Quantum Engineering Conundrum. CHRISTOPHER MONROE, University of Maryland — There is newfound rush and excitement in Quantum Information Science, as this field seems to be moving toward an industrial/engineering phase. However, this evolution will require that quantum science, long the domain of academics and other researchers, make the leap to sustained engineering efforts in order to fabricate practical devices. I will address the conundrum, that full-blooded engineering does not generally happen on campuses, while many in the professional engineering and computer science community do not believe in quantum physics.

Thursday, June 8, 2017 8:00AM - 10:00AM —
Session M2 Cavity QED with Ultracold Atoms 306-307 - Monika Schleier-Smith, Stanford University
8:00AM M2.00001 Quantum Crystals of Matter and Light, TOBIAS DONNER, Institute for Quantum Electronics, ETH Zurich, Switzerland — The coupling of a quantum gas to the field of an optical high-finesse cavity can be employed to induce global-range atom-atom interactions. If these are sufficiently strong, such a many-body system undergoes a structural phase transition. Introducing a 3D optical lattice to this system, the collisional short-range interactions can be brought to competition with these global-range interactions and at the same time with the zero-point motion of the particles. We explore a rich phase diagram hosting four distinct phases: a superfluid, a lattice supersolid, a Mott insulator and a charge density wave. In a different experiment, we couple a superfluid cloud of atoms simultaneously to two intersecting optical cavities. This arrangement leads to symmetry enhancement and the resulting system exhibits a continuous spatial U(1)-symmetry. The combination of two continuous symmetries—the gauge symmetry of the superfluid and the spatial symmetry—is a prerequisite for a supersolid state of matter, which we explore in our experiments.

8:30AM M2.00002 Quantum Many-body Physics with Multimode Cavity QED, BENJAMIN LEV, Stanford University — Phase transitions, where observable properties of a many-body system change discontinuously, can occur in both open and closed systems. Ultracold atoms have provided an exemplary model system to demonstrate the physics of closed-system phase transitions, confirming many theoretical models and results. Our understanding of dissipative phase transitions in quantum systems is less developed, and experiments that probe these physics even less so. By placing cold atoms in optical cavities, and inducing strong coupling between light and excitations of the atoms, one can experimentally study phase transitions of open quantum systems. We will report our observation of a novel form of nonequilibrium phase transition, the condensation of supermode-density-wave-polaritons. These polaritons are formed from a hybrid “supermode” of cavity photons coupled to atomic density waves of a quantum gas. These results, found in the few-mode-degenerate cavity regime, demonstrate the potential of fully multimode cavities to exhibit physics beyond mean-field theories, possibly in the presence of dynamic synthetic gauge fields. Such systems will provide experimental access to nontrivial phase transitions in driven dissipative quantum systems as well as enabling the studies of non-equilibrium spin glasses and neuromorphic computation.

9:00AM M2.00003 Supersolidity and tunable symmetries with ultracold atoms in optical cavities, PHILIP ZUPANCIC, JULIAN LEONARD, ANDREA MORALES, TILMAN ESSLINGER, TOBIAS DONNER, ETH Zurich — By coupling a Bose-Einstein condensate to two optical cavities we gain experimental access to new phases of matter. For large detuning of the cavities from the atomic resonance, the combination of self-organisation processes with Z_2 symmetry in each cavity gives rise to one enhanced U(1) symmetry that corresponds to translational invariance of the atoms in one direction. We report on the observation of a phase transition to a supersolid state that breaks this continuous symmetry, and show spectroscopic measurements of the Nambu-Goldstone and Higgs modes present in this phase. The light fields leaking from the cavities enable real-time surveillance of the system dynamics. Approaching the atomic resonance, the continuous invariance is lifted as cavity-cavity coupling comes into play.

9:12AM M2.00004 Emergent equilibrium in many-body optical bistability1, MICHAEL FOSS-FEIG, Army Research Laboratory, PRADEEP NIROULA, Harvard University, JEREMY YOUNG, MOHAMMAD HAFezi, ALEXEY GORSHKOV, Joint Quantum Institute, RYAN WILSON, United States Naval Academy, MOHAMMAD MAGHREBI, Michigan State University — Many-body systems constructed of quantum-optical building blocks can now be realized in experimental platforms ranging from exciton-polariton fluids to Rydberg gases, establishing a fascinating interface between traditional many-body physics and the non-equilibrium setting of cavity-QED. At this interface the standard intuitions of both fields are called into question, obscuring issues as fundamental as the role of fluctuations, dimensionality, and symmetry on the nature of collective behavior and phase transitions. We study the driven-dissipative Bose-Hubbard model, a minimal description of atomic, optical, and solid-state systems in which particle loss is countered by coherent driving. Despite being a lattice version of optical bistability—a foundational and patent non-equilibrium model of cavity-QED—the steady state possesses an emergent equilibrium description in terms of an Ising model. We establish this picture by identifying a limit in which the quantum dynamics is asymptotically equivalent to non-equilibrium Langevin equations, which support a phase transition described by model A of the Hohenberg-Halperin classification. Simulations of the Langevin equations corroborate this picture, producing results consistent with the behavior of a finite-temperature Ising model.

1M.F.M., J.T.Y., and A.V.G. acknowledge support by ARL CDQI, ARO MURI, NSF QIS, ARO, NSF PFC at QJI, and AFOSR. R.M.W. acknowledges partial support from the NSF under Grant No. PHYS-1516421. M.H. acknowledges support by AFOSR-MURI, ONR and Sloan Foundation

9:24AM M2.00005 Observation of dynamic instability from coherent coupling of atomic motion and spin, JUSTIN GERBER, JONATHAN KOHLER, EMMA DOWD, DAN STAMPER-KURN, University of California - Berkeley — The collective spin precession of an atomic ensemble about an applied magnetic field can be approximated by the dynamics of a negative mass harmonic oscillator when the spin precesses close to its highest energy state. The amplitude of a negative mass oscillator increases as it loses energy meaning that when a negative mass oscillator is coupled to a positive mass oscillator the system undergoes an instability in which, through a cascade of near-resonant pair creation processes, the amplitude of each oscillator grows exponentially. We have experimentally realized this instability by using the field of an optical cavity to coherently couple the collective spin and mechanical degrees of freedom of an atomic ensemble. We demonstrate control of this instability by tuning the parameters of the coupled system.

9:36AM M2.00006 Observation of two-mode thermal squeezing through coherent coupling of positive- and negative-mass oscillators, JONATHAN KOHLER, JUSTIN GERBER, EMMA DOWD, DAN STAMPER-KURN, Univ of California - Berkeley — Measurement and control of either the mechanical or rotational degrees of freedom of an atomic ensemble have been well demonstrated through coupling to an optical cavity. We have previously used autonomous cavity feedback to demonstrate the stabilization of a precessing collective spin near its high-energy stationary state, where excitations away from this state evolve like an effective negative-mass oscillator. When the dynamics of this negative-mass mode are coherently coupled to the collective atomic motion, we observe a parametric instability, which leads to the spontaneous amplification of a correlated mode of the hybrid system. Under the correct conditions, this interaction drives the system into a two-mode squeezed state. I will present the latest results of our measurements of the correlations created through this process.
optical lattices. Galilean covariance, dynamical instabilities, and a slowing down consistent with negative acceleration. We show that these features can be exploited when tunneling is suppressed the differential phase imparted by the laser is irrelevant and only p-wave interaction occur. If tunneling is allowed it imparts a lattice-site dependent phase on the atoms that becomes important when the atoms tunnel. For the case of spin polarized fermions, we observe a spectrally narrow dark-polariton resonance up to extremely-high Rydberg states (n~121), and demonstrate strong photon-photon interactions within the dot through strong blockade of cavity transmission, demonstrated through antibunching of the transmitted field. By combining this breakthrough with degenerate-cavity realizations of tunable 2D photonic puddles that we have developed in parallel, this work points the way to explorations of crystalline and topological quantum materials composed of cavity Rydberg polaritons.

Thursday, June 8, 2017 8:00AM - 10:00AM –

Session M3 Spin-Orbit Coupling in Cold Gases

8:00AM M3.00001 Interacting fermions under spin-orbit coupling in an optical lattice clock. SARAH BROMLEY, TOBIAS BOTHWELL, DHRAV KEDAR, SHIMON KOLKOWITZ, ARGHAVAN SAFAVI-NAINI, ANA MARIA REY, JUN YE, Univ of Colorado - Boulder — Synthetic gauge fields are a promising tool for creating complex Hamiltonians in ultracold neutral atom systems that may mimic the fractional Quantum Hall effect and other topological states. Interactions are a necessary ingredient for new phases and phenomena. To access the interplay between spin-orbit coupling (SOC) and interactions we study the density-dependent frequency shift in an optical lattice clock. Optical lattice clocks allow the SOC to occur naturally during clock interrogation when the clock laser imparts a lattice-site dependent phase on the atoms that becomes important when the atoms tunnel. For the case of spin polarized fermions, when tunneling is suppressed the differential phase imparted by the laser is irrelevant and only p-wave interaction occur. If tunneling is allowed then the site-dependent phase accumulated by the atoms open up the s-wave interaction channel.

8:12AM M3.00002 Spin-orbit-coupled Fermi gases of two-electron ytterbium atoms1, CHENGDONG HE, BO BONG, ELNUR HACIYEV, ZEJIAN REN, BOJEONG SEO, SHANCHAO ZHANG, Hong Kong Univ of Sci & Tech, XIONG-JUN LIU, Peking University, GYU-BOONG JO, Hong Kong Univ of Sci & Tech — Spin-orbit coupling (SOC) has been realized in bosonic and fermionic atomic gases opening an avenue to novel physics associated with spin-momentum locking. In this talk, we will demonstrate all-optical method coupling two hyperfine ground states of \(^{173}\text{Yb}\) fermions through a narrow optical transition \(^{1}\text{S}_0 \rightarrow {}^{3}\text{P}_1\). An optical AC Stark shift is applied to shift the ground hyperfine levels and separate out an effective spin-1/2 subspace from other spin states for the realization of SOC. The spin dephasing dynamics and the asymmetric momentum distribution of the spin-orbit coupled Fermi gas are observed as a hallmark of SOC. The implementation of all-optical SOC for ytterbium fermions should offer a new route to a long-lived spin-orbit coupled Fermi gas and greatly expand our capability in studying novel spin-orbit physics with alkaline-earth-like atoms. Other ongoing experimental works related to SOC will be also discussed.

1Funded by Croucher Foundation and Research Grants Council (RGC) of Hong Kong (Project ECS26300014, GRF16300215, GRF16311516, and Croucher Innovation grants); MOST (Grant No. 2016YFA0301604) and NSFC (No. 11574008)

8:24AM M3.00003 Observation of the supersolid stripe phase in spin-orbit coupled Bose-Einstein condensates1, JINRU LI, JEONGWON LEE, WUJIE HUANG, SEAN BURCZESKY, BORIS SHTEYNAS, FURKAN TÖP, ALAN JAMISON, WOLFGANG KETTERLE, Massachusetts Inst of Tech-MIT — Supersolidity combines the property of superfluid flow with long-range spatial periodicity of solids and has not been observed since predicted in condensed matter systems. The concept of supersolidity was then generalized to include other superfluid systems which break continuous translational symmetry. Bose-Einstein condensates with spin-orbit coupling are predicted to possess a stripe phase with supersolid properties. We report the first observation of the predicted density modulation of the stripe phase using Bragg reflection – the evidence for spontaneous long-range order in one direction while maintaining a sharp momentum distribution – the hallmark of superfluid Bose-Einstein condensates. In our system, the spin-orbit coupling was realized in an optical superlattice as described in [1]. Briefly two lowest bands in the superlattice were used as pseudospins and a Raman process was implemented to provide coupling between pseudospin and momentum. Our work establishes a system with unique continuous symmetry breaking properties, associated Goldstone modes and superfluid behavior.


1We acknowledge the support from the NSF through the Center for Ultracold Atoms and by award 1506369, from ARO-MURI Nonequilibrium Many-body Dynamics (grant W911NF-14-1-0003) and from AFOSR-MURI Quantum Phases of Matter (grant FA9550-14-1-0035).

8:36AM M3.00004 Negative-mass hydrodynamics in a spin-orbit coupled Bose-Einstein condensate1, KHALID HOSSAIN, M. A. KHAMMECHI, M. E. MOSSMAN, Washington State University, YONGPING ZHANG, Shanghai University, TH. BUSCH, OIST Graduate University, MICHAEL FORBES, Washington State University, University of Washington, PETER ENGELS, Washington State University — Negative effective mass is peculiar; whereas objects usually accelerate away from a push, negative-mass objects will accelerate towards the push. This strange behaviour can be realized in spin-orbit coupled (SOC) BECs where the dispersion relationship can be engineered to exhibit negative curvature. In this talk we will describe an experiment, where trapped \(^{87}\text{Rb}\) atoms expand in the presence of a spin-orbit coupling, demonstrating an interesting array of dynamical phenomena, including the breaking of Galilean covariance, dynamical instabilities, and a slowing down consistent with negative acceleration. We show that these features can be described with a simple theory of negative-mass hydrodynamics, and argue that this also explains a related phenomena of self-trapping seen in optical lattices.

1This work was partially supported by NSF.
and explore the important role of layer-spin coupling. Zeeman field in two layers, which can be realized easily in experiments. We study the ground phase diagram of such time-reversal invariant BEC with a Zeeman field. Here we propose that time-reversal symmetry can be restored in bilayer spin-orbit coupled ultracold atomic gases using opposite quantum phenomena. In these experiments, time-reversal symmetry is explicitly broken by the Raman coupling that corresponds to an effective Zeeman field.

Recent experimental realization of spin-orbit coupling for ultracold atomic gases provides a new powerful platform for exploring many interesting quantum phenomena. In these experiments, time-reversal symmetry is explicitly broken by the Raman coupling that corresponds to an effective Zeeman field in two layers, which can be realized easily in experiments. We study the ground phase diagram of such time-reversal invariant BEC and explore the important role of layer-spin coupling.

Time-reversal invariant bilayer spin-orbit coupled Bose-Einstein condensates. MATTHEW MAISBERGER, LINCHENG WANG, KUEI SUN, CHUANWEI ZHANG, University of Texas at Dallas — The recent experimental realization of spin-orbit coupling for ultra-cold atomic gases provides a new powerful platform for exploring many interesting quantum phenomena. In these experiments, time-reversal symmetry is explicitly broken by the Raman coupling that corresponds to an effective Zeeman field. Here we propose that time-reversal symmetry can be restored in bilayer spin-orbit coupled ultracold atomic gases using opposite Zeeman field in two layers, which can be realized easily in experiments. We study the ground phase diagram of such time-reversal invariant BEC and explore the important role of layer-spin coupling.

Strongly correlated magnetic phases of the spin-orbit coupled spin-1 Bose-Hubbard chain. JEDEDIAH PIXLEY, WILLIAM COLE, Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, MATTEO RIZZI, Institute of Physics, IAN SPIELMAN, Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland — Motivated by the ability to engineer artificial gauge fields in ultracold atomic gases we consider the strong coupling phases of the one-dimensional spin-1 Bose-Hubbard model in the presence of a spin orbit coupling. We determine the low energy magnetic Hamiltonian that describes the bosonic Mott insulating phases with an odd integer filling, which is a spin-1 ferromagnetic bilinear-biquadratic model in a spiral magnetic field. We solve the effective spin Hamiltonian using the density matrix renormalization group and determine the zero temperature quantum phase diagram.

Damping of spin-dipole mode and generation of quadrupole mode excitations in a spin-orbit coupled Bose-Einstein condensate. CHUAN-HSUN LI, DAVID BLASING, YONG CHEN, Purdue University — In cold atom systems, spin excitations have been shown to be a sensitive probe of interactions and quantum statistical effects, and can be used to study spin transport in both Fermi and Bose gases. In particular, spin-dipole mode (SDM) is a type of excitation that can generate a spin current without a net mass current. We present recent measurements and analysis of SDM in a disorder-free, interacting three-dimensional (3D) $^87$Rb Bose-Einstein condensate (BEC) by applying spin-dependent synthetic electric fields to actuate head-on collisions between two BECs of different spin states. We experimentally study and compare the behaviors of the system following SDM excitations in the presence as well as absence of synthetic 1D spin-orbit coupling (SOC). We find that in the absence of SOC, SDM is relatively weakly damped, accompanied with collision-induced thermalization which heats up the atomic cloud. However, in the presence of SOC, we find that SDM is more strongly damped with reduced thermalization, and observe excitation of a quadrupole mode that exhibits BEC shape oscillation even after SDM is damped out. Such a mode conversion bears analogies with the Beliaev coupling process or the parametric frequency down conversion of light in nonlinear optics.

Spin-tensor-momentum-coupled Bose-Einstein condensates. XI-WANG LUO, KUEI SUN, CHUANWEI ZHANG, Physics Department, The University of Texas at Dallas — The recent experimental realization of spin-orbit coupling for ultracold atomic gases provides a new powerful platform for exploring many interesting quantum phenomena. Here the spin represents spin-vector (spin-1/2 or spin-1) and orbit represents linear momentum. We propose a scheme to realize a new type coupling between spin-tensor and linear momentum in spin-1 ultra-cold atomic gases. We study ground state properties of such spin-tensor-momentum-coupled Bose-Einstein condensates (BECs) and find interesting stripe superfluid phases that have not been explored in previous spin-orbit coupled BECs. A dynamical process to generate stripe phases with a tunable period of spin-density modulations is discussed.

Negative-Mass Hydrodynamics: Solitons and Shockwaves. EDWARD DELIKATNY, MICHAEL FORBES, Washington State University — In this talk, I will present a microscopic description of the shockwaves and solitons that form when a trapped Bose-Einstein Condensate (BEC) is released and expands in the presence of Spin-Orbit Coupling (SOC). The SOC dispersion has regions of negative curvature $\left( \frac{\partial^2}{\partial k^2} E(k) < 0 \right)$ which emulate an effective negative mass. We seed the edges of the trapped BEC with momenta in the negative mass region, the edges then push against the outward expansion leading to a self-trapping phenomenon. Using negative mass hydrodynamics we see a build up and trapping of shockwaves in the center of the BEC. Although remarkably stable, the shockwaves ultimately decay into trains of solitons which lead to a dynamic instability of the trapped BEC.

Thursday, June 8, 2017 8:00AM - 10:00AM –
Session M4 Energy and Time Domain Spectroscopy of Fullerenes and Endofullerenes
309 - Steven Manson, Georgia State University
Spectacular effects in the scattering process, primarily associated with polarization of $A^+$ program which initially studied $C$ in particular, rare encapsulated fullerenes, i.e., endohedrals, where an atom or molecule is trapped within the fullerene cage. I will discuss the using neutral atomic or molecular species, photoionization of ions presents unique challenges, especially large molecules such as fullerenes and Berkeley Natl Lab — Over the past 11 years, a comprehensive program on the photoionization cross-section of fullerene and endohedral fullerene

1 The research is being funded by the US National Science Foundation.

8:30AM M4.00002 Multiscale dynamics in fullerenes, from attosecond to microsecond timescale. , FRANCK LEPINE, CNRS Lyon — Fullerenes are benchmark molecules for the study of ultrafast mechanisms as they provide a broad range of processes dealing with dynamics from attosecond to long (microsecond) timescale. Modern light sources (such as intracavity FEL or HHG sources) provide new means to observe processes on various timescales and for broad excitation range. In this presentation we will discuss results on XUV induced processes where variation of photoemission delay on attosecond timescale, non-adiabatic dynamics and correlation effects are playing a role. This offers the opportunity to understand photo-induced processes on a broad multiple timescale perspectives.

9:00AM M4.00003 Electron elastic scattering off endo-fullerenes1, VALERIY DOLMATOV, University of North Alabama — The given presentation highlights the physically transparent, relatively simple, and yet reasonably complete approximation to the problem of low-energy electron elastic scattering off endohedral fullerenes $A@C$ along with corresponding findings unraveled on its basis. It is believed that, as of today, the highlighted results provide the most complete information about features of $e+@C$ scattering brought about by the fullerene-cage-related, correlation-related, and polarization-related impacts of the individual, and coupled members of the $A@C_{60}$ target on the scattering process. Each of the impacts is shown to bring spectacular features into $e+@C_{60}$ scattering. A remarkable inherent quality of the developed approximation is its ability to account for mutual coupling between electronic excited configurations of $C$ with those of the encapsulated atom $A$ without reference to complicated details of the electron structure of $C$ itself. Spectacular effects in the scattering process, primarily associated with polarization of $A@C_{60}$ by an incident electron, are thoughtfully detailed both quantitatively and qualitatively in a physically transparent manner for ease of understanding and convenience of the audience.  

1 This study was performed in collaboration with Professors M. Ya. Amusia, L. V. Chernysheva, and UNA undergraduate students. The past support by the NSF grant PHY-1305085 is acknowledged.

9:30AM M4.00004 Photoionization of fullerene and endohedral fullerene ions at the Advanced Light Source, Lawrence Berkeley National Laboratory.1, DAVID KILCOYNE, Lawrence Berkeley Natl Lab — Over the past 11 years, a comprehensive program on the photoionization cross-section of fullerene and endohedral fullerene molecular ions has been conducted at the ALS using the merged-beams technique pioneered during the 1960’s in the UK. In contrast to targets using neutral atomic or molecular species, photoionization of ions presents unique challenges, especially large molecules such as fullerenes and in particular, rare encapsulated fullerene, i.e., endohedrals, where an atom or molecule is trapped within the fullerene cage. I will discuss the program which initially studied $C_{60}^+$ and follow with a near-complete investigation into the photoionization of $Xe@C_{60}^{2+}$ and $C_{60}^{2+}$ including some remarks on the current progress on exotic endohedrals such as $Sc_{2}N@C_{60}^{2+}$ and $Ce@C_{60}^{2+}$ and ending with preliminary results from the study of $Au@C_{60}^{2+}$. Atomic ion photoionization remains a principal objective of the program which motivated a recent NSF MRI proposal to replace the recently decommissioned ALS apparatus.

1 The Advanced Light Source is supported by the Director, Office of Science, Office of Basic Energy Sciences, of the US Department of Energy under Contract No. DE-AC02-05CH11231.

Thursday, June 8, 2017 8:00AM - 10:00AM – Session M5 Ultrafast Dynamics and New Short Pulse Light Sources 310 - Zenghu Chang, University of Central Florida
phase of the pulses in order to determine the most appropriate approach for pulse compression. Our results suggest that the multi-plate achieves a broad supercontinuum spectrum, as well as the energy throughput and stability of the system. We further characterize the spectral throughput of the pulses in order to determine the most appropriate approach for pulse compression. Our results suggest that the multi-plate continuum technique is a viable route to obtaining few cycle pulses at high average powers.

1Supported by the AFOSR under award number FA9550-16-1-0149.

8:12AM M5.00002 Characterizing attosecond x-ray pulses, STEFAN PABST, Harvard-Smithsonian CFA & Stanford University, MARCUS DAHLSTRM, Stockholm University — Attosecond x-ray pulses offer unprecedented opportunities for probing and triggering new types of ultrafast motion. At the same time, their characterization faces new challenges that do not exist in the UV regime. Inner-shell ionization is the dominant ionization mechanism in the x-ray regime and triggers secondary processes like fluorescence, Auger decay, and shake-up. We show that these secondary events create additional delay-dependent modulations. Our recently proposed wavepacket-based characterization scheme can eliminate the impact of these unwanted side effects and is a reliable method for reconstructing attosecond x-ray pulses.

S.P. is funded by the Alexander von Humboldt Foundation and by the NSF through a grant to ITAMP. J.M.D. is funded by the Swedish Research Council, Grant No. 2014-3724.

8:24AM M5.00003 A Statistical Model of Capillary-Based High-Harmonic Generation, PETER HORAK, ARTHUR DEGEN-KNIFTON, WILLIAM S. BROCKLESBY, Univ of Southampton — We present a novel, computationally fast method for estimation of high-harmonic spectra generated from ultrashort laser pulses propagating through gas-filled capillaries. In the regime of high pulse intensities, ionization-induced nonlinearities break up the pump pulse into a train of short sub-pulses. We show that a statistical analysis of the number, peak intensities, and temporal widths of these sub-pulses allows us to calculate approximate high-harmonic spectra via numerical simulations that run up to 100 times faster than full explicit simulations. While our current model does not include all aspects of high-harmonic phase matching and is therefore limited in predicting absolute output powers, we validate the model by comparison with full explicit simulations and with previous experimental results and find good qualitative agreement in features such as spectral broadening with pump pulse energy and gas pressure, photon flux versus capillary length, and spectral shaping by selectively exciting discrete harmonics.

1U.S. Army Research Office under grant number W911NF-14-1-0383

8:36AM M5.00004 Attosecond Molecular-Frame Angular Distribution of Electronic Coherence, SHUNGO MIYABE, RIKEN, R. LUCCHESI, Texas A&M University, C. W. MCCURDY, Lawrence Berkeley National Laboratory, University of California, Davis — Using ab initio electron-ion scattering calculations, it is demonstrated that for a molecule, oriented in space and excited by an attosecond pulse, the degree of electronic coherence left in the ion depends sensitively not only on the orientation of the electric field polarization vector in the molecular frame, but also on the details of the angular distribution in the molecular-frame of electrons ejected in different ionization channels. Accurate modeling of the degree of coherence induced by attosecond ionization in the molecular ion can require a coupled-channel electron-ion scattering wavefunction, which takes interactions of various ionization channels into account and also the inclusion of electron correlation in the wavefunctions of the ionic states, both of which make a notable difference the computed results presented here for the water and glycine molecules. Numerical simulations reported here are based on one-photon single ionization amplitudes calculated using the complex-Kohn variational method, and the amount of coherence in the ion is expressed in terms of the N-electron reduced density matrix of the full (N + 1)-electron system of the ion plus ionized electron.

1Supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, U.S. DOE

8:48AM M5.00005 Ultrafast Dynamics in Molecular Systems Studied Using Polarization Spectroscopy, NIRANJAN SHIVARAM, ELIO CHAMPENOIS, SAID BAKHTI, RICHARD THURSTON, PAVAN MUDDUKRISHNA, ALI BELKACEM, Chemical Sciences Division, Lawrence Berkeley National Laboratory — Studying ultrafast dynamics in complex polyatomic molecules using photo-electron and photo-ion spectroscopy can be very challenging due to the presence of many competing processes. Photon-in photon-out methods like the widely used transient absorption spectroscopy can be very helpful in isolating some of these processes. Here, we discuss a different approach to measure ultrafast dynamics in molecules using the technique of polarization spectroscopy which is a special case of four-wave mixing. Two pulses (drive and probe) with a relative polarization of 45 degrees interact via the third order nonlinear optical properties of species generated from ultrashort laser pulses propagating through gas-filled capillaries. We then discuss the extension of this method to study ultrafast excited state dynamics in molecules like O-nitrophenol using UV and two IR pulses. This method has the potential to be more sensitive than transient absorption by 2 to 3 orders of magnitude without the requirement of resonant transitions to probe the dynamics.

1Supported by Defense Threat Reduction Agency (Grant No. HDTRA1-12-1-0014) is gratefully acknowledged.

9:00AM M5.00006 Dynamic modification of optical nonlinearities related to femtosecond laser filamentation in gases, DMITRI ROMANOV (1.3), MARYAM TARAZKAR (2.3), ROBERT LEVIS (2.3), (1) Department of Physics, (2) Department of Chemistry, and (3) Center for Advanced Photonics Research, Temple University, Philadelphia, PA — During and immediately after the passing of a filamenting laser pulse through a gas-phase medium, the nonlinear optical characteristics of the emerging filament-wake channel undergo substantial transient modification, which stems from ionization and electronic excitation of constituent atoms/molecules. We calculate the related hyperpolarizability coefficients of individual ions, and we develop a theoretical model of filament channel evolution applicable to atmospheric-pressure and high-pressure gases. The evolution is mediated by energetic free-electron gas that results from the strong-field ionization and gains considerable energy via inverse Bremsstrahlung process. The ensuing impact ionization and excitation of the residual neutral atoms/molecules proceeds inhomogeneously both inside the channel and on its surface, being strongly influenced by the thermal conduction of the electron gas. The model shows critical importance of channel-surface effects, especially as regards the temperature evolution, which is ultimately dictated by the total absorbed energy in the filament channel. The transient modifications of linear and nonlinear optical properties of filament wake channels. Medium-specific estimates are made for atmospheric- and high-pressure Argon, as well as for molecular nitrogen gas.

1Support of Defense Threat Reduction Agency (Grant No. HDTRA1-12-1-0014) is gratefully acknowledged.
9:12AM M5.00007 Ultrafast double hydrogen migration in ethanol1 — NORA G. KLING, RAJIB OBAID, Univ of Connecticut - Storrs, SERGIO DIAZ-TENDERO, Universidad Autónoma de Madrid, HUI XIONG, MARGARET SUNDBERG, SOROU什 KHOSRAVI, MICHAEL DAVINO, ANN MARIE CARROLL, Univ of Connecticut - Storrs, TIMUR OSIPOV, SLAC National Accelerator Laboratory, FERNANDO MARTIN, Universidad Autónoma de Madrid, NORA BERRAH, Univ of Connecticut - Storrs — Hydrogen migration is ubiquitous in nature. Strong-field induced single hydrogen migration in small hydrocarbons has been studied with a variety of light sources, and, for acetylene and allene, has even been controlled via the carrier-envelope phase of a laser pulse. Previous strong field laser experiments have also shown that for more complex targets, such as ethanol, two hydrogen atoms can migrate, producing the H$_3$O$^+$ hydronium ion. Here we use 35 fs, 790 nm, mid-10$^{-14}$ W/cm$^2$ laser pulses, to induce double hydrogen migration in ethanol and record the resulting ionic fragments with a cold-target recoil ion momentum spectrometer (COLTRIMS) apparatus. Following Coulomb explosion, the molecules fragment into many channels, including the coincident H$_2$O$^+$ + C$_2$H$_4^+$ channel of interest. Theoretical support indicates that the first hydrogen comes from the terminal carbon, and the second comes from the adjacent carbon, occurring on a 10’s to 100’s of fs timescale.

1This work is supported by the Department of Energy, Office of Science, Basic Energy Sciences, Division of Chemical Sciences, Geosciences and Biosciences under grant No. DE-SC0012376.

9:24AM M5.00008 Mechanisms and time-resolved dynamics for trihydrogen cation (H$_3^+$) formation from organic molecules in strong laser fields — N. EKANAYAKE, M. NAIRAT, Department of Chemistry, Michigan State University, Michigan, USA, B. KADERIYA, P. FEIZOLLAH, B. JOCHIM, T. SEVERT, B. BERRY, KANAKA RAJU P., K. D. CARNES, S. PATHAK, D. ROLLES, A. RUĐENKO, I. BEN-ITZHAK, J. R. Macdonald Laboratory, Department of Physics, Kansas State University, Kansas, USA, J. E. JACKSON, B. G. LEVINe, M. DANTUS, Department of Chemistry, Michigan State University, Michigan, USA — Strong-field laser-matter interactions often lead to exotic chemical reactions. H$_3^+$ formation from organic molecules is one such case which requires multiple bonds to break and form. Here, we present the first experimental evidence for the existence of two different reaction mechanisms for H$_3^+$ formation from organic molecules irradiated by a strong-field laser. The assignment of the two different mechanisms was accomplished through the strong-field ionization of methanol isotopomers, ethylene glycol, and acetone. Our findings are supported by femtosecond time-resolved measurements, coincidence measurements, and ab initio calculations with the most plausible transition states involved in the two mechanisms. This exotic chemical reaction is important as it shows that a strong laser field can not only selectively break multiple bonds but also can lead to the formation of multiple new bonds within an extremely short timescale, on the order of 100 femtoseconds. This work is supported by the U.S. Department of Energy under Grants DOE SISGR (DE-SC0002325) and DE-FG02-86ER13491.

9:36AM M5.00009 Multimode Vibrational Wave Packet Dynamics of Strong-Field-Ionized Methyl Iodide Probed by Femtosecond XUV Absorption Spectroscopy — ZHI-HENG LOH, ZHENGRONG WEI, JIALIN LI, Nanyang Technological University — Studies of vibrational wave packets (VWPs) created on the neutral electronic ground-state by intense laser fields have identified $R$-selective depletion (RSD) as the dominant mechanism for their generation. Another mechanism that is proposed to give rise to VWPs, bond softening (BS), remains hitherto unobserved. Here, we employ femtosecond XUV absorption spectroscopy to investigate the VWP dynamics of CH$_2$I$_2$ induced by intense laser fields. Analysis of the first-moment time traces computed about the neutral depletion region reveals both the fundamental and the hot bands of the CI stretch mode. The initial oscillation phases of these vibrations distinguishes the contributions of RSD and BS to the generation of the VWP in the neutral species. The relative oscillation amplitudes that are associated with the two phases suggest that the CI VWP is generated predominantly by BS. In the case of the CH$_2$I$_2^+$ X $^2$E/sub)/I ion state, VWP motion along the CI stretch mode is dominant over the CH$_2$ umbrella mode. Moreover, the amplitudes of the VWPs are only 1 pm (CI distance) and 1$^0$ (HCl bond angle). The ability to resolve such VWP dynamics points to the exquisite sensitivity of femtosecond XUV absorption spectroscopy to structural changes.

1This work is supported by a NTU start-up grant, the A*Star SERC PSF (122-PSF-0011), the Ministry of Education AcRF (MOE2014-T2-2-052), and the award of a Nanyang Assistant Professorship to Z.-H.L.

9:48AM M5.00010 Strong-field fragmentation of diiodomethane studied with time-resolved three-body Coulomb explosion1 — BALRAM KADERIYA, Y. MALAKAR, KANAKA RAJU P., T. SEVERT, X. LI, W.L. PEARSON, F. ZIAEE, Kansas State University, K. JENSEN, Univ. of Nebraska, J. RAJPUR, I. BEN-ITZHAK, D. ROLLES, A. RUĐENKO, Kansas State University — Laser Coulomb explosion imaging (CEI) is an efficient tool for mapping time-dependent changes of molecular geometry in many light-induced bond breaking or rearrangement processes. Here, we apply the three-body CEI technique to map in space and time nuclear wave packets created in strong-field ionization and dissociation of diiodomethane molecules. Analyzing coincident three-particle momentum maps in the triple ionized final state, we disentangle different ionization and break-up pathways and trace the time evolution of both, bond lengths and angles for major reaction channels. By combining different representations of the three-body breakup (kinetic energy release vs. relative ion emission angle, Dalitz plots, Newton diagrams etc.), we identify contributions due to bound and dissociating parts of the nuclear wave packet in the singly charged ionic state, observe signatures of I$_2$/I$^+_2$ elimination and highlight the role of intermediate long-lived doubly charged states.

1Supported by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U. S. DOE. K. R. P. and W. L. P. supported by NSF Award No. IIA-143049, K.J. supported by the NSF-REU grant No. PHYS-1461251.
8:00AM M6.00001 Ultracold and ultrafast: Probing quantum gases with femtosecond laser pulses, PHILIPP WESSELS, BERNHARD RUFF, TOBIAS KROKER, The Hamburg Centre for Ultrafast Imaging, STEFEN PEHMÖLLER, Institut für Experimentalphysik, University of Hamburg, JULIETTE SIMONET, Center for Optical Quantum Technologies, MARKUS DRESCHER, Institut für Experimentalphysik, University of Hamburg, KLAUS SENGSTOCK, Center for Optical Quantum Technologies — Ultracold lasers open new pathways for probing and manipulating ultracold atomic systems in order to address fundamental questions in quantum physics. The short pulses act as a highly localized instantaneous trigger to drive complex dynamics and enable access to coherence properties in macroscopic quantum targets and superfluid matter. We report on first experiments exploring ultracold $^{87}$Rb atoms and Bose-Einstein condensates (BEC) exposed to ultrashort laser pulses of 280 fs duration. The intense light pulses create ions within the focal region via strong-field ionization and the remaining atoms are detected by absorption imaging. Additionally, we quantify the momentum transferred to the atoms by the femtosecond laser pulse. Since the amount of generated ions is tunable, a tool with the potential to create hybrid quantum systems of few ions immersed in the trapped cloud is provided. First results already indicate the formation of a long-lived ultracold plasma state. Analyzing the charged fragments after ionization promises further insight so that we discuss perspectives on detecting ions and electrons in a new experimental setup to investigate coherence transfer from a macroscopic wave function to its microscopic constituents.

8:12AM M6.00002 Ultracold Molecule Assembly with Photonic Crystals, JESUS PEREZ-RIOS, MAY KIM, CHEN-LUNG HUNG, Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA — We present a viable experimental scheme for ultracold molecule assembly in a tailored nanophotonic environment. In particular, a photonic crystal waveguide is specially designed to trap an array of cold atoms and induce strong radiative coupling between the photoassociated, molecular excited state with the desired metastable or ground molecular state, thereby greatly enhancing radiative decay probability into the selected ground molecular state after photoassociation. We propose to use a single-step photoassociation scheme to convert free atom pairs directly into the deeply-bound molecular ground state with near unity conversion efficiency and with high production rate. These ground state molecules will remain trapped along the nanophotonic structure, which can then serve as an efficient light-molecule interface, opening up the possibility to coherently control the internal states of trapped molecules and perform state-sensitive, non-destructive molecule detection for future quantum applications.

8:24AM M6.00003 Neutral Atom Imaging Using a Pulsed Electromagnetic Lens, ERIK ANCIAX, JAMIE GARDNER, YI XU, MARK RAIZEN, University of Texas-Austin — We present a novel technique for neutral atom imaging relying on a pulsed electromagnetic hexapole lens. Using a prototype lens with a supersonic beam of metastable neon, we have successfully imaged complex patterns with lower distortion and higher resolution than has been shown in any previous atom imaging experiment. Simulations relying on a pulsed electromagnetic hexapole lens. Using a prototype lens with a supersonic beam of metastable neon, we have successfully imaged complex patterns with lower distortion and higher resolution than has been shown in any previous atom imaging experiment. Simulations suggest that with improvements in aberration correction our imaging scheme will be able to achieve nanoscale resolution, allowing for surface sensitive nanoscale atom microscopy and nanofabrication.

8:36AM M6.00004 A monolithic glass bowtie cavity trap for ultracold atoms, KEVIN WRIGHT, JESSE EVANS, YANPING CAI, DANIEL ALLMAN, Dartmouth — We have built a monolithic, symmetric bowtie cavity that is optimized for use as an in-vacuum crossed-beam dipole trap for ultracold atoms. The all-glass bonded construction has good passive stability, and is compatible with experiments involving laser冷却 cells, or rapidly changing magnetic fields. The hydrodynamically-guided technique used to assemble the cavity results in bond strengths and vacuum compatibility similar to optical contacting, but with somewhat relaxed tolerances on surface quality and preparation. Furthermore, hydrodynamically bonded has a long curing time that allows precise optimization of optical alignment during bonding of complex assemblies. We will report on our application of this technique to optical cavity construction, our progress toward trapping and cooling lithium atoms in a ring bowtie cavity, and discuss prospects for coupling the cavity modes to the motion of atoms trapped in the beam intersection region.

8:48AM M6.00005 Cold Atom Laboratory: exploring ultracold gas mixtures aboard the International Space Station, DAVID AVELINE, ETHAN ELLIOTT, JASON WILLIAMS, ROBERT THOMPSON, Jet Propulsion Laboratory — We report on the current status of the Cold Atom Laboratory (CAL) mission to be operated aboard the International Space Station (ISS), with emphasis on results achieved in the CAL ground test bed (GTB) facility. Utilizing, a compact atom chip trap loaded from a dual-species magneto optical trap of rubidium and potassium, CAL is a multi-user facility developed by NASA’s Jet Propulsion Laboratory (JPL) to provide the first persistent quantum gas platform in the microgravity environment of space. In the unique environment of microgravity, the confining potentials necessary to the process of cooling atoms can be arbitrarily weakened, creating gases at picoKelvin temperatures and ultra-low densities, while the complete removal of the confining potential allows for ultracold clouds that can float virtually fixed relative to the CAL apparatus. The new parameter space of cold atom research by a globe spanning group of researchers with broad applications in fundamental physics and inertial sensing. In this paper, we describe validation and development of critical technologies in the CAL GTB, including the demonstration of the first microwave evaporation and generation of dual-species quantum gas mixtures on an atom chip.

9:00AM M6.00006 High-purity, robust alkali vapor sources without vacuum feedthroughs, RUDOLPH KOHN, Space Dynamics Laboratory, MATTHEW BIGELOW, Applied Technology Associates, ERIC IMHOF, Space Dynamics Laboratory, MATTHEW SQUIRES, SPENCER OLSON, BRIAN KASCH, DAVID HOSTUTLER, Air Force Research Laboratory — The authors report the successful implementation of a method for producing rubidium vapor at sufficient purity and with sufficient quantity to load cold atom experiments. This method requires no vacuum feedthroughs and has measurable advantages in several parameters over comparable sources. Using a high-capacity vapor source, the purity of the vapor is measured to be 99.99% when exposed to air, allowing for easy handling. Currently, this method is being integrated into the authors systems and its use in loading a basic 3D vapor cell magneto-optical trap (MOT) has been demonstrated, in addition to loading a 2D+ MOT which has been subsequently used to load a 3D MOT.

9:12AM M6.00007 A high-power fiber-coupled semiconductor light source with low spatio-temporal coherence, ROBERT SCHITTOKO, ANTON MAZURENKO, M. ERIC TAI, ALEXANDER LUKIN, MATTHEW RISPOLI, TIM MENKE, ADAM M. KAUFMAN, MARKUS GREINER, Harvard University — Interference-induced distortions pose a significant challenge to a variety of experimental techniques, ranging from full-field imaging applications in biological research to the creation of potentials in quantum gas microscopy. Here, we present a design of a high-power, fiber-coupled semiconductor light source with low spatio-temporal coherence that bears the potential to reduce the impact of such distortions. The device is based on an array of non-lasing semiconductor emitters mounted on a single chip whose optical output is coupled into a multi-mode fiber. By populating a large number of fiber modes, the low spatial coherence of the input light is further reduced due to the differing optical path lengths amongst the modes. We present experimental measurements verifying the low degree of spatial coherence achievable with such a source, including a detailed analysis of the speckle contrast at the fiber end.

1 We acknowledge support from the National Science Foundation, the Gordon and Betty Moore Foundations EPiQS Initiative, an Air Force Office of Scientific Research MURI program and an Army Research Office MURI program.
A precision measurement of the electrons electric dipole moment using trapped molecular ions, WILLIAM B. CAIRNCROSS, DANIEL N. GRESH, MATT GRAU, KEVIN C. COSSEL, YIOI NI, TÂNYA ROUSSY, YUVAL SHAGAM, JUN YE, ERIC A. CORNELL, JILA, NIST and University of Colorado — A search for a permanent electric dipole moment of the electron (eEDM) constitutes an essentially background-free test for physics beyond the Standard Model. While some extensions to the Standard Model suggest an eEDM at presently achievable levels of sensitivity, none has yet been detected \[1\]. Independent measurements using different experimental techniques provide essential confirmation of this result and potential for sensitivity improvements. We will report on the first precision measurement of the eEDM using trapped molecular ions, demonstrating a uniquely long coherence time that provides excellent rejection of systematic errors and high eEDM sensitivity.

1 Gratefully acknowledge support from AFRL

9:48AM M6.00010 Dynamical manifestations of quantum chaos1, EDUARDO JONATHAN TORRES HERRERA, Instituto de Física, Benemérita Universidad Autónoma de Puebla, LEA SANTOS, Department of Physics, Yeshiva University — A main feature of a chaotic quantum system is a rigid spectrum, where the levels do not cross. Dynamical quantities, such as the von Neumann entanglement entropy, Shannon information entropy, and out-of-time correlators can differentiate the ergodic from the nonergodic phase in disordered interacting systems, but not level repulsion from level crossing in the delocalized phase of disordered and clean models. This is in contrast with the long-time evolution of the survival probability of the initial state. The onset of correlated energy levels is manifested by a drop, referred to as correlation hole, below the asymptotic value of the survival probability. The correlation hole is an unambiguous indicator of the presence of level repulsion.

Thursday, June 8, 2017 8:00AM - 10:00AM — Session M7 Precise Tests of Fundamental Symmetries 313 - Eric Norrgard, Yale University

8:00AM M7.00001 A precision measurement of the electrons electric dipole moment using trapped molecular ions, WILLIAM B. CAIRNCROSS, DANIEL N. GRESH, MATT GRAU, KEVIN C. COSSEL, YIOI NI, TÂNYA ROUSSY, YUVAL SHAGAM, JUN YE, ERIC A. CORNELL, JILA, NIST and University of Colorado — A search for a permanent electric dipole moment of the electron (eEDM) constitutes an essentially background-free test for physics beyond the Standard Model. While some extensions to the Standard Model suggest an eEDM at presently achievable levels of sensitivity, none has yet been detected \[1\]. Independent measurements using different experimental techniques provide essential confirmation of this result and potential for sensitivity improvements. We will report on the first precision measurement of the eEDM using trapped molecular ions, demonstrating a uniquely long coherence time that provides excellent rejection of systematic errors and high eEDM sensitivity.

1 Gratefully acknowledge support from AFRL

8:48AM M6.00010 Dynamical manifestations of quantum chaos1, EDUARDO JONATHAN TORRES HERRERA, Instituto de Física, Benemérita Universidad Autónoma de Puebla, LEA SANTOS, Department of Physics, Yeshiva University — A main feature of a chaotic quantum system is a rigid spectrum, where the levels do not cross. Dynamical quantities, such as the von Neumann entanglement entropy, Shannon information entropy, and out-of-time correlators can differentiate the ergodic from the nonergodic phase in disordered interacting systems, but not level repulsion from level crossing in the delocalized phase of disordered and clean models. This is in contrast with the long-time evolution of the survival probability of the initial state. The onset of correlated energy levels is manifested by a drop, referred to as correlation hole, below the asymptotic value of the survival probability. The correlation hole is an unambiguous indicator of the presence of level repulsion.

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8:48AM M6.00010 Dynamical manifestations of quantum chaos1, EDUARDO JONATHAN TORRES HERRERA, Instituto de Física, Benemérita Universidad Autónoma de Puebla, LEA SANTOS, Department of Physics, Yeshiva University — A main feature of a chaotic quantum system is a rigid spectrum, where the levels do not cross. Dynamical quantities, such as the von Neumann entanglement entropy, Shannon information entropy, and out-of-time correlators can differentiate the ergodic from the nonergodic phase in disordered interacting systems, but not level repulsion from level crossing in the delocalized phase of disordered and clean models. This is in contrast with the long-time evolution of the survival probability of the initial state. The onset of correlated energy levels is manifested by a drop, referred to as correlation hole, below the asymptotic value of the survival probability. The correlation hole is an unambiguous indicator of the presence of level repulsion.

1 Gratefully acknowledge support from AFRL
8:48AM M7.00005 The Electric Dipole Moment of Radium. MATTHEW DIETRICH, MICHAEL BISHOF, KEVIN BAILEY, JOHN GREENE, ROY HOLT, Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA, WOLFGANG KORSCH, Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506, USA, ZHENG-TIAN LU, Physics Department, University of Science and Technology of China, Hefei, China, PETER MUELLER, THOMAS O’CONNOR, Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA, TENGZI RABGA, ROY READY, JAIDEEP SINGH, National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA — Due to its large nuclear octupole deformation and high atomic mass, the radioactive Ra-225 isotope is a favorable case for an electric dipole moment (EDM); it is particularly sensitive to CP-violating interactions in the nuclear medium. We have developed a cold-atom approach of measuring the atomic EDM of Ra-225 atoms held stationary in an optical dipole trap. We previously demonstrated this technique with an initial experimental upper limit of |(d(225Ra))|< -5.2 e-23 e-cm, and have since improved this limit 36-fold to 1.4e-23 e-cm. This is not only the first time laser-cooled atoms have been used to measure an EDM, but also the first time the EDM of any octupole deformed species has been measured. Upcoming improvements are expected to dramatically improve our sensitivity, and significantly improve on the search for new physics in several sectors. This work is supported by U.S. DOE, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.


9:12AM M7.00007 Prospects for testing CPT and Lorentz symmetry with electronic transitions, ARNALDO VARGAS, V. ALAN KOSTELECKY, Indiana Univ - Bloomington — Empirical evidence for minuscule deviations from the principle of relativity could help physicists develop a theory that accurately describes gravity at the quantum scale. Measurements of electronic transitions are among the most precise and accurate measurements in science, and they offer a sensible approach to the search for Lorentz and CPT violation. Using the Standard-Model Extension, phenomenological models for Lorentz violation in commonly measured atomic transitions are obtained. This includes models for experiments with ordinary matter, muonic atoms, and antimatter. Clock-comparison experiments are also considered, including experiments with microwave and optical atomic clocks. In all cases, potential signals for Lorentz and CPT violation are singled out and estimates of the sensitivity of the experiments are discussed.

9:24AM M7.00008 Testing Lorentz and CPT invariances in quantum electrodynamics with Penning traps, YUNHUA DING, V. ALAN KOSTELECKY, Indiana University Bloomington — The Lorentz and CPT invariances of relativity are fundamental in physics. However, tiny violations of these invariances could emerge in an underlying unified theory such as strings. This talk explores Lorentz- and CPT-violating quantum electrodynamics, presenting the general Lagrange density for Lorentz violation with operators of mass dimension up to six and analyzing results from precision experiments on particles and antiparticles confined to a Penning trap. Observable signals are discussed, and new bounds for Lorentz-violating coefficients are extracted.

9:36AM M7.00009 The ALPHATRAP g-Factor Experiment, IOANNA ARAPOGLOU, ALEXANDER EGL, MARTIN HOCKER, SANDRO KRAEMER, TIM SAILE, ANDREAS WEGEL, J. R. CRESPO LOPEZ-URRUTIA, ROBERT WOLF, SVEN STURM, KLAUS BLAUM, Max Planck Institute for Nuclear Physics, Heidelberg, Germany — ALPHATRAP is a high-precision Penning-trap experiment that aims for the most stringent test of bound-state quantum electrodynamics (BS-QED) in the strong field regime. These fields are provided by heavy highly-charged ions (HCl), such as hydrogen-like 208Pb161+, where the electron is exposed to the strong binding potential of the nucleus. The storage and manipulation of the ions is achieved using a double Penning-trap system in which the electron’s g-factor is deduced from measuring its magnetic moment. The setup includes several ion creation possibilities for offline ion production, additional to the online injection of heavy HCl from the Heidelberg Electron Beam Ion Trap. This will deliver the heavy HCl via an ion beam-line, to the cryogenic double Penning-trap system. The latter consists of the so called Precision Trap for high-precision measurements of the ion cyclotron frequency in a homogeneous magnetic field, and the Analysis Trap for spin state detection of the bound electron in a magnetic bottle configuration. This experimental setup not only enables high-precision tests of BS-QED, but also allows the determination of fundamental constants, such as the fine structure constant α and the atomic mass of the electron me, to competitive precision.

9:48AM M7.00010 High-precision calculation of La− atomic properties for anion laser cooling, MARIANNA SAFRONOVA, University of Delaware, ULYANA SAFRONOVA, University of Nevada, Reno, SERGEY PORSEV, University of Delaware — Anion laser cooling holds the potential to allow the production of ultracold ensembles of any negatively charged species. The negative ion of lanthanum, La−, was proposed as the best candidate for laser cooling of any atomic anion [1]. A very exciting application of La− laser cooling includes cooling of antiprotons for antihydrogen formation and subsequent tests of CPT invariance and weak equivalence principle [2]. A calculation of anion properties is a very difficult task, with complicated electronic structure of lanthanides presenting additional major problems. In this work, we present novel theoretical treatment of La−. Affinity, energy levels, E1 matrix elements, transition rates, branching ratios, lifetimes, and hyperfine constants are calculated using high-precision CI+All-order method. Calculated theoretical transition energies are in agreement with measured values and show improved theoretical accuracy for negative ions. Recommended values of transition rates and branching ratios of importance to the realization of laser cooling of La− are presented and critically evaluated for their accuracy. [1] S. M. O’Malley and D. R. Beck, PRA 81, 032503 (2010). [2] A. Kellerbauer and J. Walz, N. J. Phys. 8, 45 (2006).
8:00AM M8.00001 High-fidelity operations in microfabricated surface ion traps¹. PETER MAUNZ, Sandia National Laboratories — Trapped ion systems can be used to implement quantum computation as well as quantum simulation. To scale these systems to the number of qubits required to solve interesting problems in quantum chemistry or solid state physics, the use of large multi-zone ion traps has been proposed [1]. Microfabrication enables the realization of surface electrode ion traps with complex electrode structures. While these traps may enable the scaling of trapped ion quantum information processing (QIP), microfabricated ion traps also pose several technical challenges. Here, we present Sandia’s trap fabrication capabilities and characterize trap properties and shuttling operations in our most recent high optical access trap (HOA-2). To demonstrate the viability of Sandia’s microfabricated ion traps for QIP we realize robust single and two-qubit gates and characterize them using gate set tomography (GST). In this way we are able to demonstrate the first single qubit gates [2] with a diamond norm of less than $1.7 \times 10^{-4}$, below a rigorous fault tolerance threshold for general noise of $6.7 \times 10^{-4}$ [3]. Furthermore, we realize Mølmer-Sørensen two-qubit gates with a process fidelity of 99.58(6)%, also characterized by GST. These results demonstrate the viability of microfabricated surface traps for state of the art quantum information processing demonstrations. [1] D. Kielpinski, C. Monroe, and D. J. Wineland, Nature 417, 709 (2002). [2] R. Blume-Kohout et al. arXiv:1606.07674. [3] P. Aliferis and J. Preskill, Phys. Rev. A 79, 012332 (2009).

1This research was funded, in part, by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA).

8:30AM M8.00002 Quantum computing with atoms in a 3D optical lattice: addressing and sorting atoms. DAVID WEISS, Penn State — Trapping long-lived neutral atom qubits in a 3D optical lattice will ultimately allow their entanglement with many near neighbors. To date, we have prepared 50 single atoms near the ground states of their lattice sites, and have demonstrated high fidelity single qubit addressing at each site, with minimal crosstalk despite the challenges of the 3D geometry [Y. Wang, A. Kumar, T.-Y. Wu & D.S. Weiss, Science 352, 1562-1565 (2016)]. I will describe this work, and explain how we are going about sorting the atoms in 3D to generate arbitrary occupancy patterns, the next step before entangling nearby pairs of atoms.

9:00AM M8.00003 Practical applications of compressed sensing in quantum state tomography. CARLOS RIOFRIO, Freie Universitt Berlin — As quantum systems get closer to technological applications, the problem of identifying, certifying, and characterizing them becomes more daunting. In fact, a complete characterization of a quantum system requires determining a number of parameters that grow exponentially with the system size. New paradigms that allow for efficient signal processing must be developed and tested to overcome this roadblock. In this talk, we present an overview of the most recent developments in quantum state tomography via compressed sensing. We show a complete analysis based on experimental data from two different systems: First, a photonic circuit that prepares highly entangled photons corresponding to 4-qubit states, which we use as a testbed to showcase our tomographic procedure in a variety of scenarios; Second, a 7-qubit system of trapped ions which encodes a single logical qubit via a color code, in which highly incomplete data is observed. We show how compressed sensing and model selection ideas can be combined in practice.

9:30AM M8.00004 Arbitrary Dicke-State Control of Symmetric Rydberg Ensembles. IVAN DEUTSCH, University of New Mexico — We study the production of arbitrary superpositions of Dicke states via optimal control. We show that N atomic hyperfine qubits, interacting symmetrically via the Rydberg blockade, are well described by the Jaynes-Cummings Model (JCM), familiar in cavity QED. In this isomorphism, the presence or absence of a collective Rydberg excitation plays the role of the two-level system and the number of symmetric excitations of the hyperfine qubits plays the role of the bosonic excitations of the JCM. This system is fully controllable through the addition of phase-modulated microwaves that drive transitions between the Rydberg-dressed states. In the weak dressing regime, this results in a single-axis twisting Hamiltonian, plus time-dependent rotations of the collective spin. For strong dressing we control the entire Jaynes-Cummings ladder. Using optimal control, we design microwave waveforms that can generate arbitrary states in the symmetric subspace. This includes cat states, Dicke states, and spin squeezed states. With currently feasible parameters, it is possible to generate arbitrary symmetric states of $10^{-4}$ hyperfine qubits in 1 microsec, assuming a fast microwave phase switching time. The same control can be achieved with a “dressed-ground control” scheme, which reduces the demands for fast phase switching at the expense of increased total control time. More generally, we can achieve control on larger ensembles of qubits by designing waveforms that are bandwidth limited within the coherence time of the system. We use this to study general questions of the “quantum speed limit” and information content in a waveform that is needed to generate arbitrary quantum states.

Thursday, June 8, 2017 8:00AM - 10:00AM – Session M9 Quantum Gases in Low Dimensions 315 - Joseph Thywissen, University of Toronto

8:00AM M9.00001 FFLO superfluidity in a spin imbalanced Fermi gas¹. ANNA L. MARCHANT, JACOB A. FRY, YI JIN, MELISSA C. REVELLE, RANDALL G. HULET, Department of Physics and Astronomy and Rice Quantum Institute, Rice University, Houston, TX 77005 — Ultracold atomic gases confined in optical lattices have proven to be highly versatile, tunable systems, capable of emulating condensed matter systems. Using the lowest two hyperfine states of $^6$Li to create a pseudo-spin-1/2 system we can engineer a spin imbalance in the gas, analogous to applying a magnetic field to a superconductor. Using a 2D optical lattice to create an array of 1D tubes the tunneling between tubes can be precisely controlled whilst a Feshbach resonance is used to tune the atomic interactions. Previously we identified a universal crossover regime from 1D- to 3D-like behavior in the phase separation of this spin-imbalanced Fermi gas when varying the lattice tunneling. This crossover region is expected to be a promising regime in which to observe the elusive polarized superfluid FFLO where magnetism is accommodated by the formation of pairs with finite momentum. Here we present our progress towards the observation of this exotic superfluid state. By compensating the optical potential along the weak axial direction of the lattice we can carry out 1D time-of-flight expansion to study the momentum-independent behavior of the gas and thus search for experimental signatures of the FFLO phase.

1Supported by the NSF, ONR, ARO MURI and the Welch Foundation
8:12AM M9.00002 Dynamics of small trapped one-dimensional Fermi gas under oscillating magnetic fields

X. Y. YIN, The Ohio State University, YANGQIAN YAN, Indiana University Purdue University Indianapolis, D. HUDSON SMITH, The Ohio State University — Deterministic preparation of an ultracold harmonically trapped one-dimensional Fermi gas consisting of a few fermions has been realized by the Heidelberg group. Using Floquet formalism, we study the time dynamics of two- and three-fermion systems in a harmonic trap under an oscillating magnetic field. The oscillating magnetic field produces a time-dependent interaction strength through a Feshbach resonance. We explore the dependence of these dynamics on the frequency of the oscillating magnetic field and three-fermion systems in a harmonic trap under an oscillating magnetic field. The oscillating magnetic field produces a time-dependent interaction strength through a Feshbach resonance. We explore the dependence of these dynamics on the frequency of the oscillating magnetic field and three-fermion systems in a harmonic trap under an oscillating magnetic field. The oscillating magnetic field produces a time-dependent interaction strength through a Feshbach resonance. We explore the dependence of these dynamics on the frequency of the oscillating magnetic field.

We find an unbounded coupling to all excited states at the infinitely strong interaction strength through a Feshbach resonance. We explore the dependence of these dynamics on the frequency of the oscillating magnetic field and three-fermion systems in a harmonic trap under an oscillating magnetic field. The oscillating magnetic field produces a time-dependent interaction strength through a Feshbach resonance. We explore the dependence of these dynamics on the frequency of the oscillating magnetic field and three-fermion systems in a harmonic trap under an oscillating magnetic field. The oscillating magnetic field produces a time-dependent interaction strength through a Feshbach resonance. We explore the dependence of these dynamics on the frequency of the oscillating magnetic field.

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Here, we present our realization of an ultracold 2D Fermi gas trapped in a homogeneous disk-shaped potential. The radial confinement is realized by a ring-shaped blue-detuned beam with steep walls. Additionally, a digital micro mirror device can be used to remove residual inhomogeneities and to imprint arbitrary repulsive potentials onto the system.

8:36AM M9.00004 The normal state of a strongly interacting two-dimensional Fermi gas

PUNEET A MURTHY, Heidelberg University, IGOR BOETTCHER, Simon Fraser University, RALF KLEMT, MARVIN HOLTEN, GERHARD ZURN, TILMAN ENNS, MATHIAS NEIDIG, PHILIPP PREISS, SELIM JOCHIM, Heidelberg University — We explore the normal phase of a strongly interacting two-dimensional Fermi gas in the BEC-BCS crossover. We use spatially resolved RF spectroscopy to measure the homogeneous response of the system for a wide range of temperatures and interaction strengths. We observe the formation of two-body dimers at high temperatures. At lower temperatures close to the superfluid critical temperatures, we find that the RF spectra show large density-dependent deviations from the dimer binding energy. Whereas pairing on the BEC side can explained by two-body physics, we observe that the pair formation in the strongly interacting crossover regime is a many-body phenomena. Surprisingly, our analysis of the density-dependent shifts suggests that the physics across the entire crossover can be captured in a mean-field picture.


Paul Dyke, Tyson Peppler, Marta Zamorano, Sascha Hoinka, Chris Vale, Swinburne University of Technology — Ultracold gases have become an important paradigm for studying many-body quantum phenomena. One example is a two-component 2D Fermi gas with tunable interactions that allows the study of the BCS to BEC superfluid crossover. We produce a 2D Fermi gas in a highly oblate trapping potential between the anodes of a cylindrically focused, blue detuned, TEM01 mode laser beam. A weak magnetic field curvature provides a highly harmonic confinement in the two radial directions. We investigate the collective oscillations, in particular the breathing mode frequency, of a 2D Fermi gas of Li-6 atoms throughout the 2D to 3D crossover. The breathing mode frequency provides insight into the thermodynamic equation of state which displays different limiting behaviors in 2D and 3D. We observe in the 3D regime a breathing mode frequency approaching \( \sqrt{2}\omega_r \), where \( \omega_r \) is the radial trap frequency. In the weakly and non-interacting 2D regime we see that the breathing frequency approaches \( 2\omega_r \), consistent with the prediction of a classical scale invariance. However, for stronger interactions our results display an increase in the breathing mode frequency above \( 2\omega_r \), by around 4%, indicating that this classical scale invariance is broken by a quantum anomaly.

9:00AM M9.00006 Exact nonequilibrium dynamics of finite-temperature Tonks-Girardeau gases in arbitrary trapping potentials.

Yasar Atas, University of Queensland, Dimitri Gargard, University of Birmingham, Isabelle Bouchoule, Institut d’Optique, Karen Kheruntsyan, University of Queensland — We develop an exact approach for calculating the out-of-equilibrium dynamics of finite-temperature Tonks-Girardeau gases in arbitrary trapping potentials. Using the Fredholm determinant approach and the Bose-Fermi mapping we show how the problem can be reduced to a single-particle basis, wherein the finite-temperature effects enter the solution via an effective “dressing” of the single-particle wavefunctions by the Fermi-Dirac occupation factors. We demonstrate the utility and computational efficiency of the approach in two nontrivial out-of-equilibrium scenarios: collective breathing-mode oscillations in a harmonic trap and collisional dynamics in the Newton’s cradle setting involving real-time evolution in a periodic Bragg potential.

9:12AM M9.00007 Quantum effects in cold-atom breathers

Vladimir Yurovsky, Tel Aviv Univ., Maxim Olshanii, UMass Boston, Boris Melamed, Tel Aviv Univ. — The one-dimensional (1D) Gross-Pitaevskii equation (GPE) has exact oscillatory solutions — breathers — predicted by the inverse scattering transform. In the mean-field approximation, they are formed from bright solitons by four-fold quench of the attractive interaction strength. Here, we address quantum counterparts of the breather states, applying the same quench to the Lieb-Liniger-McGuire model (the quantum version of the 1D GPE). Using exact Bethe-ansatz solutions for up to \( N = 20 \) atoms, we find that the quench leads to formation of all multi-soliton (multi-string) states, possible for \( N = 20 \), while two-soliton pairs dominate. The calculated fidelity exhibits a damped oscillatory dynamics. One of the decay mechanisms — dephasing due to non-equidistant energy spectrum of the two-soliton states — is expected to be suppressed at large \( N \). In addition, the dephasing due to the solitons’ kinetic energy spread leads to decay of the fidelity oscillation amplitude by half in the course of \( \sim 2.5 \) classical soliton periods for \( 4 \leq N \leq 20 \). The results suggest a possibility of observation of macroscopic quantum effects.

This research was supported by NSF and BSF.
9:24AM M9.00008 Observing Spin-Charge Separation in a 1D Fermi Gas1. ANDREW MARCUM, ARIF MAWARDI ISMAIL, FRANCISCO FontA, KENNETH O’HARA, The Pennsylvania State University — The low energy excitations of an interacting Fermi gas in one dimension are collective sound-like modes which independently govern spin transport and density transport in such systems. In general, these spin- and density-waves travel with different interaction-dependent sound velocities. In electronic systems, this phenomenon – referred to as spin-charge separation as density transport implies charge transport – has been observed indirectly in tunneling experiments. Here, we aim to directly observe spin-“charge” (i.e. density) separation in an ultracold two-component Fermi gas of atoms. Absorption imaging allows for the direct observation in real space of the dynamics of spin-density and “charge”-density waves excited in an ultracold gas of spin-1/2 fermions confined in an array of 1D optical waveguides (formed by a 2D optical lattice). To excite spin waves in a two-component mixture of $^6$Li atoms with minimal heating we employ a two-photon Raman transition acting only on one of the internal states to either (1) excite a spin-dipole mode or (2) locally eject one spin state from the trap. In the first approach, spin-charge separation manifests as a strong dependence of the spin-dipole mode frequency on interaction strength in contrast to a weak dependence for the density-dipole and density-quadrupole mode frequencies. In the second approach, spin-density and “charge”-density wavepackets are excited directly and propagate at different velocities in the interacting system.

1Supported by AFOSR and NSF

9:36AM M9.00009 Characterizing spin-charge separation in ultracold atoms confined to 1D1. TSUNG-LIN YANG, YA-TING CHANG, ZHENHAI O ZHAO, Department of Physics and Astronomy, Rice University, Houston TX, CHUNG-YOU SHIH, None, RANDALL HULET, Department of Physics and Astronomy, Rice University, Houston TX — One dimensional systems of fermions are predicted by Luttinger liquid theory to have different dispersion relations for spin and charge excitations. In the past, evidence of spin-charge separation has been seen in quantum wire tunneling experiments. However, independent measurements for spin and charge dispersion were not realized. Ultracold atoms, however, provide a highly tunable system to directly observe this phenomenon using Bragg spectroscopy. We realized such a system with fermionic $^6$Li in a 2-D optical lattice. By measuring the momentum transfer from a Raman transition while varying the relative detuning of the two-photon transition, we can measure the dispersion relation $\omega(k)$. The two ”spin” states are different hyperfine levels of the atom, and by appropriate choice of detuning, it may be possible to independently measure the spin and charge excitations. Using the tunability of interactions via a Feshbach resonance, we have measured the Bragg spectrum for the charge mode for a range of interaction strengths from the non-interacting Fermi gas to a strongly interacting one.

1Work supported by an ARO MURI grant, our NSF, and the Welch Foundation.

9:48AM M9.00010 One-Body Density Matrix and Momentum Distribution of Strongly Interacting One-Dimensional Spinor Quantum Gases LI YANG, HAN PU, rice university — The one-body density matrix (OBDM) of a strongly interacting spinor quantum gas in one dimension can be written as a summation of products of spatial and spin parts. We find that there is a remarkable connection between the spatial part and the OBDM of a spinless system — The one-body density matrix (OBDM) of a strongly interacting spinor quantum gas in one dimension can be written as a summation of products of spatial and spin parts. We find that there is a remarkable connection between the spatial part and the OBDM of a spinless system.

Thursday, June 8, 2017 10:30AM - 12:30PM – Session N2 Focus Session: Many-body localization 306-307 - Benjamin Lev, Stanford University

10:30AM N2.00001 Quantum Stat Mech in a Programmable Spin Chain of Trapped Ions1. CHRISTOPHER MONROE, JQI and University of Maryland — Trapped atomic ions are a versatile and very clean platform for the quantum programming of interacting spin models and the study of quantum nonequilibrium phenomena. When spin-dependent optical dipole forces are applied to a collection of trapped ions, an effective long-range quantum magnetic interaction arises, with reconfigurable and tunable graphs. Following earlier work on many-body spectroscopy and quench dynamics, we have recently studied many body non-thermalization processes in this system. Frustrated Hamiltonian dynamics can lead to prethermalization and by adding programmable disorder between the sites, we have observed the phenomenon of many body localization (MBL). Finally, by applying a periodically driven Floquet Hamiltonian tempered by MBL, we report the observation of a discrete “time crystal in the stable appearance of a subharmonic response of the system to the periodic drive.”

1This work is supported by the ARO Atomic Physics Program, the AFOSR MURI on Quantum Measurement and Verification, the IARPA LogiQ Program, and the NSF Physics Frontier Center at JQI.

11:00AM N2.00002 Exploring many-body localization in two dimensions. CHRISTIAN GROSS, Max Planck Institute of Quantum Optics — The question of thermalization in closed quantum systems is currently a topic of intense research and ultracold atoms are an ideal experimental system for its study. In this context it is particularly interesting to study systems that do not thermalize. Many-body localized systems form a generic class of such systems, which is largely unexplored in higher dimensions and at high energy densities. Here we report on experiments with single site resolved ultracold lattice bosons in two dimensions subject to random disorder. Our data indicates a transition from thermalizing behavior at low disorder to localization at higher disorder and a diverging length scale at the transition. We also discuss recent experimental progress on the local characterization of disordered lattice bosons at low energy density.
Many-body localized states appear at odds with thermalization as they preserve the memory of their initial state. This behavior has drawn significant theoretical and experimental attention in recent years. Real space localization has been observed on various platforms and under a number of experimental conditions, both with and without interactions. However, the characteristic logarithmic growth of entanglement entropy, which distinguishes the many-body localized state from the non-interacting Anderson localized state, has only been studied in numerics and has yet to be investigated experimentally. We are working towards the phenomenon of localization in one dimensional, interacting Bose-Hubbard systems using a quantum gas microscope. With site-resolved addressing and readout, our microscope provides full control over the studied system, in particular it allows us to add disorder into our system using a Fourier plane hologram. This gives us access to both local observables, such as the occupation of individual lattice sites, as well as the entanglement entropy. I will present our progress towards measuring the dependence of the entanglement entropy grows on the disorder strength and interactions in our system.

1 National Science Foundation, Gordon and Betty Moore Foundations EPIQS Initiative, Air Force Office of Scientific Research MURI program, NSF Graduate Research Fellowship Program (MNR)

We acknowledge funding from the National Science Foundation and US Army Research Office.

1 We acknowledge support from JILA-NSFPFC-1125844, ARO, MURI-AFOSR and AFOSR.

We acknowledge support from JILA-NSFPFC-1125844, ARO, MURI-AFOSR and AFOSR.

We study the possible breakdown of quantum thermalization in a model of itinerant electrons on a one-dimensional chain without disorder, allowed to thermalize. We use a multivariate statistical analysis applied to images to detect deviations from thermal equilibrium. We will discuss the timescale for equilibration in the superfluid, Mott insulator, and many-body localized regimes.

We acknowledge funding from the National Science Foundation and US Army Research Office

Session N3 Precision Sensing 308 - David Phillips, Harvard-Smithsonian Center for Astrophysics
10:30AM N3.00001 Challenging the Standard Model by High-Precision Comparisons of the Fundamental Properties of the Antiproton and the Proton. STEFAN ULMER1, RIKEN, 2-1 Hirosawa, Wako, Saitama, Japan — The Standard Model (SM) is the theory that describes Nature’s particles and fundamental interactions, although without gravitation. However, this model is known to be incomplete which inspires various searches for new physics. Among them are tests of charge, parity, time (CPT) invariance that compare the fundamental properties of matter/antimatter conjugates at lowest energy and with greatest precision. The BASE collaboration [1] at the antiproton decelerator of CERN targets high-precision comparisons of the fundamental properties of antiprotons and protons, namely, charge-to-mass ratios and magnetic moments. To perform these tests we have developed an advanced Penning-trap spectrometer which enabled the most precise measurement of the proton magnetic moment with a fractional precision of 3.3 parts in a billion [2], the most precise comparison of the proton-to-antiproton charge-to-mass ratio, with a fractional precision of 69 parts in a trillion [3], as well as the most precise measurement of the magnetic moment of the antiproton [4]. Recent improvements in the stability of the apparatus demonstrate the feasibility to improve this test by at least a factor of 100. In the talk I will summarize our most recent results and give an overview on the future perspectives of BASE. [1] C. Smorra et al., Eur. Phys. Journ. Spec. Top. 224, 16 (2015). [2] A. Mooser et al., Nature 509, 596 (2014). [3] S. Ulmer et al., Nature 524, 196 (2015). [4] H. Nagahama et al., Nature Comms. 8, 14084 (2017).

1on behalf of the BASE collaboration

11:00AM N3.00002 Precision force sensing with optically-levitated nanospheres1 . ANDREW GERACI, University of Nevada Reno — In high vacuum, optically-trapped dielectric nanospheres achieve excellent decoupling from their environment and experience minimal friction, making them ideal for precision force sensing. We have shown that 300 nm silica spheres can be used for calibrated zeptonewton force measurements in a standing-wave optical trap. In this optical potential, the known spacing of the standing wave anti-nodes can serve as an independent calibration tool for the displacement spectrum of the trapped particle. I will describe our progress towards using these sensors for tests of the Newtonian gravitational inverse square law at micron length scales. Optically levitated dielectric objects also show promise for a variety of other precision sensing applications, including searches for gravitational waves and other experiments in quantum optomechanics.

1National Science Foundation PHY-1205994, PHY-1506431, PHY-1509176

11:30AM N3.00003 High-Resolution Light Transmission Spectroscopy of Nanoparticles in Real Time1 . CAROL TANNER, NAN SUN, ALISON DEATSCHE, FRANK LI, STEVEN RUGGIERO, University of Notre Dame — As implemented here, Light Transmission Spectroscopy (LTS) is a high-resolution real-time technique for eliminating spectral noise and systematic effects in wide band spectroscopic measurements of nanoparticles. In this work, we combine LTS with spectral inversion for the purpose of characterizing the size, shape, and number of nanoparticles in solution. The apparatus employs a wide-band multi-wavelength light source and gratings spectrometers coupled to CCD detectors. The light source ranges from 210 to 2000 nm, and the wavelength dependent light detection system ranges from 200 to 1100 nm with 1 nm resolution. With this system, nanoparticles ranging from 1 to 3000 nm diameters can be studied. The nanoparticles are typically suspended in pure water or water-based buffer solutions. For testing and calibration purposes, results are presented for nanoparticles composed of polystyrene and gold. Mie theory is used to model the total extinction cross-section, and spectral inversion is employed to obtain quantitative particle size distributions. Discussed are the precision, accuracy, resolution, and sensitivity of our results. The technique is quite versatile and can be applied to spectroscopic investigations where wideband, accurate, low-noise, real-time spectra are desired.

1University of Notre Dame Office of Research, College of Science, Department of Physics, and USDA

11:42AM N3.00004 Towards a robust green astro-comb for Earth-like exoplanet searches , AAKASH RAVI, Department of Physics, Harvard University, LEOPOLDO MARTIN, INAF - Fundacion Galileo Galilei, DAVID PHILLIPS, Harvard-Smithsonian Center for Astrophysics, NICHOLAS LANGEILLER, TIMOTHY MILBOURNE, CHRISTIAN DOLLIFF, Department of Physics, Harvard University, RONALD WALSWORTH, Harvard-Smithsonian Center for Astrophysics — The detection of exoplanets using the radial velocity (RV) method has become a very exciting and active area of research. Detecting Earth-like planets, however, is still very challenging as it requires extremely precise calibration of the spectrographs used in such measurements. To address this challenge, we employ a visible wavelength frequency comb - referenced to the global positioning system - as a calibration source. Our comb calibrator is realized by spectrally broadening and shifting the output of a 1 GHz repetition rate modelocked Ti:sapphire laser using a photonic crystal fiber and then filtering the comb lines to create a 16 GHz-spacing comb. This system has been implemented at the TNG telescope on La Palma to calibrate the HARPS-N spectrograph. However, the complexity of the system has thus far prevented its routine use as it requires frequency comb specialists to be on site during measurements. Here, we propose some automation strategies and present preliminary results from our efforts. We also discuss ongoing comb-calibrated astrophysical observations, including measurements of the Sun. The solar measurements are part of an effort to understand stellar noise sources in the RV data and demonstrate the sensitivity of the instrument to detect terrestrial exoplanets.

11:54AM N3.00005 Sub-attoNewton force detection in three dimensions with a single atom sensor1 . ERIK STREED, VALDIS BLUMS, Griffith University, MARCIN PIOTROWSKI, Griffith University, CSIRO Pullenvale, IRTIZA HUSSAIN, BENJAMIN NORTON, STEVEN CONNELL, Griffith University, STEPHEN GENSEMER, Griffith University, CSIRO Pullenvale, MIRKO LOBINO, Griffith University — Ultra-sensitive force measurements are a crucial tool for investigating fundamental physical limits. Here we demonstrate a sub-attoNewton force sensor based on a single trapped ion that can resolve all three dimensional components of an applied force through super-resolution imaging. The force is detected by measuring the ion displacement with nanometer precision with a sensitivity of 372±-9 zN/√Hz in one direction, and (335, 359) +/−14 zN/√Hz and (779, 836)+/−42 zN/√Hz for the other two axes. After characterizing our system in all three dimensions, we demonstrated its accuracy by measuring a light pressure force on the ion of 95 zN.

1Australian Research Council FF, DP, and DECRA programs
12:06PM N3.00006 Towards measuring quantum electrodynamic torque with a levitated nanorod\textsuperscript{1} ZHUJING XU, JAEHOON BANG, JONGHOON AHN, THAI M. HOANG, TONGCANG LI, Purdue University — According to quantum electrodynamics, quantum fluctuations of electromagnetic fields give rise to a zero-point energy that never vanishes, even in the absence of electromagnetic sources. The interaction energy will not only lead to the well-known Casimir force but will also contribute to the Casimir torque for anisotropic materials. We propose to use an optically levitated nanorod in vacuum and a birefringent substrate to experimentally investigate the QED torque. We have previously observed the libration of an optically levitated non-spherical nanoparticle in vacuum and found it to be an ultrasensitive torque sensor. A nanorod with a long axis of 300nm and a diameter of 60nm levitated in vacuum at 10^{-8} torr will have a remarkable torque detection sensitivity on the order of 10^{-28} Nm/\sqrt{Hz}, which will be sufficient to detect the Casimir torque.

\textsuperscript{1}This work is partially supported by the National Science Foundation under grant no.1555035-PHY.

12:18PM N3.00007 Thermoluminescence-based heat flux measurements across a composite polymer structure\textsuperscript{1}, FIROUZEH SABRI, UoM-Dept. of Physics and Materials Science, STEVE ALLISON, EMCO, MAKUNDIA ARYAL, PRATIKSHYA PARAJULI, UoM — Phosphor thermometry provides an accurate, remote, and instantaneous temperature reading mechanism that can be easily incorporated into temperature sensors designed for cryogenic temperatures as well as high temperatures. Phosphor thermometry is based on excitation and subsequent temperature dependent emission, typically in the visible spectrum. The emission results from the shielded 4f state of a rare earth constituent in the phosphor, in this case Eu3+ and is similar in spectrum to the isolated atom. The most common measurement strategies are the lifetime and intensity ratio approach. Recent efforts by the authors has demonstrated the feasibility of PDMS+La2O2S:Eu3+ composite polymers as temperature sensors that have the same temperature response as the powders alone. The work here describes recent efforts to design, create, and characterize a thin, flexible, heat flux measurement unit based on phosphor thermometry principles. Results will show heat flux calculations based on temperature measurements performed across a sandwich layer consisting of three separate layers of composite materials over a range of temperatures.

\textsuperscript{1}The authors would like to acknowledge IFTI and FIT at UoM for partial funding.

Thursday, June 8, 2017 10:30AM - 12:30PM — Session N4 Non-linear Optics 309 - Bonnie Schmittberger, JQI/University of Maryland

10:30AM N4.00001 Subfemtosecond pulse synthesis via coherent broadband generation in Raman-active crystal\textsuperscript{1} MARIJA SHUTOVA, ALEXANDRA ZHDANOVA, ALEXEI SOKOLOV, Texas A&M University — Subfemtosecond single- or sub-cycle broadband pulses of light are under active study because of their many applications; for example, detecting electron drift and atomic ionization; moreover, single cycle pulses offer the possibility of optical arbitrary waveform generation. Our group works on synthesizing such ultrashort pulses in ultraviolet-visible-near infrared range by making use of broadband generation in a Raman-active crystal. We have previously proven that the multi-color Raman sidebands generated in this way are mutually coherent and thus can be recombined to obtain ultrashort pulses of broadband radiation by proper phase alignment. We present a setup scheme which uses dichroic mirrors to combine near infrared pump and Stokes beams along with several sidebands in visible range in one beam in collinear scheme and control the phase of each sideband with nanometer precision. Finally, we examine the relative phase between each sideband by analyzing the beating of SHG and SFG signals generated in BBO crystal, moreover, the subfemtosecond duration of resultant pulse can be proved by looking at multiphoton ionization of xenon gas, since it has been shown that the ion yield is related to the duration of the pulse.

\textsuperscript{1}The work is supported by NSF(grant No.PHY-1307153 and CHE-1609608);Robert A.Welch Foundation(grant A1547);Office of Naval Research Award(N00014-16-1-2578).M.S.thanks Herman F.Heep and Minnie Belle Heep TAMU Endowed Fund administered by the TAMU Foundation.

10:42AM N4.00002 Gaussian Beam Propagation for Nonlinear Optics featuring Orbital Angular Momentum Transfer\textsuperscript{1} R. NICHOLAS LANNING, ZHIHAO XIAO, Louisiana State University, MI ZHANG, IRINA NOVIKOVA, EUGENIY E. MIKHAILOV, College of William and Mary, JONATHAN P. DOWLING, Louisiana State University — We present a general, Gaussian spatial mode separation modal propagation formalism for describing the generation of higher order multi-spatial mode beams generated during nonlinear interactions. Furthermore, to implement the theory, we simulate optical angular momentum transfer interactions, and show how one can optimize the interaction to reduce the undesired pollution of the spatial mode structure.

\textsuperscript{1}This research was supported by AFOSR grant FA9550-13-1-0098. In addition, R. N. L., Z. X. and J. P. D. acknowledge additional support from the ARO, the NSF, and the Northrop Grumman Corporation.

10:54AM N4.00003 Improvement of Two-Mode Squeezing in the Presence of Loss with a Phase-Sensitive Amplifier TIAN LI, BRIAN ANDERSON, BONNIE SCHMITTBERGER, TRAVIS HORROM, Joint Quantum Institute, NIST and Univ. of Maryland, KEVIN JONES, Department of Physics, Williams College, PAUL LETT, Joint Quantum Institute, NIST and Univ. of Maryland and Quantum Measurement Division, National Institute of Standards and Technology — We demonstrate a phase-sensitive amplifier (PSA) to pre-amplify quantum correlations in twin light beams before degradation due to loss and detector efficiency. We use four-wave mixing (4WM) in Rb vapor to generate bright beams in a two-mode squeezed state. After which, a second 4WM interaction in a PSA configuration amplifies one half of the two-mode state before a loss is intentionally introduced. It is well known that, in the case of a PSA, no extra noise will be added given the correct relative phases (e.g. at the maximal amplification and the maximal deamplification) among the inputs. We thus lock our PSA phase at the phase where we are able to have the maximal, noiseless, amplification of one half of the two-mode squeezed state and compare with its twin beam. Due to this noiseless pre-amplification, we demonstrate that phase-sensitive amplification placed before losses can improve correlations between the beams, or squeezing.
11:06AM N4.00004 Quantum droplets of light in the presence of synthetic magnetic fields. KALI WILSON, NICLAS WESTERBERG, MANUEL VALIENTE, CALLUM DUNCAN, Heriot-Watt University, EWAN WRIGHT, University of Arizona, PATRIK OBERG, DANIELE FACCIOL. Heriot-Watt University — Recently, quantum droplets have been demonstrated in dipolar Bose-Einstein condensates, where the long range (nonlocal) attractive interaction is counterbalanced by a local repulsive interaction. In this work, we investigate the formation of quantum droplets in a two-dimensional nonlocal fluid of light. Fluids of light allow us to control the geometry of the system, and thus introduce vorticity which in turn creates an artificial magnetic field for the quantum droplet. In a quantum fluid of light, the photons comprising the fluid are treated as a gas of interacting Bose-particles, where the nonlocal interaction comes from the nonlinearity inherent in the material, in our case an attractive third-order thermo-optical nonlinearity. In contrast to matter-wave droplets, photon fluid droplets are not stabilised by local particle-particle scattering, but from the quantum pressure itself, i.e., a balance between diffraction and the nonlocal nonlinearity. We will present a numerical and analytical investigation of the ground state of these droplets and of their subsequent dynamics under the influence of a self-induced artificial magnetic field, and discuss experimental work with the possibility to include artificial gauge interactions between droplets.

11:30AM N4.00006 Photon number-selective dipolar-exchange induced transparency with Rydberg atoms. DAVID PETROSYAN, Inst of Elec Structure & Laser, FORTH, Greece — A three-level atomic medium can be made transparent to a resonant probe field in the presence of a control field acting on an adjacent atomic transition to a long-lived state, which can be represented by a highly excited Rydberg state. The long-range interactions between the Rydberg state atoms then translate into strong, non-local, dispersive or absorptive interactions between the probe photons. These interactions can be used to achieve deterministic quantum logic gates and single photon sources. We show that long-range dipole-dipole exchange interaction with one or more spins — two-level systems represented by atoms in suitable Rydberg states — can play the role of control field for the optically-dense medium of atoms. This induces transparency of the medium for a number of probe photons \(n_2\), not exceeding the number of spins \(n_1\), while all the excess photons are resonantly absorbed upon propagation. The system can thus serve as a photon-number filter or a transistor, with the number of appropriately prepared spins \(n_1 = 0, 1, \ldots\) being the switch.

11:42AM N4.00007 Towards efficient photon-photon interaction at room temperature. REIHANEH SHAHROKHSHAH, MEHDI NAMAZI, STEVEN SAGONA-STOPEN, BERTUS JORDAAN, EDEN FIGUEROA, Physics department, Stony Brook University — Strong atom mediated photon-photon interactions are the backbone of future deterministic quantum gates. Here we present our current results regarding the interaction of few photon level fields mediated by \(^{87}\)Rb atoms in a room temperature atomic vapor. We have implemented a double-lambda atomic scheme [1]. The first EIT system uses a weak probe coupling to the \(D_1, 5\S_1/2, F = 1 \leftrightarrow 5\P_1/2, F = 1\) transition and strong control field coupling to the \(5\S_1/2, F = 2 \leftrightarrow 5\P_1/2, F = 1\) transition, while the second EIT system addresses the same atomic levels albeit with an extra 80 MHz one photon detuning. The presence of few photon level signal field is used to steer the phase of the probe photon wave packet. We have achieved meaningful crossed phase modulation for 400ns long probe and signal pulses containing only a few photons. The magnitude of the probe field phase shift per photon in the signal field is quantified using a homodyne detector and is several orders of magnitude larger as compared to what we have observed in our previous characterization of a Kerr nonlinearity [2]. [1] Z.-Y. Liu, et al. Phys. Rev. Lett., 117, 203601 (2016). [2] C. Kupchak, et al, Sci. Rep, 5, 16581 (2015).

11:54AM N4.00008 Quantum Nonlinear Interferometry for Occultation Satellite Remote Sensing, FELIX JAETAE SEO, JIA SU, QUINTON RICE, DULITHA JAYAKODIGE, WILLIAM MOORE, PAT MCCORMICK, BAGHER TABIBI, Hampton University, HAMPTON UNIVERSITY TEAM — Quantum nonlinear interferometry is of great interest for quantum information and sensing applications. The quantum measurement of atmospheric gases is proposed with the principle of the nonlocal correlation of signal and idler beams by spontaneous parametric down conversion (SPDC). If the phase and amplitude of idler in the mid-infrared from a nonlinear crystal in the transmitter satellite at geosynchronous equatorial orbit (GEO) are nonlocally correlated to those of its own signal, and if the phase difference between two idlers of nonlinear crystals in the transmitter (GEO) and receiver (LEO or GEO) satellites forms a constructive interference, the measurement of signal interference between visible photons from two nonlinear crystals provides the information of interaction between idler photon and atmospheric gases. The transmittance reduction of idler due to atmospheric gas absorption results in the interference amplitude reduction, which is nonlocally correlated to the interference amplitude of signal beams. If the nonlocal interference visibility of signal beams indicates the normalized difference of outer and inner envelopes, the absorption coefficients and the concentration of atmospheric gases can be analyzed through the quantum nonlinear interferometry. Therefore, the nonlocal and nonlinear quantum interferometry is proposed to develop satellite remote sensing with shallow and deep occultation techniques, and promote the laser interferometer space antenna for gravitational wave measurement.

1Acknowledgement: This work is supported by NASA NNX15AQ03A, NSF HRD-1137747, and ARO W911NF-15-1-0535.

12:06PM N4.00009 Atmospheric remote sensing via optically pumped CO\(_2\) laser. ANTON SHUTOV, MARIA SHUTOVA, ALEXANDER GOLTSOV, ALEXEI SOKOLOV, Texas A&M University, MARLAN SCULLY, Texas A&M University, Baylor University — With the growing global warming problem atmospheric remote sensing, especially remote detection of CO\(_2\) levels, has become a hot topic nowadays. Here we discuss an idea on how CO\(_2\) gas in air can be turned into a laser medium. This type of CO\(_2\) laser is pumped via Raman vibrational mode excitation of the nitrogen present in air. We propose an experiment to implement this type of a laser, where vibrational excitation of nitrogen is produced by a pair of Raman-resonant laser pulses. We quantify the efficiency of the Raman excitation process by observing cascaded Raman sideband generation. When excitation of the first vibrational state takes place in some portion of nitrogen molecules, it is accompanied by generation of multiple Stokes and anti-Stokes sideband. Following the excitation of the vibrations in nitrogen, carbon dioxide molecules become excited due to collisions and lasing takes place as in a conventional carbon dioxide laser.

1The work is funded by: NSF(PHY1307153), Office of Naval Research(AwardN00014-16-1-3054, N00014-16-1-2578), Robert A.Welch Foundation(GrantA-1261,A-1547), AS,MS thank the Herman F.Heep and Minnie Belle Heep TAMU Endowed Fund held by the TAMU Found.
12:18PM N4.00010 Double-Mueller polarimetry in KTP (Potassium Titanyl Phosphate) crystal, CHITRA SHAJI, DRUTHIL LAL S B, ALOK SHARAN, Department of Physics, Pondicherry University, Puducherry — Ultra-structural properties of material are being probed by Double Stokes-Mueller polarimetry (DSMP) technique. It makes use of higher dimensions of Stokes vector (9 X 1) and Mueller matrix (4 X 9) to characterize the nonlinear optical properties of a material. Second harmonic generation (SHG) at 532nm using 1064nm as fundamental cw beam from Nd:YAG laser in type II phase matched KTP (Potassium Titanyl Phosphate) crystal is studied using DSMP. The experimental measurements for determining double Mueller matrix are carried out in the Polarization In Polarization Out (PIPO) arrangement. Nine input polarization states are incident on the sample and the linear Stokes vector of the emerging light from the sample is measured. The KTP crystal is oriented such that the SHG signal efficiency at the incident horizontal and vertical polarizations is high as compared to diagonal polarization states. The susceptibility tensor components and the phase difference between them at this orientation are determined from the double Mueller matrix elements. These determined values give information regarding the crystal axis orientations. To our knowledge, this is the first report of the use of DSMP technique to determine the crystal orientations of a biaxial crystal.

Thursday, June 8, 2017 10:30AM - 12:30PM
Session N5 DAMOP GEC: Antimatter Collisions at Low Energies

11:00AM N5.00002 Positronium collisions with atoms, protons, and antiprotons1, ILYA FABRIKANT, University of Nebraska-Lincoln — Recently observed similarities between positronium (Ps) scattering and electron scattering from several atoms and molecules [1] in the intermediate energy range were explained [2,3] by the dominance of the electron exchange interaction with the target atom or molecule. An explicit proof of this equivalence was given using the framework of the impulse approximation [2], valid above the Ps ionization threshold. For lower collision energies a pseudopotential method [3] was developed. It was successfully applied to the calculation of Ps scattering from heavy rare gas atoms, and gave results in good agreement with those of the beam experiments [1]. The same method was applied to Ps collisions with molecular hydrogen [4]. In general we observe the similarity between electron and Ps scattering at energies above the Ps ionization threshold. However, below the threshold the two sets of cross sections are different because of the different nature of the long-range interaction between the projectile and the target, the polarization interaction in the case of electron collisions and the van der Waals interaction in the case of Ps collisions. In particular the Ramsauer-Townsend minimum is not seen in theoretical cross sections for the heavy rare gas atoms. The second part of this talk will summarize recent results on the threshold behavior of Ps collisions with protons and antiprotons [5]. Partial cross sections for elastic and quasielastic scattering exhibit oscillations as functions of lnE where E is the Ps energy. The quantum-mechanical threshold behavior of hydrogen and antihydrogen formation show features which make them different from results of classical trajectory Monte Carlo simulations. 1 S. J. Brawley, S. Armitage, J. Beale, D. E. Leslie, A. I. Williams, and G. Laricchia, Science 330, 789 (2010). 2 I. I. Fabrikant and G. F. Gribakin, Phys. Rev. Lett. 112, 243201 (2014). 3 I. I. Fabrikant and G. F. Gribakin, Phys. Rev. A 90, 052717 (2014). 4 R. S. Wilde and I. I. Fabrikant, Phys. Rev. A 92, 032708 (2015). 5 I. I. Fabrikant, A. W. Bray, A. S. Kadyrov, and I. Bray, Phys. Rev. A 94, 012701 (2016).

1In collaboration with G. F. Gribakin, R. S. Wilde, and I. Bray. Supported by the US National Science Foundation.

11:30AM N5.00003 Resonances in Positron Annihilation on Molecules – Which Bells Ring2, CLIFFORD M. SURKOF, Physics Department, University of California, San Diego — Positron collisions with molecules can result in the excitation of high-Q vibrational Feshbach resonances – temporary positron-molecule bound states that exhibit greatly enhanced annihilation rates. A simple theory agrees well with data for annihilation spectra as a function of incident positron energy for selected molecules, such as methyl halides, in which infrared-active vibrations dipole-couple the incident positron to the bound state. However additional effects appear to be prominent in most molecules, including the excitation of combination and overtone modes. Until now, limited energy resolution has inhibited the study of these effects. A recently developed, high-energy-resolution, cryogenic trap-based beam is used to investigate two other ways to “ring the molecule’s bells”: positron coupling to infrared-inactive modes and the excitation of combination modes. The operation of the new beam system will be briefly described followed by a discussion of high-resolution data for molecules that provide evidence of resonant annihilation due to infrared m active modes. Data exploring the possible excitation of combination modes will also be discussed and related to broad and featureless regions of the annihilation spectra observed in many molecules.

2This work is supported by NSF grant PHY 14-01794.
3Work done in collaboration with M. R. Natisin and J. R. Danielson.
12:00PM N5.00004 Low Energy Positron Scattering, Transport, and Applications
STEPHEN BUCKMAN, Australian National University — Relatively intense, high-energy-resolution beams of low-energy positrons are now available through the use of buffer-gas (Surko) traps. These have led to measurements of interaction cross sections for a broad range of atoms and molecules, including molecules of biological interest. The increased energy resolution, and experimental techniques developed for scattering in strong magnetic fields has also enabled highly accurate measurements of discrete excitation processes such as electronic and vibrational excitation, positronium formation and ionization in a range of atomic and molecular species. This talk will review some of these measurements and discuss their application in new and sophisticated models of positron transport which aim, for example, to provide a better understanding of the atomic and molecular processes which occur when positrons are emitted in the body during a Positron Emission Tomography scan. This work is part of a broad collaboration between the ANU (James Sullivan, Joshua Machacek), Finders University (Michael Brunger), James Cook University (Ronald White and co-workers) CSIC Madrid (Gustavo Garcia) and the Institute of Physics, Belgrade (Zoran Petrovic and colleagues).

Thursday, June 8, 2017 10:30AM - 12:30PM –
Session N6 Bose-Fermi Mixtures 311-312 - Christophe Salomon, ENS, Paris

10:30AM N6.00001 One, two, three, many: few body losses in many-body ensembles
, FREDERIC CHEVY, SEBASTIEN LAURENT, MATTHIEU PIERCE, TARIK YEFSAH, CHRISTOPHE SALOMON, Ecole Normale Superieure — Recent experiments have demonstrated the possibility of achieving super fluidity in Bose-Fermi mixtures. In my talk I will address the remarkable stability of these systems and show that in weakly-coupled mixtures, the loss rate is proportional to Tan’s contact parameter that quantifies the short-range behaviour of two-body correlations in the fermionic system. Using a \(^7\)Li/\(^6\)Li mixture we probe the recombination rate in both the thermal and dual-superfluid regimes. We find excellent agreement with our model in the BEC-BCS crossover. At unitarity where the fermion-fermion scattering length diverges, we show that the loss rate is proportional to the \(1/3\) power of the fermionic density. Our result interpolate between the three-body losses expected in the weakly attractive (BCS) limit and the dominant two-body dimer-dimer processes in the strongly attractive (BE) regime.

10:42AM N6.00002 Two-Element Mixture of Bose and Fermi Superfluids
1, RICHARD ROY, ALAINA GREEN, RYAN BOWLER, SUBHADEEP GUPTA, Department of Physics, University of Washington, UW ULTRACOLD MIXTURES TEAM — We report on the production of a stable mixture of bosonic and fermionic superfluids composed of the elements \(^{174}\)Yb and \(^6\)Li which feature a strong mismatch in mass and distinct electronic properties. We demonstrate elastic coupling between the superfluids by observing the shift in dipole oscillation frequency of the bosonic component due to the presence of the fermions. The measured magnitude of the shift is consistent with a mean-field model and its direction determines the previously unknown sign of the interspecies scattering length to be positive. We also observe the exchange of angular momentum between the superfluids from the excitation of a scissors mode in the bosonic component through interspecies interactions. We explain our observation using an analytical model based on superfluid hydrodynamics.

1This work was supported by NSF Grant No. PHY-1306647, AFOSR Grant No. FA 9550-15-1-0220, and ARO MURI Grant No. W911NF-12-1-0476.

10:54AM N6.00003 Collective modes of a BEC immersed in a Fermi sea
1, BO HUANG, RIANNE S. LOUS, ISABELLA FRITSCHE, FABIAN LEHMANN, MICHAEL JAG, EMIL KIRILOV, RUDOLF GRIMM, MIKHAIL A. BARANOV, Inst. for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, and University of Innsbruck, Austria — The collective dynamics of a trapped Bose-Einstein condensation (BEC) can change significantly when the BEC is strongly interacting with a degenerate Fermi gas. We realize such a quantum mixture with a \(^{41}\)K BEC immersed in a large single-component degenerate Fermi gas of \(^6\)Li, and both elements are trapped in an elongated optical dipole trap while the interspecies contact interaction is manipulated by a magnetic Feshbach resonance between the lowest spin state of both elements near 335.08 G. When the interspecies repulsive interaction increases, the two components start to repel each other, i.e. the BEC density is enhanced while the fermions are depleted at the trap center, and finally become spatially separated when the interaction is sufficiently strong. Across this transition, we measure the frequencies of BEC collective oscillations and observe a substantial change of the frequency of the radial breathing mode. We interpret our observations with a mean-field model beyond the local-density approximation.

1This work is supported by the Austrian Science Fund FWF within the collaborative research grant FoQuS.

11:06AM N6.00004 Phase Separation in a Bose-Fermi Mixture of \(^6\)Li and \(^{41}\)K
, RIANNE S. LOUS, BO HUANG, ISABELLA FRITSCHE, FABIAN LEHMANN, MICHAEL JAG, EMIL KIRILOV, RUDOLF GRIMM, Inst. for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, and Inst. for Experimental Physics, University of Innsbruck — We report on the observation of phase separation between a \(^{41}\)K Bose-Einstein condensate (BEC) and a \(^6\)Li Fermi sea with strong repulsive interspecies interactions. After evaporation in an optical dipole trap, we obtain a BEC of \(^{41}\)K atoms and a Fermi sea of \(^6\)Li atoms with \(T_{T_F} < 0.07\). We explore this double-degenerate mixture by tuning the heteronuclear interaction with the help of a Feshbach resonance at 335.08 G. We use three-body recombination as a probe to study the overlap between the two species for various interaction strengths. We see a decrease in loss rate when the interactions become strongly repulsive and compare the loss rate to that of a non-condensed bosonic cloud. In a phase-separated mixture, losses only happen at the interface of the two species and are therefore reduced, when compared to a mixed phase of both species. To understand our loss rate results, we calculate the spatial overlap between the two components with a mean-field model. This model fits nicely to our experimental results and reveals effects beyond the local density approximation (LDA).

1This work is supported by the Austrian Science Fund FWF within the collaborative research grant FoQuS.

11:18AM N6.00005 Dual-Degeneracy in a Bose-Fermi Mixture with Extreme Mass Imbalance
, B. J. DESALVO, KRUTIK PATEL, JACOB JOHANSEN, CHENG CHIN, The James Franck Institute, The Enrico Fermi Institute, and Department of Physics, The University of Chicago — We have produced the first quantum degenerate mixture of bosonic \(^{133}\)Cs and fermionic \(^6\)Li. Owing to a narrow Feshbach resonance at 892 G, this system offers a flexible platform in which to study strongly interacting Bose-Fermi mixtures with large mass imbalance. To produce this sample, we first sequentially laser cool and load each species into separate optical dipole traps. The two species are evaporatively cooled and then combined at \(T/T_F \sim 0.2\) for \(^6\)Li. By tuning the interspecies interactions via the Feshbach resonance, we explore the phase diagram of this system and will present our efforts to observe beyond mean-field effects.
11:30AM N6.00006 Testing universality of Efimov Physics based on a mass-imbalanced Li-Cs mixture, JACOB JOHANSEN, BRIAN DESALVO, KRUTIK PATEL, CHENG CHIN, The University of Chicago — Efimov states are notable for their universal geometric scaling and are observable in ultracold atomic systems employing magnetic Feshbach resonances. In addition to geometric scaling, which we observed previously by taking advantage of a reduced Efimov scaling constant in our mass imbalanced \(^6\text{Li}-^{133}\text{Cs}\) system, an interesting pattern has emerged in Efimov measurements: while expected to be non-universal, the absolute positions of Efimov resonances appear to scale simply with van der Waals length. Theories attempting to explain this observation have predicted a dependence on the strength of the Feshbach resonance for narrow resonances, yet experiments attempting to probe this regime have so far been inconsistent with the predicted dependence. In this talk, we focus primarily on our recent measurements showing dependence on Feshbach resonance strength. We directly compare two Feshbach resonances, one broad and one very narrow, which are nearly identical with the exception of the resonance strength, and find a striking difference in the first Efimov resonance. Our measurement makes significant strides toward resolving the discrepancy between experiment and theory which exists in the field today.

11:42AM N6.00007 Thermodynamics and Structural Transition of Binary Fermi-Bose Mixtures of Ultracold Atoms, TOM KIM, CHIH-CHUN CHIEN, University of California, Merced — A mixture of spin-polarized fermionic and repulsive bosonic ultracold atoms can go through phase separation if the boson-fermion interaction is sufficiently large and the temperature sufficiently low. By evaluating the grand partition function from standard statistical mechanics, we obtain the thermodynamic free energies and its associated quantities at finite temperatures. We examine the stability of a mixture from the structure of the free energy. For a uniform box potential, strong interspecies repulsion separates the two components, and the thermodynamic quantities of each component can be systematically determined. A mixture in a harmonic trap distorts the density profiles. By using the local density approximation, we found several different structures, such as partially mixed regions or fully separated regions, depending on the mass ratio and interactions.

11:54AM N6.00008 Toward Creation of Triplet Ground State NaLi Molecules, HYUNGMOK SON, Massachusetts Institute of Technology, Harvard University, TIMUR RVACHOV, ARIEL SOMMER, JULIANA PARK, Massachusetts Institute of Technology, SEPEHR EBADI, University of Toronto, MARTIN ZWIERLEIN, WOLFGANG KETTERLE, ALAN JAMISON, Massachusetts Institute of Technology — Ultracold heteronuclear molecules offer a unique platform for the study of many-body physics, quantum information processing, and controlled chemistry at the quantum level. For this purpose, diatomic molecules in absolute, singlet ground states have been created with various combinations of alkali atoms. The NaLi molecules is unique in that the triplet ground state is expected to have a long collisional lifetime, giving access to novel spin lattice Hamiltonians that harness both the electric and magnetic moments. In addition, as the lightest bialkali dimer, the low density of states will provide us with the potential to study resolved Feshbach resonances between the molecules. We report our progress on the creation of a large sample of fermionic NaLi molecules in the triplet ground state through STIRAP from weakly-bound molecules, which may be produced through magneto-association or two-stage photo-association.

12:06PM N6.00009 Photoassociation spectroscopy of heteronuclear LiYb molecules, ALAINA GREEN, RICHARD ROY, RYAN BOWLER, SUBHADEEP GUPTA, University of Washington — We probe the electronically excited potentials of Li*Yb with photoassociation (PA) spectroscopy in a dual-species optical dipole trap. Previous studies of interspecies PA by trap-loss spectroscopy in a double MOT were hindered by strong homonuclear photoassociative loss of Li to states in the excited-state \(\Sigma\) potentials [1]. We null this background by performing PA on a cycling transition in a mixture of spin-polarized \(^6\text{Li}\) and \(^{174}\text{Yb}\). The Pauli blocking of Li s-wave PA enables the observation of interspecies PA as well as yet unreported \(\text{Li}_2\) photoassociation resonances to excited \(\Sigma\) states. We intend to utilize knowledge of the interspecies spectrum to perform Raman spectroscopy on the electronic ground state of LiYb, moving towards the coherent production of polar ultracold molecules with a paramagnetic degree of freedom. [1] R. Roy, et al. J. Phys. Rev. A. 94, 033413 (2016).

12:18PM N6.00010 A new apparatus for enhanced optical and electric control of ultracold KRb molecules, GIACOMO VALTOLINA, JACOB COVEY, LUIGI DE MARCO, KYLE MATSUDA, WILLIAM TOBIAS, JUN YE, JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder, CO 80309, USA — Ultracold KRb molecules represent an ideal platform for studying many-body physics with long-range dipolar interactions. The field of ultracold polar molecules has recently made enormous progress and many different bi-alkali molecules have been produced in their ground state. Recently, dipolar spin-exchange interactions and many-body dynamics have been observed with Fermionic KRb molecules in an optical lattice, and controlled chemistry in a lattice has been realized. However, the ability to apply large electric fields to polarize the molecules has been limited to several kV/cm. Additionally, high resolution in situ has been lacking for polar molecules despite the enormous progress in the quantum gas field. We present a new apparatus for producing Fermionic KRb molecules where stable, homogeneous electric fields in the range of 30 kV/cm are expected, while also accommodating arbitrary gradients in two dimensions. This apparatus is designed for high resolution addressing and detection, and imaging resolutions well below 1 micron are expected. We present details on this apparatus and its construction, and describe the procedure used to produce ultracold gases of atoms and molecules. Further work will lead to high resolution detection of strongly dipolar quantum systems.

Thursday, June 8, 2017 10:30AM - 12:30PM — Session N7 Strong Field Phenomena in Soft and Condensed Matter 313 - Arvinder Sandu, University of Arizona

10:30AM N7.00001 Anisotropy in high-harmonics from bulk and 2D crystals, SHAMBHU GHIMIRE, Stanford PULSE Institute — We present our experimental results on observation of anisotropic high-order harmonics from bulk and atomically thin 2D crystals. For linear polarization, the rotation of 100 cut bulk MgO crystal around its normal produces a strong 4-fold distribution consistent to its cubic crystal structure [1]. The ellipticity dependence is also strongly anisotropic and depends on the orientation of crystallographic axis with respect to the major axis of laser polarization [1]. We use real-space electron trajectory analysis to investigate the underlying electron dynamics. We also find that much of the anisotropy originates in the crystal structure of solids such as in MoS2, we measure 6-fold distribution dictated by its hexagonal crystal structure [2]. Finally, single layer MoS2 produces additional set of even order harmonics because of the lack of reflection symmetry [2]. The understanding of microscopic origin of anisotropy could lead to an all-optical method suitable for probing the distribution of valance charge density in bulk and 2D crystalline solids. References: [1] Y. You et al., Nature physics, DOI: 10.1038/nphys3955, (2016) [2] Liu et al., Nature Physics, DOI: 10.1038/nphys3946, (2016)
11:00AM N7.00002 High-order sideband generation: colliding quasiparticles, probing Berry curvature, and generating tunable frequency combs in semiconductors\textsuperscript{1}. MARK SHERWIN, Physics Department and Institute for Terahertz Science and Technology, UC Santa Barbara, Santa Barbara, CA 93106 — High-order sideband generation (HSG) is a recollision phenomenon that is closely related to high-order harmonic generation (HHG). A weak laser, tuned near the band gap of a semiconductor, resonantly injects pairs of quasiparticles (electrons and holes) while the semiconductor is driven by a strong terahertz-frequency electric field. The terahertz field accelerates the photo-injected electrons and holes first away, then back towards each other. If the electrons and holes recombine, a high-order sideband is emitted. The sidebands form a frequency comb with teeth spaced by twice the terahertz frequency, and anchored by the frequency of the laser that generates the electron-hole pairs. Recently, we have observed HSG spectra containing sidebands up to 90th order and spanning over 12 percent of the laser wavelength, which is near 800 nm. As the electrons and holes are accelerated through the band structure of GaAs quantum wells, the holes experience significant Berry curvature, which leaves its imprint on the polarizations of the high-order sidebands.

\textsuperscript{1}This work was supported by the NSF under grant DMR 1405964.

11:30AM N7.00003 HHG in solids: dynamics of multilevel adiabatic states spanning the band structure\textsuperscript{1}. METTE GAARDE, Louisiana State University — We investigate high harmonic generation in a solid, modeled as a multilevel system dressed by a strong infrared laser field \cite{Gaarde2015}. We show that the cutoff energies and relative strengths of the multiple plateaus that emerge in the harmonic spectrum can be understood both qualitatively and quantitatively by considering the dynamics of the laser-dressed system. Such a model was recently used to interpret the multiple plateaus exhibited in harmonic spectra generated by solid argon and krypton \cite{Goulielmakis2004}. We show that when the multilevel system originates from the Bloch states at the gamma-point of the band structure, the laser-dressed states (which are equivalent to the so-called Houston states \cite{Wirth2011}) map out the band structure away from the gamma-point as the laser field increases. This means that the cutoff energy of a given plateau can never exceed the maximum band gap between the valence band (VB) and the conduction band (CB) responsible for that plateau, thereby extending the cutoff limitation proposed in \cite{Goulielmakis2004} to a multiband system. Finally, we discuss how this understanding leads to a semiclassical three-step picture in momentum space that describes the HHG process in a solid. In this picture, the delocalized electron first tunnels from the VB to the CB at the zero of the vector potential and then is accelerated on the CB as the vector potential increases and decreases through an optical half-cycle. The coherence between the VB and the CB populations leads to the emission of XUV radiation, with photon energies corresponding to the instantaneous energy difference between the VB and the CB. This means that each energy below the cutoff energy is emitted twice in each laser half-cycle. \cite{Wu2014,Goulielmakis2004,Keizer2016,Vampa2014}.

\textsuperscript{1}This work was supported by the National Science Foundation under Grant No. PHY-1403236.

12:00PM N7.00004 Route to Coherent Electronics ELEFTHERIOS GOULIELMAKIS, Max-Planck-Institut fr Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany — Laser-driven generation of coherent radiation in bulk solids extending up to the extreme ultraviolet part of the spectrum \cite{Luu2015} has recently open up completely new possibilities for study of electronic phenomena which lie beyond the scope of standard condensed phase physics spectroscopies. I will present how previous \cite{Goulielmakis2004} and new tools of attosecond metrology \cite{Wirth2011,Keizer2016,Vampa2014} can now allow us to gain detailed insight into the fundamental microscopic processes responsible for the EUV emission in solids. We will show that this emission is in reality a macroscopic probe of nanoscale intraband coherent electric currents \cite{Luu2015} and the frequency of which is extending into multiPetahertz range. On the basis of these findings, I will try to persuade you that we are now entering the realm of coherent electronics. A regime in which electronic circuitry can be conceived on the atomic level and where electronic properties of materials can be accessed \cite{Wirth2011} and controlled on attosecond time scales.

\cite{Luu2015,Goulielmakis2004,Keizer2016,Vampa2014}.

Thursday, June 8, 2017 10:30AM - 12:30PM —
Session N8 Quantum Networks and Photon Sources 314 - Steven Olmschenk, Denison University

10:30AM N8.00001 An integrated diamond nanophotonics platform for quantum optical networks\textsuperscript{1}. MIHIR BHASKAR, ALP SIPAHIGIL, RUFFIN EVANS, DENIS SUKACHEV, CHRISTIAN NGUYEN, MICHAEL BUREK, BARTHOLOMEUS MACHIELSE, JOHANNES BORREGAARD, HAIG ATIKIAN, CHARLES MEUWLY, Harvard Univ, LACHLAN ROGERS, PETR SIYUSHEV, MATTHIAS METSCH, Ulm Univ, HONGKUN PARK, MARKO LOONCAR, MIKHAIL LUKIN, Harvard Univ — We demonstrate a platform for quantum optical networks based on silicon-vacancy (SiV) and germanium-vacancy (GeV) color centers in diamond nanodevices. By placing SiV centers inside diamond photonic crystal cavities, we realize a quantum optical switch controlled by a single SiV. Raman transitions are used to realize a single-photon source with a tunable frequency and bandwidth in a diamond waveguide. We measure intensity correlations of indistinguishable Raman photons emitted into a single waveguide, observing a quantum interference effect resulting from the superradiant emission of two entangled SiV centers. We incorporate GeV centers into nanoscale waveguides and demonstrate high single atom-photon interaction probabilities in a single-pass. We discuss prospects for a high-cooperativity (C >10) spin-photon interface using GeV centers in diamond nanocavities.

\textsuperscript{1}NSF, CUA, AFSOR MURI, ONR MURI, ARL

10:42AM N8.00002 Decoherence-protected storage of a photonic polarization qubit in a single atom MATTHIAS KOERBER, OLIVIER MORIN, STEFAN LANGENFELD, ANDREAS NEUZNER, STEPHAN RITTER, GERHARD REMPE, Max Planck Institute for Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany — The ability to faithfully store quantum information is a key requirements for many quantum technologies. Here, we present a quantum memory based on a single 87 Rb atom in a high-finesse optical resonator, capable of storing and retrieving single-photon polarization qubits with an overall efficiency of 18% when probed with coherent laser pulses containing one photon on average. Initially the polarization of the photon is mapped onto the atom via a stimulated Raman adiabatic passage (STIRAP). Because the two atomic levels used to encode the qubit shift in opposite directions in the presence of a magnetic field the memory is susceptible to magnetic field fluctuations. This limits the coherence time to a few hundred microseconds. Using an optical Raman transfer we temporarily map the qubit to a protected subspace, thereby extending the coherence time to tens of milliseconds. It can be further increased to more than 100 milliseconds by means of a spin-echo technique. Our results are an important milestone towards the implementation of a quantum repeater allowing for long-distance quantum communication.
The proposed scheme can be directly applied in practical quantum communications and quantum networking scenarios. We give bounds on the maximum value of the total number of entangled links of a path. The results allow us to perform efficient routing to find the shortest paths in entangled quantum networks. The hop distance, the number of spanned nodes, and the probability of the existence of an entangled link in the network. In this work we define a decentralized routing for entangled quantum networks. We show that the probability distribution of the entangled links can be modeled by a specific distribution in a base-graph. The results allow us to perform efficient routing to find the shortest paths in entangled quantum networks by using only local knowledge of the quantum nodes. We give bounds on the maximum value of the total number of entangled links of a path. The proposed scheme can be directly applied in practical quantum communications and quantum networking scenarios.

11:06AM N8.00004 An Approach for trapped Ba+ ion-photon entanglement and quantum frequency conversion, JAMES SIVERNS, XIAO LI, Joint Quantum Institute, Univ of MD, College Park, 20742, QUDSIA QURAISHI, Army Research Lab and Joint Quantum Institute, University of MD, 20742, ARL/JQI COLLABORATION — Networking remotely situated trapped ion quantum memories involves the extraction, propagation and detection of photons which are entangled with internal qubit states of an ion [1]. Given the cumulative losses of these processes it is important to have a high-probability method to extract the photon. Even with high probability photon extraction, extending the networking range is challenging as the flying qubit’s wavelength is severely attenuated when propagated in optical fiber. In this case, quantum frequency conversion has been proposed as an approach to extend the networking range. Here, we compare several methods of ion–photon entanglement generation, including strong and weak excitation methods, showing the fidelity and entanglement probability vary as a function of the photon collection optic’s numerical aperture. We project that the highest photon generation probability (approximately 95%) in 138Ba+ is achieved via shelving to a long-lived, low-lying D-state with a projected fidelity of approximately 89% [2]. We then outline an approach for quantum frequency conversion of the extracted photon, with a view to hybrid or long-distance networking, useful for extending the range of ion-based quantum networks and hybrid quantum networks compromised of different types of quantum memories. [1] C. Monroe, et. al., Phys. Rev. A 89, 022317 (2014). [2] J. Siverns, X. Li and Q. Quraishi, App. Opt. 56, 3, B222 (2017).

11:18AM N8.00005 Towards a Quantum Memory assisted MDI-QKD node, MEHDI NAMAZI, Stony Brook University, GIUSEPPE VALLONE, University of Padova, BERTUS JORDAAN, CONNOR GOHAM, REIHAANEH SHAHROKHSHAHI, Stony Brook University, PAOLO VILLORESI, University of Padova, EDEN FIGUEROA, Stony Brook University. The creation of large quantum network that permits the communication of quantum states and the secure distribution of cryptographic keys requires multiple operational quantum memories. In this work we present our progress towards building a prototypical quantum network that performs the memory-assisted measurement device independent QKD protocol [1,2]. Currently our network combines the quantum part of the BB84 protocol with room-temperature quantum memory operation, while still maintaining relevant quantum bit error rates for single-photon level operation [3]. We will also discuss our efforts to use a network of two room temperature quantum memories, receiving, storing and transforming randomly polarized photons in order to realize Bell state measurements. [1] New Journal of Physics 16, 043005 (2014) [2] Phys. Rev. A 89, 012301 (2014) [3] arXiv:1609.08676

11:30AM N8.00006 Enhanced photon indistinguishability in pulse-driven quantum emitters, HERBERT F FOTSO, University at Albany SUNY — Photon indistinguishability is an essential ingredient for the realization of scalable quantum networks. For quantum bits in the solid state, this is hindered by spectral diffusion[1, 2], the uncontrolled random drift of the emission/absorption spectrum as a result of fluctuations in the emitter’s environment. We study optical properties of a quantum emitter in the solid state when it is driven by a periodic sequence of optical pulses with finite detuning with respect to the emitter. We find that a pulse sequence can effectively mitigate spectral diffusion and enhance the photon indistinguishability. The bulk of the emission occurs at a set target frequency[3]. Photon indistinguishability is enhanced and is restored to its optimal value after every even pulse. Also, for moderate values of the sequence period and of the detuning, both the emission spectrum and the absorption spectrum have lineshapes with little dependence on the detuning. We describe the solution and the evolution of the emission/absorption spectrum as a function time. [1] K.-M. Fu et al, PRL 103, 256404 (2009); V. M. Acosta et al, PRL 108, 206401 (2012). [2] S. Yang et al, Nat. Photonics 10, 507 (2016); N. Trautmann and G. Alber, Phys. Rev. A 93, 053807 (2016). [3] H. F. Fotso et al, PRL 116, 033603 (2016).

11:42AM N8.00007 Phase-tuned entangled state generation between distant spin qubits, CLEMENS MATTHIESEN, University of California, Berkeley, ROBERT STOCKILL, MEGAN STANLEY, LUKAS HUTHMACHER, CLAIRE LE GALL, METE ATATÜRE, University of Cambridge — Entanglement is the central resource in quantum information processing, sensing and communication. Distribution of entanglement through non-local interactions, using photon interference and detection, is an attractive feature of flexible computation architectures where spatially separate nodes are locally controlled and connected via photonic channels. I will present recent work from the Atatüre group in Cambridge on the generation of entangled states between two electron spins confined in optically active indium-gallium-arsenide (InGaAs) quantum dots situated metres apart. The combination of a minimal single-photon state-projection scheme and the strong coherent light-matter interaction in these systems enables a distant entanglement rate of 7.3 kHz, the highest reported to date. With full control over the single-photon interference, we demonstrate the creation of entangled states with arbitrary phase.
11:54AM N8.00008 Correlation in photon pairs generated using four-wave mixing in a cold atomic ensemble1, ANDREW RICHARD FERDINAND, Center for Quantum Information and Control, University of New Mexico, ALEJANDRO MANJAVacas, University of New Mexico, FRANCISCO ELOHIM BECERRA, Center for Quantum Information and Control, University of New Mexico — Spontaneous four-wave mixing (FWM) in atomic ensembles can be used to generate narrowband entangled photon pairs at or near atomic resonances. While extensive research has been done to investigate the quantum correlations in the time and polarization of such photon pairs, the study of high dimensional quantum correlations contained in their spatial degrees of freedom has not been fully explored. In our work we experimentally investigate the generation of correlated light from FWM in a cold ensemble of cesium atoms as a function of the frequencies of the pump fields in the FWM process. In addition, we theoretically study the spatial correlations of the photon pairs generated in the FWM process, specifically the joint distribution of their orbital angular momentum (OAM). We investigate the width of the distribution of the OAM modes, known as the spiral bandwidth, and the purity of OAM correlations as a function of the properties of the pump fields, collected photons, and the atomic ensemble. These studies will guide experiments involving high dimensional entanglement of photons generated from this FWM process and OAM-based quantum communication with atomic ensembles.

1This work is supported by AFOSR grant FA9550-14-1-0300

12:06PM N8.00009 Generation of subnatural-linewidth biphotons from a hot rubidium atomic vapor cell1, LINGBANG ZHU, CHI SHU, XIANXIN GUO, PENG CHEN, Department of Physics, Hong Kong University of Science and Technology, YANHONG XIAO, Department of Physics, Fudan University, HEEJEONG JEONG, SHENGWANG DU, Department of Physics, Hong Kong University of Science and Technology — We report the generation of narrowband entangled photon pairs (biphotons) from a hot atomic vapor cell. Making use of backward spontaneous four-wave mixing with electromagnetically induced transparency (EIT), we produced subnatural-linewidth (1.9 MHz to 6 MHz) biphotons from a Doppler-broadened (0.5 GHz) hot (63 C) paraffin-coated rubidium 87 vapor cell. The biphoton coherence time is controllable and can be tuned up to 100 ns by EIT. The uncorrelated photons from resonance Raman scattering are suppressed by a spatially separated and tailored optical pumping beam. The spectral brightness is as high as 14,000 s^{-1} MHz^{-1}. As compared with the cold-atom experiment, the hot atomic vapour cell configuration is much simpler for operation and maintenance, and it is a continuous biphoton source. Our demonstration may lead to miniature narrowband biphoton sources based on atomic vapour cells for practical quantum applications and engineering.

1The work was supported by Hong Kong Research Grants Council (Project No. 16301214), and in part by the CAS/SAFEA International Partnership Program for Creative Research Teams. L.Z. acknowledges support from the Undergraduate Research Opportunities Program University, USA.

12:18PM N8.00010 Room-temperature solid-state single-photon source with purity and controllable waveforms, CHUN-YUAN CHENG, SHIH-WEN FENG, CHEN-YEH WEI, JIYEN-RU CHEN, YA-WEN CHUANG, YANG-HSIUNG PAN, CHIH-SUNG CHU, Natl Tsing Hua Univ — Single photon generation has emerged as an essential and indispensable to photonic quantum technologies. Here we demonstrate a room-temperature quantum-dot-based source of single photons with purity of 99% and control-lable waveforms. We show that the high purity of the single photons does not vary with excitation power and that the emitted photons can be tuned over different samples. The waveform-controlled single photons also have potential applications of optimum quantum state transfer in networks, high-efficiency quantum storage and retrieval of single photons, or quantum key distribution with high key creation rates.

Thursday, June 8, 2017 10:30AM - 12:30PM –
Session N9 Excitations in Degenerate Quantum Gases 315 -

10:30AM N9.00001 Can a supersonically expanding Bose-Einstein Condensates be used to study cosmological inflation? , SWARNAV BANIK, STEPHEN ECKEL, AVINASH KUMAR, TED JACOBSON, IAN SPIELMAN, GRETCHEN CAMPBELL, Univ of Maryland-College Park — The massive scale of the universe makes the experimental study of cosmological inflation difficult. This has led to an interest in developing analogous systems using table top experiments. Here, we present the basic features of an expanding universe by drawing parallels with an expanding toroidal Bose Einstein Condensate (BEC) of 23Na atoms. The toroidal BEC serves as the background vacuum and phonons are the analogue to photons in the expanding universe. We study the dynamics of phonons in both non-expanding and expanding condensates and measure dissipation using the structure factor. We demonstrate red shifting of phonons and quasi-particle production similar to pre-heating after the inflation of universe. At the end of expansion, we also observe spontaneous non-zero winding numbers in the ring. Using Monte-Carlo simulations, we predict the widths of the resulting winding number distribution, which agree well with our experimental findings.

10:42AM N9.00002 Nonequilibrium quantum dynamics of partial symmetry breaking for a vortex state of ultracold bosons in a ring trap1, XINXIN ZHAO, Peking University, and Colorado School of Mines, MARIE A. MCLAIRN, Colorado School of Mines, JAVIER VIJANDE, Universidad de Valencia (UV) and IFIC (UV-CSIC), ALBERT FERRANDO, Universitat de Valencia, LINCOLN D. CARR, Colorado School of Mines, and Universitat Heidelberg, MIGUEL A. GARCIA, Colorado School of Mines, and Universitat de Barcelona — One common subject for an isolated system is the memory of the system's initial state. Here we investigate a vortex in a Bose-Einstein condensate on an optical ring lattice in response to partial symmetry breaking. Bosons are originally trapped in a discrete ring trap with six sites and periodic boundary conditions, whose six-fold rotational symmetry is suddenly broken but retains a three-fold rotational symmetry. During real time evolution, no critical behavior is manifested in the system’s microscopic and macroscopic features, fidelity and total current. Instead, a critical point at which the system forgets its initial symmetry state is well characterized by a new measurement, symmetry memory. Similar critical phenomena are equally discovered in larger systems, which makes it pervasive in this type of partial symmetry breaking. Further studies uncover a physical understanding of the two typical trends of critical symmetry breaking strength with the help of a newly identified energy gap in the low-lying excited states identified by its discrete rotational symmetry properties.

1NSF, AFOSR, AvH Foundation, and CSC
10:54AM N9.00003 Dissipative hydrodynamics in a quantum-fluid piston shock1. MAREN MOSSMAN, Washington State Univ, MARK HÖEFER, University of Colorado, Boulder, P. G. KEVREKIDIS, University of Massachusetts, Amherst, PETER ENGELS, Washington State Univ — Dilute-gas Bose-Einstein condensates are effective systems for modelling and analyzing quantum hydrodynamic behavior. Recently, much emphasis has been placed on the study of quantum turbulence in these systems. We discuss theoretical, numerical and experimental results of a prototypical piston shock experiment in which a repulsive barrier is driven through a Bose-Einstein condensate. We show that under appropriate conditions the behavior is that of a dissipative rather than that of a dispersive system. Effective dissipation can be generated by the emergence of a turbulent bulge in the BEC. Experimental results are accompanied by detailed numerical simulations for the parameters of the experiment. Current status and future directions of the experiment will be discussed.

1We gratefully acknowledge funding from the NSF.

11:06AM N9.00004 Atom loss in a matter-wave soliton train, RICK MUKHERJEE, KADEN R. A. HAZZARD, Rice University — Solitons are localized perturbations that propagate and collide without distortion, which appear in integrable models. One such notable model is the Gross-Pitaevskii equation realized in Bose-Einstein condensates (BEC), which allow one to control the model parameters and tuneably break integrability. One approach to forming solitons in a BEC is to sweep the interaction strength to a negative value, forming a train of ~ 10 matter-wave solitons. Even though this was realized in a BEC over a decade ago, questions remain about details of their formation and decay. For example, which properties are manifestations of the physics of single solitons, and which arise from inter-soliton interactions? Recent experiments at Rice University find surprising behavior in the atom loss after an interaction quench. To understand the atom loss mechanism better, we numerically solve the Gross-Pitaevskii equation including dissipation. We compare these results to simpler analytic models that include the effects of dissipation in simplified manners, for example including the effect of dissipation by a rate equation. We find that some aspects of the non-trivial behavior of the number of atoms can be captured by simple models of single soliton physics.

11:18AM N9.00005 Damping of Collective Oscillations in a Box Trap1, NICK PROUKAKIS, KEAN LOON LEE, Joint Quantum Centre (JQC) Durham-Newcastle, Newcastle Univ., UK, EUGENE ZAREMBA, Queen’s Univ., Kingston, Canada, PATRIK TURZAK, CHRIS EIGEN, ALEX GAUNT, ROB SMITH, ZORAN HADZIBABIC, NUR NAVID, Cavendish Laboratory, Univ. of Cambridge, UK — We model numerically the lowest-lying collective mode of a Bose gas in a box trap excited by a kick in the potential, as in a Bose-Einstein condensate experiment. Our analysis is performed at finite temperatures (below the critical region), based on the so-called ZNG model, in which the condensate is described by a dissipative Gross-Pitaevskii equation which is self-consistently coupled to a dynamical thermal cloud described by a quantum Boltzmann equation, which is proved most successful in describing damping observed in harmonic traps. For typical parameters probed far from the hydrodynamic region, we find a single oscillation — whose frequency agrees well with experiments — with the thermal cloud rapidly damping out higher self-consistently modes. Our results are confirmed by an independent analysis with the stochastic projected Gross-Pitaevskii equation. Intuitively, we find damping in a box trap to depend much more weakly on temperature than in harmonic traps, in broad agreement with experimental data.

1EPSRC; NSERC; ERC; Royal Society

11:30AM N9.00006 Dynamics and Interaction of Quantized Vortex Lines in Trapped Bose–Einstein Condensates, FRANCO DALFOVO, SIMONE SERAFINI, ELENA ISEN, TOM BIENAIMÉ, RUSSELL N. BISSET, GIACOMO LAMPORESI, GABRIELE FERRARI, INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, 38123 Trento, Italy, LUCA GALANTUCCI, CARLO F. BARENGHI, JQC Durham–Newcastle, and School of Mathematics and Statistics, Newcastle Univ., Newcastle upon Tyne, NE1 7RU, UK — We report experimental and numerical observations of the dynamics and the interaction of 3D quantum vortex filaments in a cigar-shaped atomic Bose–Einstein condensate. Vortices are spontaneously created by the Kibble-Zurek mechanism by quenching the system across the BEC transition. We then use an innovative imaging technique which exploits self-interference effects of out-coupled atoms in order to extract both the position and orientation of vortex lines from a temporal sequence of absorption images. We combine experiments and numerical Gross–Pitaevskii simulations to study the interaction between two vortices approaching at various relative speeds and angles. We show that the interaction between vortex lines in a finite system is rather different from the one in infinite uniform superfluids. In particular, the presence of boundaries induce new effects, such as rebounds, double reconnections, and ejections. These processes may play an important role in the dynamics of trapped condensates in multi-vortex and turbulent-like configurations, and, on a wider perspective, they can represent novel keys for better understanding the behavior of superfluids near boundaries.

11:42AM N9.00007 Spatiotemporal optical vortices1, NIHAL JHAIJ, ILIA LARKIN, ERIC ROSENTHAL, SINI ZAHEDPOUR, JARED WAHLSTRAND, HOWARD MILCHBERG, University of Maryland — We present the first experimental evidence, supported by theory and simulation, of spatiotemporal optical vortices (STOVs). A STOV is an optical vortex with phase and energy circulation in a spatiotemporal plane. Depending on the sign of the material dispersion, the local electromagnetic energy flow is saddle or spiral about the vortex. STOVs are shown to be a fundamental element of the nonlinear collapse and subsequent propagation of short optical pulses in material media. STOVs conserve topological charge, constraining their birth, evolution, and annihilation. We measure a self-generated STOV consisting of a ring-shaped null in the electromagnetic field about which the phase is spiral, forming a dynamic torus that is concentric with and tracks the propagating pulse. Our results, here obtained for optical pulse collapse and filamentation in air, are generalizable to a broad class of nonlinearly propagating waves.

1Supported by NSF grant PHY-1413768 and ARO Atomtronics MURI

11:54AM N9.00008 Quantum turbulence in a “racetrack” atomtronic circuit1, MARK EDWARDS, BENJAMIN ELLER, OLETUNDE OLADEHIN, Georgia Southern University, CHARLES CLARK, Joint Quantum Institute — We have studied the flow produced by stirring an ultracold atomtronic system consisting of a gaseous Bose–Einstein condensate (BEC) confined in a “racetrack” potential. The BEC is assumed to be strongly confined in a horizontal plane by a vertical harmonic trap, and, within this plane, subjected to an arbitrary two-dimensional potential. The racetrack potential is made up of two straight parallel channels connected on both ends by semicircular channels of the same width and (energy) depth as the straightaways. The Gross–Pitaevskii equation was used to simulate the behavior of the BEC in this potential when stirred by rotating paddles of various shapes including ellipses and rectangles. The rich variety of topological excitations produced during the stirring was studied by looking at the optical density, momentum distribution, velocity field and the vorticity. The momentum spectrum was studied for the development and presence of scalings indicative of quantum turbulence. Here we also report the type and number of excitations and effect of racetrack shape on their behavior.

1Supported by NSF grant PHY-1413768 and ARO Atomtronics MURI
12:06PM N9.00009 Thermally activated phase slips of a Bose-Einstein condensate in a ring trap , MASAYA KUNIMI, IPPEI DANSHTA, Yukawa Institute for Theoretical Physics, Kyoto University — Recently, the NIST group has experimentally measured the lifetime of the superflow of Bose-Einstein condensates in ring traps and found that it significantly depends on the temperature [1]. If the superflow decays dominantly due to thermally activated phase slips(TAPS), the lifetime is expected to obey the Arrhenius law. They argued that the measured lifetime is inconsistent with the Arrhenius law. However, their estimation of the energy barrier, which determines a dominant contribution to the temperature dependence of the lifetime, is not quantitatively accurate so that more profound theoretical analyses are needed in order to examine the possibility of the superflow decay via TAPS. In this work, we quantitatively calculate the lifetime of the superflow due to TAPS by the Kramers formula combined with the mean-filed theory [2,3]. Recently, this formalism has been successfully applied to explaining the experiments of the damping of dipole oscillations of 1D Bose gases in optical lattices [4], in terms of TAPS [3]. We will compare our results with the NIST experiment. [1] A. Kumar, et al., arXiv:1608.02894. [2] J. S. Langer and V. Ambegaokar, Phys. Rev. 164, 498 (1967). [3] M. Kunimi and I. Danshita, arXiv:1610.08982. [4] L. Tanzi et al., Sci. Rep. 6, 25965 (2016).

12:18PM N9.00010 Signatures of two-step impurity mediated vortex lattice melting in Bose-Einstein condensate1 , BISHWAJYOTI DEY, Department of Physics, SP Pune University, Pune 411007, India. — We study impurity mediated vortex lattice melting in a rotating two-dimensional Bose-Einstein condensate (BEC). Impurities are introduced either through a protocol in which vortex lattice is produced in an impurity potential or first creating the vortex lattice in the absence of random pinning and then cranking up the impurity potential. These two protocols have obvious relation with the two commonly known protocols of creating vortex lattice in a type-II superconductor: zero field cooling protocol and the field cooling protocol respectively. Time-splitting Crank-Nicolson method has been used to numerically simulate the vortex lattice dynamics. It is shown that the vortex lattice follows a two-step melting via loss of positional and orientational order. This vortex lattice melting process in BEC closely mimics the recently observed two-step melting of vortex matter in weakly pinned type-II superconductor Co-intercalated NbSe2. Also, using numerical perturbation analysis, we compare between the states obtained in two protocols and show that the vortex lattice states are metastable and more disordered when impurities are introduced after the formation of an ordered vortex lattice.

1 The author would like to thank SERB, Govt. of India and BCUD-SPPU for financial support through research grants.

Thursday, June 8, 2017 2:00PM - 4:00PM —
Session P2 Novel Magnetism

2:00PM P2.00001 Magnetic Correlations in Cold Atomic Systems , LODE POLLET, LMU Munich — Magnetic correlations have recently been measured experimentally in cold atomic systems. These stretch over the entire system size fitting under the fermionic microscope realizing Heisenberg antiferromagnetism and constitute one of the greatest developments in recent years in this field. In the first part of the talk I review the experiment performed in the Bloch/Gross group by M. Boll et al (Science 353, Iss 6305, p. 1257 (2016)) on Hubbard chains, demonstrating a simultaneous measurement of spin and charge. Correlations up to three sites have been discerned, allowing to extract an entropy density not greater than 0.5. I briefly comment on recent developments by this team. In the second part I move on to the two-dimensional case. The establishment of an antiferromagnetic Heisenberg phase in the Greiner lab (A. Mazurenko et al, arXiv:1612.08436) paves the way to study open questions in the doped regime. Finally, I discuss the challenges to study FFLO instabilities (J. Guenberger et al, Phys. Rev. B 94, 075157 (2016)) for Hubbard systems with population imbalance as well as p-wave superfluidity by spin-nematic Fermi surface deformations (J. Guenberger et al, Phys. Rev. Lett. 113, 195301 (2014) and Ising antiferromagnetic transitions in explicitly $SU(2)$ broken Hubbard models.

2:30PM P2.00002 One-dimensional Fermi gases with odd-wave interaction , XIAOLING CUI, Institute of Physics, Chinese Academy of Sciences — In this talk, I will discuss the intriguing physics induced by odd-wave interaction in one-dimensional(1D) Fermi gases. First, I will show that by applying a weak odd-wave attraction (or repulsion), the long-sought magnetic orders of itinerant Ferromagnetism (or Neel anti-ferromagnetism) can be conveniently engineered in the strongly interacting spin-1/2 trapped Fermi gas. Second, I will show that a spinless Fermi gas near odd-wave resonance and confined in optical lattices can be a promising system to realize the Kitaev chain model. By exactly solving the two-body problem we have established an effective lattice model for lowest-band fermions, which paves the way for quantum simulating Majorana fermions in 1D atomic systems.

3:00PM P2.00003 Photonic Landau Levels in Curved Space , JONATHAN SIMON, University of Chicago — I will present recent work realizing topological phases of photons in curved space. The talk will focus on our recent exploration of Landau levels on a conical surface, generated using a non-planar (twisted) optical resonator to induce a synthetic magnetic field for optical photons, and employed to validate the Wen-Zee action describing the interplay of manifold curvature and magnetic fields. I will then describe experiments demonstrating interactions between individual resonator photons mediated by cavity Rydberg electromagnetically induced transparency (cReit). I will conclude with an outlook on marrying twisted resonators and cReit to assemble topological few-body states either photon-by-photon or through engineered photonic thermalizers. This work showcases the unique possibilities for Hamiltonian engineering and control in the photonic sector, a provides a taste of ongoing and upcoming breakthroughs in photonic quantum materials.

3:30PM P2.00004 Quantum simulation of the 2D Hubbard model , MICHAEL KOEHL, University of Bonn — We experimentally study the emergence of antiferromagnetic correlations between ultracold fermionic atoms in a two dimensional optical lattice with decreasing temperature. We determine the uniform magnetic susceptibility of the two-dimensional Hubbard model from simultaneous measurements of the in-situ density distribution of both spin components. At half filling and strong interactions our data approach the Heisenberg model of localized spins with antiferromagnetic correlations. Furthermore, we study quantum criticality in the two-dimensional Hubbard model, observe universal scaling, and find the dynamical critical exponent of the metal-insulator transition.

Thursday, June 8, 2017 2:00PM - 4:00PM —
Session P3 Rydberg Molecules and Polarons

308 - Tom Killian, Rice University
2:00PM P3.00001 Macrodimers and Long-Range Rydberg Molecules

JOHANNES DEIGLMAYR, ETH Zurich — The large polarizability of atoms in highly excited states, so-called Rydberg states, leads to strong and long-ranging interactions between such atoms. Interacting pairs of Rydberg atoms represent a very exotic molecular system, characterized by high internal excitation, high density of electronic states, internuclear separations exceeding one micrometer, and lifetimes beyond tens of microseconds. I will discuss the computational methods we have developed to determine the electronic structure of interacting Rydberg-atom pairs [1] and our spectroscopic approaches to verify these calculations. Recently, we could observe the formation of macrodimers, vibrational bound states of two interacting Rydberg atoms, which were predicted in 2002 by Boisseau and coworkers [2,3]. I will discuss the employed sequential photoassociation scheme and the validity of the Born-Oppenheimer approximation for these states. In an extended outlook, I will discuss our current and planned experiments towards determining electron-atom-scattering phase shifts from high-resolution spectroscopy of another class of exotic molecules, long-range Rydberg molecules where a Rydberg atom and a ground-state atom located inside the Rydberg orbit are bound to each other [4].


1This work was supported by ETH Zurich under Research Grant ETH-22 15-1

2:30PM P3.00002 Creation of Rydberg Polarons in a Bose Gas

RICHARD SCHMIDT, Harvard University — In this talk we review the theory of various types of Bose polarons that can be realized in ultracold atomic systems. We then report the spectroscopic observation of Rydberg polarons in a Bose gas which is in excellent agreement with theoretical predictions [1]. This novel type of polaron is created by excitation of Rydberg atoms in a strontium Bose-Einstein condensate and it is distinguished by the occupation of a large number bound molecular states [2]. The cross-over from few-body bound molecular oligomers to many-body polaron features is described with a functional determinant theory that solves an extended Froehlich Hamiltonian for an impurity in a Bose gas. The detailed analysis of the red-detuned tail of the excitation spectrum describes the contribution from the region of highest density in the condensate and provides a clear signature of Rydberg polarons. This work [1] has been performed in collaboration with groups at Rice University, Harvard University, and the TU Vienna.

References:

3:00PM P3.00003 Observation of spin-dependent relativistic effects in ultra-long-range Cs$_2$ Rydberg molecules

JIN YANG, University of Oklahoma, SAMUEL MARKSON, ITAMP, Harvard-Smithsonian Center for Astrophysics, SETH RITTENHOUSE, The United States Naval Academy, RICHARD SCHMIDT, HOSSEIN SADEGHPOUR, ITAMP, Harvard-Smithsonian Center for Astrophysics, JAMES SHAFFER, University of Oklahoma — Recent research reveals spin-dependent relativistic effects play a significant role in the structure of ultra-long-range Rydberg molecules formed by the scattering of an electron from a ground state atom. Spin-dependent relativistic effects lead to striking features in the spectra of these molecules, like mixing between singlet and triplet states. To give a more precise prediction of the spectra, spin-orbit coupling and hyperfine interactions have to be considered. These effects are particularly important for Cs because several prominent, low energy p-wave resonances exist in the electron-ground state atom scattering and cause avoided crossings to occur. We use a Hamiltonian that includes spin-dependent interactions between the Rydberg electron and ground state atoms, to reproduce experimentally measured Cs ultra-long-range Rydberg molecule spectra correlating to the 31D+6S, 32D+6S, 38D+6S and 39D+6S asymptotes. Good agreement is found between theory and experiment. New, interesting features in the spectra can be related to the corresponding spin-dependent relativistic effects.

1We acknowledge funding from the NSF.

3:12PM P3.00004 Anisotropic blockade using pendular Rydberg butterfly molecules

MATTHEW EILES, JESUS PEREZ-RIOS, HYUNWOO LEE, CHRIS GREENE, Purdue University Department of Physics and Astronomy — The photoassociation spectrum of “butterfly” Rydberg molecules in a weak electric field has been recently observed, revealing that these molecules are, due to their dipole moments and bond lengths, deep in the pendular regime even at small field strengths (1 V/cm) [3,4]. Their properties — excellent field alignment and orientation, extended charge distributions, and the parameter tunability determined by the Rydberg state — make these molecules ideal candidates for exploring many-body physics in dipolar gases. We have calculated the long-range interaction between molecules prepared in a quasi-one-dimensional trap; this interaction is dominated at long range by the anisotropic dipole-dipole force. By varying the angle between the applied field and the trap axis, this contribution can be tuned to zero at the magic angle, which presents a clear experimental signature in the density of Rydberg molecules which rises sharply near the magic angle due to the anisotropic excitation “blockade” mechanism. Verification of these interactions through this straightforward experimental scheme will encourage the use of these molecules to study polaron physics in a mixed system, angulon/pendulon interactions, or crystal phase formation.


1This work was supported by ETH Zurich under Research Grant ETH-22 15-1

3:24PM P3.00005 Progress towards long-range Rydberg molecules with $^{87}$Sr

ROGER DING, JOSEPH WHALEN, FRANCISCO CAMARGO, F. BARRY DUNNING, THOMAS KILLIAN, Rice University — Many recent experiments have probed the interactions between highly-excited Rydberg atoms and nearby ground state atoms, allowing the study of a wide range of phenomena such as few-body, long-range Rydberg molecules in thermal gases [5,6] and many-body effects in Bose-Einstein condensates [7,8] . These experiments have exclusively been performed with bosons. We report our results working with the fermionic isotope $^{85}$Sr ($I = 9/2$) with which one can hope to see modified molecular structure and suppression of short-range collisional loss due to the Pauli exclusion principle. We will describe the spectra for two-photon excitation to the $5sns^3S_1$ Rydberg state from a spin-polarized sample and our progress towards obtaining Rydberg molecular spectra.

1Research supported by the AFOSR, the NSF, and the Robert A. Welch Foundation.

Free-space microwave-to-optical conversion via six-wave mixing in Rydberg atoms$^1$. JINGSHAN HAN, THIBAULT VOGT, CHRISTIAN GROSS, Center for Quantum Technologies, National University of Singapore, DIETER JAKSCH, Clarendon Laboratory, University of Oxford, MARTIN KIFFNER, WENHUI LI, Center for Quantum Technologies, National University of Singapore — The interconversion of millimeter waves and optical fields is an important and highly topical subject for classical and quantum technologies. In this talk, we report an experimental demonstration of coherent and efficient microwave-to-optical conversion in free space via six-wave mixing in Rydberg atoms$^2$. Our scheme utilizes the strong coupling of millimeter waves to Rydberg atoms as well as the frequency mixing based on electromagnetically induced transparency (EIT) that greatly enhances the nonlinearity for the conversion process. We achieve a free-space conversion efficiency of 0.25% with a bandwidth of about 4 MHz in our experiment. Optimized geometry and energy level configurations should enable the broadband interconversion of microwave and optical fields with near-unity efficiency. These results forecast the tremendous potential of Rydberg atoms for the efficient conversion between microwave and optical fields, and thus pave the way to many applications.

$^1$This work is supported by Singapore Ministry of Education Academic Research Fund Tier 2 (Grant No. MOE2015-T2-1-085).

2:48PM P4.00005 Characterization of a cryogenic buffer-gas beam using matrix isolation infrared spectroscopy, CAMERON J. E. STRAATSMA, MAYA I. FABRIKANT, HEATHER J. LEWANDOWSKI, JILA, University of Colorado — Cryogenic buffer-gas beams have many advantages over traditional supersonic jet sources including the ability to produce intense beams of exotic molecular clusters and radicals. We report on the characterization of a cryogenic buffer-gas beam used as a source of cold molecules in a matrix isolation Fourier transform infrared spectroscopy experiment. Using laser ablation of a solid target inside a buffer-gas cell, carbon clusters are produced, cooled, and entrained in a cryogenic beam of neon gas. This beam is directed towards an IR transparent window where it freezes, effectively trapping the molecules in a solid, inert matrix from which vibrational modes in the range of 800 cm$^{-1}$ to 4000 cm$^{-1}$ can be investigated. In addition to the characterization of our apparatus with carbon clusters, we report on efforts to investigate transition metal oxide molecules (i.e. VO) as well as cold chemical reactions involving CH.

3:00PM P4.00006 Continuous all-optical deceleration of molecular beams and demonstration with Rb atoms, XUEPING LONG, Univ of California - Los Angeles, ANDREW JAYICH, Univ of California - Santa Barbara, WESLEY CAMPBELL, Univ of California - Los Angeles — Ultracold samples of molecules are desirable for a variety of applications, such as many-body physics, precision measurement and quantum information science. However, the pursuit of ultracold molecules has achieved limited success: spontaneous emission into many different dark states makes it hard to optically decelerate molecules to trappable speed. We propose to address this problem with a general optical deceleration technique that exploits a pump-dump pulse pair from a mode-locked laser. A molecular beam is first excited by a counter-propagating “pump” pulse. The molecule then decays back to the initial ground state by a co-propagating “dump” pulse via stimulated emission. The delay between the pump and dump pulse is set to be shorter than the excited state lifetimes in order to limit decays to dark states. We report progress benchmarking this stimulated force by accelerating a cold sample of neutral Rb atoms.

3:12PM P4.00007 Quantum-state controlled radical-ion reactions, HEATHER LEWANDOWSKI, PHILIPP SCHMID, JAMES GREENBERG, MIKHAIL (KYLE) MILLER, University of Colorado / JILA — Radicals and ions frequently play an important role in gaseous media such as the Interstellar Medium (ISM), the upper atmosphere, flames, plasmas, etc. Although collisions in the ISM between ions and radicals are very rare events, the long timescales involved mean such reactions make important contributions to the pathways for assembly and destruction of complex chemical species. Unfortunately, experimental measurements of the rates and particularly the dynamics of reactions between ions and radicals are very few and far between. Our system overcomes some of the experimental challenges by using trapped molecular ions and Stark decelerated neutral radicals. Here, we can study reactions between molecules in single quantum states down to millikelvin temperatures. Our very high sensitivity allows us to study reactions where the reaction rate can be as low as one reaction per minute.

3:24PM P4.00008 Rovibronic spectroscopy of sympathetically cooled $^{40}$CaH$^+$, AARON CALVIN, SMITHA JANARDAN, JOHN CONDOLUCI, RENE RUGANGCO, School of Chemistry and Biochemistry, Georgia Institute of Technology, ERIC PRETZSCH, School of Physics, Georgia Institute of Technology, GANG SHU, School of Chemistry and Biochemistry, Georgia Institute of Technology, KENNETH BROWN, School of Chemistry and Biochemistry; Physics; Computational Science and Engineering, Georgia Institute of Technology — CaH$^+$ is an astrophysically relevant molecule with proposed applications in fundamental physics. We use CaH$^+$ co-trapped with Doppler cooled Ca$^+$ to perform spectroscopy using two photon photodissociation with a frequency doubled mode locked Ti:Sapphire laser. This method was used to measure the vibronic spectrum of the $1\Sigma, v = 0 \rightarrow 2\Sigma, v' = 0, 1, 2, 3$ transition. Measurements of the same transition with the deuterated isotopologue confirmed the assignment and showed an 687 cm$^{-1}$ mismatch with theory. The broad bandwidth of the pulsed Ti:sapphire provided an advantage for the initial search for transitions, but did not allow spectral resolution of rotational transitions. Here, we use femtosecond pulse shaping to spectrally narrow the linewidth of the femtosecond laser. This allowed us to obtain rotational constants for the $2\Sigma, v'' = 0, 1, 2, 3$ and $1\Sigma, v = 0$ states.

2 J. Condoluci, et al. article in preparation
3 A. Calvin, et al. article in preparation

3:36PM P4.00009 Achieving Single-Molecule Spectroscopy with Fast State Regeneration, VINCENT CARRAT, MARK G. KOKISH, BRIAN C ODOM, Northwestern University — Single atomic or molecular ions provide well-isolated systems suitable for high-precision spectroscopy, but require a large number of measurements in order to probe fundamental physics. However, this drawback can be mitigated by implementing high repetition rates using fast optical state preparation techniques. To implement a trap for molecular ions, we need a method to implement for molecules. Following our previous demonstration of optical rovibrational cooling, we report our progress toward demonstrating fast rovibrational spectroscopy of a single $^{1}A^{2}I^{+}$ ion. Adapting the recipe from quantum logic spectroscopy, we co-trap a single $^{1}A^{2}I^{+}$ ion alongside a $^{1}B^2\Sigma$ ion. $^{3}B^2\Sigma$ serves as a coolant ion for ground motional state preparation and a means to detect the internal state of $^{1}A^{2}I^{+}$. The internal state of $^{1}A^{2}I^{+}$ can be transferred to $^{3}B^2\Sigma$ through a series of momentum kicks induced by multiple absorption events, a process made possible by the highly diagonal Franck-Condon factors in $^{1}A^{2}I^{+}$. After state readout, $^{1}A^{2}I^{+}$ can then be returned to its ground rovibrational state via optical pumping for the next measurement. Since we are relying on fast optical manipulations, we aim to reach a repetition rate of at least several Hertz.

1Supported by AFOSR Grant No. FA9550-13-1-0116, NSF Grant No. PHY-1404455, and NSF GRFP DGE-1324585

3:48PM P4.00010 Coherent control and preparation of pure quantum states of a single molecular ion, CHRISTOPH KURZ, CHIN-WEN CHOU, DAVID B. HUME, Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA, PHILIPP N. PLESSOW, Institute of Catalysis Research and Technology, Karlsruhe Institute of Technology, Karlsruhe, Germany, DAVID R. LEIBRANDT, DIETRICH LEIBFRIED, Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA — We demonstrate control of individual molecules based on quantum-logic spectroscopy [1, 2]. In our experiment, we drive the motional sidebands of Raman transitions in a molecular ion and probe the secular motion with a co-trapped atomic ion. Detection of motional excitation projects the molecule into a pure internal state. The state of the molecule can subsequently be coherently manipulated, as demonstrated by Rabi oscillations between magnetic sublevels of rotational states. We need only one far off-resonant continuous-wave laser to manipulate the molecule. This makes our approach applicable to coherent control and precision measurement of a vast class of molecular ions.


1This work was supported by the U.S. Army Research Office and the NIST quantum information program. C. Kurz acknowledges support from the Alexander von Humboldt foundation.
2:00PM P5.00001 Quench dynamics of a spinor condensate with strong spin-dependent interactions, HIL F H CHEUNG, YOGESH S PATIL, MUKUND VENKATTORE, Cornell University — Spinor condensates exhibit a rich phase diagram of magnetically ordered phases arising from the interplay between spin-dependent interactions and superfluidity. The spinor condensates studied to date (23Rb and 23Na) exhibit weak spin-dependent interactions with little coupling between the spin (magnon) excitations and the mass (phonon) excitations. In contrast, the F=1 spinor condensates of 7Li exhibit commensurate strengths of spin-dependent and spin-independent interactions, leading to qualitative changes in the equilibrium phases and spinor dynamics. We describe the quench dynamics of a 7Li spinor gas between a spin nematic and ferromagnetic phase, discuss the emergent ferromagnetic spin texture and topological defects in accordance with the Kibble-Zurek mechanism and contrast this behavior with that observed in weakly interacting spinor condensates such as 87Rb.

2:12PM P5.00002 Quantum Interferometry with Microwave-dressed F=1 Spinor Bose-Einstein Condensates: Role of Initial States and Long Time Evolution, QIMIN ZHANG, ARNE SCHWETTMANN, Unv of Oklahoma, EITE TIESINGA, Joint Quantum Institute, NIST and the University of Maryland — We numerically investigate atom interferometry based on spin-exchange collisions in F = 1 spinor Bose-Einstein condensates in the regime where both the truncated Wigner and the Bogoliubov approximations break down. The interferometer promises to beat the shot-noise limit even in the case of large atom-number population in the arms of the interferometer. Spin-exchange collisions in F = 1 spinor Bose-Einstein condensates, where two atoms with magnetic quantum number mF = 0 collide and change into a pair with mF = ±1, are useful to implement matter-wave quantum optics in spin space, such as quantum-enhanced interferometry, because the collisions generate entanglement and they can be precisely controlled using microwave dressing. Here, we show numerically that the sensitivity of spin-mixing interferometry can be enhanced to go beyond quantum optics in spin space, such as quantum-enhanced interferometry, because the collisions generate entanglement and they can be precisely controlled using microwave dressing. We also discuss a good agreement between our data and the mean field theory, and two applications of spin singlets in quantum information science.

2:24PM P5.00003 Efficient production of spin singlets in lattice-confined spinor condensates1, LICHAO ZHAO, ZIHE CHEN, TAO TANG, YINGMEI LIU, Department of Physics, Oklahoma State University — We present an efficient experimental scheme for a production of spin singlets in an antiferromagnetic spinor condensate confined by a cubic optical lattice. Via two independent detection methods, we demonstrate that about 80 percent of atoms in the lattice-confined spinor condensate can form spin singlets, immediately after the atoms cross a first-order saddle to Mott-insulator phase transition in a sufficiently low microwave dressing field. We also discuss a good agreement between our data and the mean field theory, and two applications of spin singlets in quantum information science.

2:36PM P5.00004 Precise measurements on a quantum phase transition in antiferromagnetic spinor Bose-Einstein condensates1, CHANDRA RAMAN, ANSHUMAN VinIT, School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA — We have experimentally investigated the quench dynamics of antiferromagnetic spinor Bose-Einstein condensates in the vicinity of a zero temperature quantum phase transition at zero quadratic Zeeman shift q. A key feature of this work was removal of magnetic field inhomogeneities, resulting in a steep change in behavior near the transition point. The quadratic Zeeman shift at the transition point was resolved to 250 mHz uncertainty, equivalent to an energy resolution of k_B × 12 picoKelvin. To our knowledge, this is the first demonstration of sub-Hz precision measurement of a phase transition in quantum gases. It paves the way toward observing shifts of the transition point due to finite particle number N that scale as 1/N, and also, to potential Heisenberg limited spectroscopy with antiferromagnetic spinor gases.

2:48PM P5.00005 Coarsening in the one-dimensional spin-1 spinor Bose-Hubbard model, KAZUYA FUJIMOTO, RYUSUKE HAMAZAKI, University of Tokyo, MASASHITO UEDA, University of Tokyo, RIKEN CEMS — A spinor gas has a rich variety of phases, being a suitable system to investigate coarsening in an isolated quantum system. Most recent works for the coarsening in ultra-cold atomic gases focus on two-dimensional systems and find domain-growth laws characteristic of the classical binary liquid [1,2]. Under such a background, we theoretically study the cosneasing in the one-dimensional spin-1 spinor Bose-Hubbard model. In terms of the cosneasing, this system is essentially different from the previous ones because, in the one-dimensional system, the domain wall does not have the curvature and cannot move by itself. This leads to an expectation that the one-dimensional coarsening belongs to a universality class different from the binary liquid. To reveal this class, we have focused on a deep superfluid regime in our model, and analytically shown that the domain-growth law is characterized by the exponential integral not seen in the binary liquid. Furthermore, we have numerically confirmed this growth law by using the truncated Wigner approximation.

3:00PM P5.00006 Efficient generation of many-body singlet states of spin-1 bosons1, WENXIAN ZHANG, HUANYING SUN, PENG XU, School of Physics and Technology, Wuhan University, Wuhan, Hubei 430072, China, HAN PU, Department of Physics and Astronomy, Rice University, Houston, Texas 77251, USA — A quantum many-body spin singlet state is theoretically predicted as the ground state of an antiferromagnetically interacting spin-1 bosons at zero magnetic field. This fragile state would be broken even in a tiny magnetic field of microGauss. We develop an efficient stepwise adiabatic merging (SAM) method to generate many-body singlet states in antiferromagnetic spin-1 bosons in optical lattices with double-well arrays, by adiabatically ramping up the double-well bias. With an appropriate choice of bias sweeping rate, the SAM protocol predicts a fidelity as high as 90% for a sixteen-body singlet state and even higher fidelities for smaller even-body singlet states in a magnetic field of a few tens milliGausses. During their evolution, the spin-1 bosons exhibit wonderful squeezing dynamics, manifested by odd-even oscillations of the experimental observable of generalized squeezing parameter. The generated many-body singlet states may find practical applications in precision measurement of magnetic field gradient.

1Supported by the National Natural Science Foundation of China under Grant No. 11574239.
3:12PM P5.00007 Spin-incoherent Luttinger liquid of one-dimensional spin-1 Bose gas, HISIANG-HUA JEN, Institute of Physics, Academia Sinica, Taipei 11529, Taiwan, SUNGKIT YIP, Institute of Physics and Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan — A plethora of studies on one-dimensional (1D) quantum systems involve their ground state properties such as spatial and momentum distributions, quantum magnetism in a spinor Bose gas, and low-energy excitations in the Luttinger liquid model. A spinful quantum system in the spin-incoherent regime also provides a new avenue for studying 1D quantum many-body systems. Spin-incoherent Luttinger liquid (SILL) forms a different universality class from the Luttinger liquid, where the temperature is large enough that the degenerate spin configurations emerge while low enough that charge excitation is forbidden. In the SILL regime of a 1D spin-1 Bose gas, we investigate its many-body properties in Tonks-Girardeau limit in a harmonic trap. With zero magnetic field in the sector of $S_z = 0$, we derive the density matrix for the three individual components of the spin-1 Bose gas (spin-up, down, and 0). The momentum distributions are broadened compared with the spinless Bose gas and in the large momentum limit follow the asymptotic $1/p^4$ dependence but with reduced coefficients. While the density matrices and momentum distributions differ between different spin components for small $N$, at large $N$ they approach each other. We show these by analytic arguments and numerical calculations up to $N=16$.

3:24PM P5.00008 Internal structure of vortices in a dipolar spinor Bose-Einstein condensate, MAGNUS O. BORGH, University of East Anglia, JUSTIN LOVEGROVE, JANNE RUOSTEKOSKI, University of Southampton — We demonstrate how dipolar interactions (DI) can have pronounced effects on the structure of vortices in atomic spinor Bose-Einstein condensates and illustrate generic physical principles that apply across dipolar spinor systems. We then find and analyze the cores of singular non-Abelian vortices in a spin-3 $^{52}$Cr condensate. Using a simpler spin-1 model system, we analyze the underlying dipolar physics and show how a dipolar healing length interacts with the hierarchy of healing lengths of the contact interaction and leads to simple criteria for the core structure: vortex core size is restricted to the shorter spin-dependent healing length when the interactions both favor the ground-state spin structure: vortex core size is restricted to the shorter spin-dependent healing length when the interactions both favor the ground-state spin condition, but can conversely be enlarged by DI when interactions compete. We further demonstrate manifestations of spin-ordering induced by the DI anisotropy, including DI-dependent angular momentum of nonsingular vortices, as a result of competition with adaptation to rotation, and potentially observable internal vortex-core spin textures.

We acknowledge financial support from the EPSRC.

3:36PM P5.00009 Chiral spin condensation in a double-valley optical lattice, XIAOPENG LI, Fudan University, YINGHAI WU, Max-Planck-Institut fur Quantenoptik — We study a spinor (two component) Bose gas confined in a one-dimensional double-valley optical lattice which has a double-well structure in momentum space. With field theory analysis we find that the spin bosons in the double-valley band generically form a spin-charge mixed chiral spin quasi-condensate. We further perform exact numeric calculations for a concrete $\pi$-flux triangular lattice system, where we confirm our predictions both in terms of the chiral spin order against interactions and quantum fluctuations. This exotic atomic Bose condensate exhibits spatially staggered spin loop currents without any charge dynamics despite the complete absence of spin-orbit coupling in the system, paving a novel venue to atom-spintronics. By calculating entanglement entropy scaling and conformal-field-theory central charge, we establish that the low energy effective theory for the chiral spin condensate is a two-component Luttinger liquid. Our predictions are readily detectable in atomic experiments through spin resolved time-of-flight techniques.

3:48PM P5.00010 Non-Abelian Geometric Phases Carried by the Quantum Noise Matrix, BHARATH H. M., MATTHEW BOGUSLAWSKI, MARYROSE BARRIOS, MICHAEL CHAPMAN, Georgia Inst of Tech — Topological phases of matter are characterized by topological order parameters that are built using Berry geometric phase. Berry phase is the geometric information stored in the overall phase of a quantum state. We show that geometric information is also stored in the second and higher order spin moments of a quantum spin system, captured by a non-abelian geometric phase. The quantum state of a spin-S system is uniquely characterized by its spin moments up to order 2S. The first-order spin moment is the spin vector, and the second-order spin moment represents the spin fluctuation tensor, i.e., the quantum noise matrix. When the spin vector is transported along a loop in the Bloch ball, we show that the quantum noise matrix gains a geometric phase. Considering spin systems, we formulate this geometric phase as an SO(3) operator. Geometric phases are usually interpreted in terms of the solid angle subtended by the loop at the center. However, solid angles are not well defined for loops that pass through the center. Here, we introduce a generalized solid angle which is well defined for all loops inside the Bloch ball, in terms of which, we interpret the SO(3) geometric phase. This geometric phase can be used to characterize topological spin textures in cold atomic clouds.

Thursday, June 8, 2017 2:00PM - 4:00PM — Session P6 Driven Cold Gases — 311-312 - Norman Yao, University of California, Berkeley

2:00PM P6.00001 A driven dissipative phase transition in an ultracold lattice gas, YOGESH S PATIL, HIL F H CHEUNG, MUKUND VENGALATTORE, Cornell University — Optical lattice gases have emerged as a powerful platform for the study of correlated quantum behavior both in equilibrium and in non-equilibrium settings. Most studies to date have benefited from the isolation of these gasses from environmental sources of dissipation to realize long-lived coherent quantum dynamics. However, a growing body of theoretical work [1,2] has focused on novel forms of many-body phases arising from the interplay between coherent quantum dynamics and dissipation. Such driven, dissipative systems are predicted to exhibit quantum critical behavior, dynamical phase transitions and quantum many-body effects that lie beyond the conventional description and classification of equilibrium phase transitions. Here, we describe the realization of a metal-to-insulator transition (MIT) in an ultracold lattice gas arising from the competition between quantum coherence and dissipation in the form of tunable photon scattering. We discuss key aspects of the phase diagram of this system, novel features arising from its non-equilibrium nature and correspondences between our system and quantum percolation models in the presence of quenched disorder. [1] S. Diehl et al., Nature Physics 4, 878 - 883 (2008) [2] L. M. Sieberer et al., Phys. Rev. Lett. 110, 195301

2:12PM P6.00002 Interaction-driven quantum phase transitions of Bose condensates in shaken optical lattices, LOGAN W. CLARK, LEI FENG, ANITA GAJ, BRANDON M. ANDERSON, K. LEVIN, CHENG CHIN, University of Chicago — Shaken optical lattices enable exciting opportunities to study exotic quantum many-body phases in ultracold atomic gases. An intriguing example occurs when shaking a Bose condensate in an optical lattice causes its dispersion to acquire new minima at non-zero quasi-momenta. In this case the condensate can undergo a quantum phase transition after which atoms occupy the new minima. Repulsive interactions cause atoms with different momentum to segregate into spatially-separated domains. Here, we will discuss the much richer phenomena which are enabled by the interactions occurring during the shaking period. These subtle interaction effects can favor new quantum phases which break additional symmetries that are otherwise present in the Hamiltonian.
2:24PM P6.00003 Floquet topological insulator in an optical lattice with modulated lattice depth. YANQIAN YAN, TONY LEE, Indiana University-Purdue University Indianapolis — We propose a simple scheme to realize a Floquet topological insulator in an optical lattice by weakly modulating the lattice depth. When the modulation frequency resonantly couples the s and p bands, the Floquet Hamiltonian becomes topologically nontrivial. We map out the topological transition as a function of frequency and amplitude. We also confirm the bulk topology by finding edge states in a lattice with open boundary conditions. An advantage of our scheme is that the modulation amplitude can be relatively small, so the heating can be minimal.

2:48PM P6.00005 Parity-time symmetry breaking transitions in an ultracold Fermi gas with Floquet dissipation. LE LUO, JIAMING LI, ANDREW HARTER, LEONARDO DE MELO, YOGESH JOGLEKAR, Indiana University-Purdue University Indianapolis — Open physical systems with balanced loss and gain exhibit a transition, absent in their solitary counterparts, which engenders modes that exponentially decay or grow with time and thus spontaneously breaks the parity-time (PT) symmetry. This PT-symmetry breaking is induced by increasing the strength of the loss and gain, but also occurs in a pure dissipative system without gain. Here we report on the first quantum version of PT-symmetry breaking transitions using ultracold Rb atoms. We simulate static and Floquet dissipative Hamiltonians by generating controlled, state-dependent atom loss in a noninteracting Fermi gas, and observe the PT-symmetry breaking transitions by tracking the atom number for each state. In contrast to a single transition in the static case, the Floquet counterpart undergoes PT-symmetry breaking and restoring transitions at vanishingly small dissipation strength. Our results show that Floquet dissipation is a versatile tool for navigating phases where the PT-symmetry is either broken or conserved. The ultracold Fermi gas, with engineered Floquet dissipation, provides a starting point for exploring the interplay between interaction and dissipation effects in open quantum systems.

3:00PM P6.00006 Engineering topological defect patterns of Bose condensates in shaken optical lattices. LEI FENG, LOGAN W. CLARK, ANITA GAJ, CHENG CHIN, University of Chicago — Topological defects emerge and play an essential role in the dynamics of systems undergoing continuous, symmetry-breaking phase transitions. Here, we study the topological defects (domain walls) which form when a Bose condensate in a shaken optical lattice undergoes a quantum phase transition and separates into domains of superfluid with finite momentum. Here, we experimentally demonstrate the ability to control the pattern of domain walls using a digital micromirror device. We further explore implementations of this technique to study dynamics near the phase transition and the evolution of topological defects.

3:12PM P6.00007 Interaction quenched ultracold few-boson ensembles in periodically driven lattices. SIMEON MISTAKIDIS, PETER SCHMELCHER, Center for Optical Quantum Technologies, University of Hamburg, THEORY GROUP OF FUNDAMENTAL PROCESSES IN QUANTUM PHYSICS TEAM — The out-of-equilibrium dynamics of interaction quenched finite ultrasonic bosonic ensembles in periodically driven one-dimensional optical lattices is investigated. It is shown that periodic driving enforces the bosons in the outer wells of the finite lattice to exhibit out-of-phase dipole-like modes, while in the central well the atomic cloud experiences a local breathing mode. The dynamical behavior is investigated with varying driving frequency, revealing a resonant-like behavior of the intra-well dynamics. An interaction quenched in the periodically driven lattice gives rise to admixtures of different excitations in the outer wells, an enhanced breathing in the center and an amplification of the tunneling dynamics. We observe then multiple resonances between the inter- and intra-well dynamics at different quench amplitudes, with the position of the resonances being tunable via the driving frequency. Our results pave the way for future investigations on the use of combined driving protocols in order to excite different inter- and intra-well modes and to subsequently control them.

3:24PM P6.00008 Lattice entanglement of ultracold atoms via lattice shaking. LUSHUAI CAO, XING DENG, XUE-TING FANG, QIAN-RU ZHU, HONG-KUN HU, MOE Key Laboratory of Fundamental Physical Quantities Measurement, School of physics, Huazhong university of Science and technology. Quantum entanglement of ultracold atoms is a key ingredient for quantum implementations, such as quantum computation. Ultracold atoms in optical lattices process various degrees of freedom (DOF) for generating entanglements, such as the site occupation, the orbital and the internal DOF, and the entanglement has been experimentally realized between the orbital and the internal DOF [Nature 527, 208], as well as between the site-occupation and internal DOF [Nature Physics 12, 783]. We propose a scheme to obtain entanglement between the orbital and the site-occupation DOF by lattice shaking. By carefully designing the shaking symmetry and taking advantage of the interaction blockade, this scheme can obtain entangled states on demand with controllable speed.

3:36PM P6.00009 An Acousto-Optical High Bandwidth Arbitrary Lattice Generator for $^{87}$Rb. Z. S. SMITH, M. E. W. REED, A. DEWAN, S. L ROLSTON, Joint Quantum Institute/University of Maryland and NIST, College Park — We discuss the implementation and characterization of our high-bandwidth arbitrary lattice generator. The periods and phases of multiple simultaneous 1D lattices can be modulated, swept and jumped at MHz rates to produce both arbitrary time-averaged potentials and dressed-band Hamiltonians. A Mach-Zehnder interferometer spans the dynamic range of the lattice allowing its complete characterization and stabilization in-situ. We demonstrate both disordered and dressed band Hamiltonians.

3:48PM P6.00010 Quantized motion of Rydberg atoms in an amplitude-modulated lattice potential. VLADIMIR MALINOFSKY, US Army Research Laboratory, Adelphi, MD 20783, KAITLIN MOORE, ANDIRA RAMOS, GEORG GEORG, Department of Physics, University of Michigan, Ann Arbor, MI 48105 — We present a model description of the spectroscopic line shape of Rydberg transitions in an amplitude-modulated Rydberg-atom lattice taking into account the quantization of the center-of-mass motion. In our model, the wave function of both ground and excited states are subject to the periodic potentials that arise from the optical-lattice fields. In contrast to other spectroscopic work, in our model the coupling (the effective Rabi frequency) is also periodic as function of the translational coordinate, and it is perfectly phase-locked to the lattice trapping potential. By solving the time-dependent Schrödinger equation in momentum representation we obtain the spectrum of the excited-state population. The numerical results for the momentum components of the ground and excited wave functions are averaged over the thermal momentum distribution of the Rydberg atoms. The effect of the lattice parameters and the interaction strength on the line shape of the Rydberg transitions is discussed.

Thursday, June 8, 2017 2:00PM - 4:00PM — Session P7 High Harmonics and Ultrafast Processes in Strong Fields

313 - Vinod Kumarapappan, Kansas State University
Characterization of induced nanoplasmonic fields in time-resolved photoemission: a classical trajectory approach applied to gold nanospheres

1. ERFAN SAYDANZAD, JIANXIONG LI, UWE THUMM, Kansas State University — Attosecond time-resolved spectroscopy is being extended from the study of the electronic dynamics in atoms and molecules to the investigation of electron propagation and collective electronic (plasmonic) effects near solid surfaces [1,2] and nanoparticles [1,3]. We simulated streaked photoelectron energy spectra as a function of the time delay between ionizing single attosecond XUV and streaking IR pulses, within a classical-trajectory Monte-Carlo-sampling approach. For the examples of streaked photoemission form 5 and 50 nm radius gold nanospheres, we discuss the imprint of sub-infrared-cycle plasmonic and electronic dynamics on streaked photoelectron spectra [4].

2. ABSTRACT WITHDRAWN

Control of threshold enhancements in harmonic generation by atoms in a two-color laser field with orthogonal polarizations

1. ANTHONY F. STARACE, The University of Nebraska - Lincoln, M.V. FROLOV, N.L. MANAKOV, T.S. SARANTSEVA, Voronezh State University, Russia, A.A. SILAEV, N.V. VVEDENSKII, Institute of Applied Physics, Nizhny Novgorod, Russia — Threshold phenomena (or channel-closing effects) are analyzed in high-order harmonic generation (HHG) by atoms in a two-color laser field with orthogonal linearly polarized components of a fundamental field and its second harmonic [1]. We show that the threshold behavior of HHG rates for the case of a weak second harmonic component is sensitive to the parity of a closing multiphoton ionization channel and the spatial symmetry of the initial bound state of the target atom, while for the case of comparable intensities of both components, suppression of threshold phenomena is observed as the relative phase between the components of a two-color field varies. A quantum orbit analysis as well as phenomenological considerations in terms of Baz’ theory of threshold phenomena [2] are presented in order to describe and explain the major features of threshold phenomena in HHG by a two-color field. [1] M.V. Frolov et al., Phys. Rev. A 93, 023430 (2016). [2] A.I. Baz’, Zh. Eksp. Teor. Fiz. 33, 923 (1957) [Sov. Phys. JETP 6, 709 (1958)].

Femtosecond Photoelectron Imaging of Dissociating and Autoionizing States in Oxygen

1. ALEXANDER PLUNKETT, ARVINDER SANDHU, Univ of Arizona — Time-resolved photoelectron spectra from molecular oxygen have been recorded with high energy and time resolution using a velocity map imaging (VMI) spectrometer. High harmonics were used to prepare neutral Rydberg states converging to the $\Sigma^-_{u}$ ionic state. These states display both autoionization and predissociation. A femtosecond laser pulse centered at 780 nm was used to probe the system, ionizing both the excited molecular states and the predissociated neutral atomic fragments. Electrons were collected in the 0-3 eV range using a VMI spectrometer and their spectra were reconstructed using a Fast Onion-peeling algorithm. By looking at IR modification to the electron spectrum, new features are observed which could originate from long-range cumbic interactions or previously unobserved molecular decay channels. Ongoing studies extent this technique to other systems exhibiting non-adiabatic dynamics.

1. This work was supported by the U. S. Army Research Laboratory and the U. S. Army Research Office under Grant No. W911NF-14-1-0383.

High harmonic generation spectroscopy of laser induced phase transitions in strongly correlated systems

1. RUI EMANUEL FERREIRA DA SILVA, Max-Born-Institut, Max Born Strasse 2A, D-12489 Berlin, Germany, IGOR BLINOV, Russian Quantum Center, Skolkovo 143025, Russia, OLGA SMIRNOVA, Max-Born-Institut, Max Born Strasse 2A, D-12489 Berlin, Germany,ALEXEY PUCHTSOV, Russian Quantum Center, Skolkovo 143025, Russia, MISHA IVANOV, Max-Born-Institut, Max Born Strasse 2A, D-12489 Berlin, Germany — We study theoretically high harmonic generation in the 1D Fermi-Hubbard model in the quantum tunneling regime with intense mid-infrared (MIR) and THz fields. This is the first theoretical study of high harmonic generation in strongly correlated solids, with electron correlation effects explicitly taken into account with no additional approximations beyond the Fermi-Hubbard Hamiltonian itself. We find that the mechanism of harmonic emission in strongly correlated solids is distinct from the one observed in semiconductors and dielectrics. The mechanism relies on the production of doublon-hole pairs via Landau-Dykke type tunneling and is inherently linked to an insulator-to-metal phase transition. We show that high harmonic generation can be used to time this phase transition with the accuracy of a few femtoseconds, i.e. within the fraction of the single oscillation of the driving electromagnetic field. Our work opens the window for the investigation of ultrafast phase transitions in the condensed phase using high harmonic spectroscopy.
Science


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angular momentum modes. In addition, a simple means of avoiding these discontinuities will be presented.

illustrate the source of the discontinuities, and provide graphical evidence of the discontinuous real electric fields for the first and third orbital

momentum mode. Such discontinuities in the phasor lead to nonphysical discontinuities in the real electromagnetic field components. We will

vortex beam phasor generated from the complex source/sink model

2

University of Nebraska-Lincoln — An analytical discontinuity is reported in what was thought to be the discontinuity-free exact nonparaxial
generation in solids, YONG SING YOU, SLAC - Natl Accelerator Lab, MENGXI WU, Louisiana State University, YANCHUN YIN, ANDREW CHEW, XIAOMING REN, SHIMA GHOLAM-MIRZAEI, University of Central Florida, DANA BROWNE, Louisiana State University, MICHAEL CHINI, ZENGHU CHANG, University of Central Florida, KENNETH SCHAVER, METTE GAARDE, Louisiana State University, SHAMBHU GHIMIRE, SLAC - Natl Accelerator Lab — Solid-state high-order harmonic generation (HHG) process has emerged as a novel

t_generation in time-domain through carrier-envelope phase (CEP) setting. We find that the XUV harmonic spectrum from MgO depends

strongly to the CEP setting. Our analysis based on quantum model shows that such dependence originates from the delay between harmonics

at the sub-cycle level. Experimental results show that the delay depends on the strength of the laser field. These features are consistent to the

emission from driven multi-band non-linear current. Thus, our results suggest a new approach to study multi-band electron dynamics in strongly

driven periodic solids with unprecedented time resolution. The time-domain information we reveal is critical for attosecond pulse metrology

based on solid-state HHG.

3:36PM P7.00009 Laser waveform control of extreme ultraviolet high harmonic generation in solids . YONG SING YOU, SLAC - Natl Accelerator Lab, MENGXI WU, Louisiana State University, YANCHUN YIN, ANDREW CHEW, XIAOMING REN, SHIMA GHOLAM-MIRZAEI, University of Central Florida, DANA BROWNE, Louisiana State University, MICHAEL CHINI, ZENGHU CHANG, University of Central Florida, KENNETH SCHAVER, METTE GAARDE, Louisiana State University, SHAMBHU GHIMIRE, SLAC - Natl Accelerator Lab — Solid-state high-order harmonic generation (HHG) process has emerged as a novel

method to produce attosecond pulses and to probe electronic structure of bulk materials. Much of these applications need time-domain in-

formation such as the phase delay between different harmonics at the sub-cycle level. Here, we use few cycle driving pulses to control the generation process in time-domain through carrier-envelope phase (CEP) setting. We find that the XUV harmonic spectrum from MgO depends strongly to the CEP setting. Our analysis based on quantum model shows that such dependence originates from the delay between harmonics at the sub-cycle level. Experimental results show that the delay depends on the strength of the laser field. These features are consistent to the emission from driven multi-band non-linear current. Thus, our results suggest a new approach to study multi-band electron dynamics in strongly

driven periodic solids with unprecedented time resolution. The time-domain information we reveal is critical for attosecond pulse metrology

based on solid-state HHG.

3:48PM P7.00010 Discontinuities in the Electromagnetic Fields of Vortex Beams from the Complex Source/Sink Model1 , ANDREW VIKARTOSKY, LIANG-WEN PI, ANTHONY F. STARACE, University of Nebraska-Lincoln — An analytical discontinuity is reported in what was thought to be the discontinuity-free exact nonparaxial vortex beam phasor generated from the complex source/sink mode. This discontinuity appears for all odd values of the orbital angular momentum mode. Such discontinuities in the phasor lead to nonphysical discontinuities in the real electromagnetic field components. We will illustrate the source of the discontinuities, and provide graphical evidence of the discontinuous real electric fields for the first and third orbital angular momentum modes. In addition, a simple means of avoiding these discontinuities will be presented.

1This work is supported in part by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, under Award No. DE-FG03-96ER14646.


Thursday, June 8, 2017 2:00PM - 4:00PM –

Session P8 Focus Session: Quantum Error Correction 314 - Roeo Ozeri, Weizmann Institute of Science

2:00PM P8.00001 Fault-tolerant encoding of a logical qubit1 , NORBERT M. LINKE, Univ of Maryland-College Park — The discovery of quantum error correction codes gave credibility to the idea of scaling up quantum computers to large sizes [1]. Showing that all elements of error correction can be realized in a fault-tolerant way is therefore of fundamental interest. Fault tolerance removes the assumption of perfect encoding and decoding operations of logical qubits. We present the implementation of the [[4,2,2]] code, an error detection protocol [2] which uses four physical qubits to encode two logical qubits, one of which can be made fault-tolerant by appropriate construction of the encoding and stabilizer circuits [3]. Remarkably, it works with a bare ancilla qubit. The results demonstrate for the first time the robustness of a fault-tolerant qubit to imperfections in the very operations used to encode it, as errors are suppressed by an order of magnitude below the physical error probability. We present data to show that this advantage over a non-fault-tolerant qubit persists even with large added error rates and experimental calibration errors [4].

The experiment is performed on a programmable quantum computer comprised of five trapped $^{171}$Yb$^+$ ions. It provides a fully connected system of atomic clock qubits with long coherence times and high gate fidelities that can be programmed to execute arbitrary quantum circuits [5].


1This work is supported by the ARO with funding from the IARPA LogiQ program and the AFOSR MURI on Quantum Measurement and Verification.
2:30PM P8.00002 Validating quantum systems in the presence of errors, J. M. TAYLOR, JPL, and NIST — Experimental groups around the world are developing complex quantum systems for quantum simulation and eventually computation. These systems will hopefully soon exceed our ability to classically simulate or reasonably understand their dynamics. I will discuss efforts to develop testing tools for such systems to confirm various aspects of their performance in the presence of errors, disorder, and noise. The overall formalism focuses on using quantum communication concepts to validate performance, and I will show how it can extend to a variety of quantum systems.

3:00PM P8.00003 Autonomous Quantum Error Correction with Application to Quantum Metrology, FLORENTIN REITER, Harvard University, ANDERS S. SORENSEN, Niels Bohr Institute, University of Copenhagen, PETER ZOLLER, CHRISTINE A. MUSCHIK, Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences and University of Innsbruck — We present a quantum error correction scheme that stabilizes a qubit by coupling it to an engineered environment which protects it against spin- or phase flips. Our scheme uses always-on couplings that run continuously in time and operates in a fully autonomous fashion without the need to perform measurements or feedback operations on the system. The correction of errors takes place entirely at the microscopic level through a build-in feedback mechanism. Our dissipative error correction scheme can be implemented in a system of trapped ions and can be used for improving high precision sensing. We show that the enhanced coherence time that results from the coupling to the engineered environment translates into a significantly enhanced precision for measuring weak fields. In a broader context, this work constitutes a stepping stone towards the paradigm of self-correcting quantum information processing.

3:12PM P8.00004 Delayed Quantum Feedback, HANNES PICHLER, ITAMP, Harvard University — We study the dynamics of photonic quantum circuits consisting of nodes coupled by quantum channels. We are interested in the regime where the time delay in communication between the nodes is significant. This includes the problem of quantum feedback, where a quantum signal is fed back on a system with a time delay. We develop a tensor network state approach to solve the quantum stochastic Schrödinger equation with time delays, which accounts in an efficient way for the entanglement of nodes with the stream of emitted photons in the waveguide, and thus the non-Markovian character of the dynamics.

3:24PM P8.00005 A Quantum Non-Demolition Parity measurement in a mixed-species trapped-ion quantum processor, MATTEO MARINELLI, VLAD NAGNEVITSKY, HSUANG-YU LO1, CHRISTA FLHMANN, KARAN MEHTA, JONATHAN HOME2, ETH Zurich — Quantum non-demolition measurements of multi-qubit systems are an important tool in quantum information processing, in particular for syndrome extraction in quantum error correction. We have recently demonstrated a protocol for quantum non-demolition measurement of the parity of two beryllium ions by detection of a co-trapped calcium ion. The measurement requires a sequence of quantum gates between the three ions, using mixed-species gates between beryllium hyperfine qubits and a calcium optical qubit. Our work takes place in a multi-zone segmented trap setup in which we have demonstrated high fidelity control of both species and multi-well ion shuttling. The advantage of using two species of ion is that we can individually manipulate and read out the state of each ion species without disturbing the internal state of the other. The methods demonstrated here can be used for quantum error correcting codes as well as quantum metrology and are key ingredients for realizing a hybrid universal quantum computer based on trapped ions. Mixed-species control may also enable the investigation of new avenues in quantum simulation and quantum state control.

1 left the group and working in a company now
2 group leader

3:36PM P8.00006 Theory of real-time feedback on oscillating qubits using weak measurement, HERMANN UYS, CSIR and Stellenbosch University, South Africa, PIETER DU TOIT, National Metrology Institute of South Africa, South Africa, SHAUN BURRE, University of Colorado, and National Institute of Standards and Technology, USA, HUMAIRAH BASSA, THOMAS KONRAD, University of KwaZulu-Natal, South Africa — We review our recent work on state estimation and feedback control of single quantum systems based on weak measurement. We discuss two classes of feedback protocols used to control qubit oscillations. The first relies on standard proportional-integral-differential control while the second comprises unitary operations aimed at reversing the phase kicks due to measurement back-action. Analytical expressions for the convergence of state estimation fidelity are also obtained in the continuous measurement limit, by evaluating the fidelity change in an incremental step of the estimation protocol.

1 This work was supported in part by a grant from the South African National Research Foundation (Grant 93602), as well as an award by the United States Airforce Office of Scientific Research (Award FA9550-14-1-0151)

3:48PM P8.00007 A state comparison amplifier with feed forward state correction, LUCA MAZZARELLA, University of Strathclyde, ROSS DONALDSÖN, ROBERT COLLINS, UGO ZANFORLIN, GERALD BULLER, Heriot-Watt University, JOHN JEFFERS, University of Strathclyde — The Quantum State Comparison Amplifier (SCAMP) is a probabilistic amplifier that works for known sets of coherent states. The input state is mixed with a guess state at a beam splitter and one of the output ports is coupled to a detector. The other output contains the amplified state, which is accepted on the condition that no counts are recorded. The system uses only classical resources and has been shown to achieve high gain and repetition rate. However the output fidelity is not high enough for most quantum communication purposes. Here we show how the success probability and fidelity are enhanced by repeated comparison stages, conditioning later state choices on the outcomes of earlier detections. A detector firing at an early stage means that a guess is wrong. This knowledge allows us to correct the state perfectly. The system requires fast-switching between different input states, but still requires only classical resources. Figures of merit compare favourably with other schemes, most notably the probability-fidelity product is higher than for unambiguous state discrimination. Due to its simplicity, the system is a candidate to counteract quantum signal degradation in a lossy fibre or as a quantum receiver to improve the key rate of continuous variable quantum communication.

1 The work was supported by the QComm Project of the UK Engineering and Physical Sciences Research Council (EP/M013472/1).

Thursday, June 8, 2017 2:00PM - 4:00PM — Session P9 Advances in atom interferometry 315 - Paul Hamilton, UCLA
Gravity sensing using Very Long Baseline Atom Interferometry. DENNIS SCHLIPPERT, ÉTIENNE WODEY, CHRISTIAN MEINERS, DOROTHEE TELL, CHRISTIAN SCHUBERT, WOLFGANG ERTMER, ERNST M. RASEL, Institut für Quantenoptik, Leibniz Universität Hannover — Very Long Baseline Atom Interferometry (VLBAI) has applications in high-accuracy absolute gravimetry, gravity-gradiometry, and for tests of fundamental physics. Thanks to the quadratic scaling of the phase shift with increasing free evolution time, extending the baseline of atomic gravimeters from tens of centimeters to meters puts resolutions of $10^{-13}$ g and beyond in reach. We present the design and progress of key elements of the VLBAI-test stand: a dual-species source of Rb and Yb, a high-performance two-layer magnetic shield, and an active vibration isolation system allowing for unprecedented stability of the mirror acting as an inertial reference. We envisage a vibration-limited short-term sensitivity to gravitational acceleration of $1 \times 10^{-13}$ m²/s²/Hz^{1/2} and up to a factor of 25 improvement when including additional correlation with a broadband seismometer. Here, the supreme long-term stability of atomic gravity sensors opens the route towards competition with superconducting gravimeters. The operation of VLBAI as a differential dual-species gravimeter using ultracold mixtures of Yb and Rb atoms enables quantum tests of the universality of free fall (UFF) at an unprecedented level of $\lesssim 10^{-13}$, potentially surpassing the best experiments to date.

Mach-Zehnder atom interferometer inside an optical fiber. MINGJIE XIN, WUISENG LEONG, ZILONG CHEN, SHAU-YU LAN, Nanyang Tech Univ — Precision measurement with light-pulse grating atom interferometry in free space have been used in the study of fundamental physics and applications in inertial sensing. Recent development of phononic band-gap fibers allows light for traveling in hollow region while preserving its fundamental Gaussian mode. The fibers could provide a very promising platform to transfer cold atoms. Optically guided matter waves inside a hollow-core photonic band-gap fiber can mitigate diffraction limit problem and has the potential to bring research in the field of atomic sensing and precision measurement to the next level of compactness and accuracy. Here, we will show our experimental progress towards an atom interferometer in optical fibers. We designed an atom trapping scheme inside a hollow-core photonic band-gap fiber to create an optical guided matter waves system, and studied the coherence properties of Rubidium atoms in this optical guided system. We also demonstrate a Mach-Zehnder atom interferometer in the optical waveguide. This interferometer is promising for precision measurements and designs of mobile atomic sensors.

Recoil-sensitive lithium interferometer without a subrecoil sample. KAYLEIGH CASSELLA, ERIC COPENHAVER, BRIAN ESTEY, University of California - Berkeley, YANYING FENG, Tsinghua University, CHEN LAI, University of California - San Diego, HOLGER MULLER, University of California - Berkeley — We report recoil-sensitive Ramsey-Bordé atom interferometry with a sample of lithium-7 atoms at 300 µK, well above the atomic recoil temperature of 6 µK. We overcome the need for additional cooling and velocity selection steps, which decrease phase sensitivity, by spectrally resolving the output ports with 160-ns Raman beam splitters. The large bandwidth pulses drive both conjugate interferometers simultaneously with nearly equal contrast, allowing for state selective detection of the summed interferometer signal. Optical pumping to a magnetically-insensitive state suppresses magnetic dephasing and extends coherence time. Sensitivity comparable to interferometers using large momentum transfer pulses can be attained at interrogation times on the order of 10-ms due to lithiums high recoil frequency and the increased available atom number. At this time scale, vibration noise is converted to amplitude noise and does not perturb the determination of the recoil frequency from the summed interference pattern. We overcome the need for additional cooling and velocity selection steps, which decrease phase sensitivity, by spectrally resolving the output ports with 160-ns Raman beam splitters. The large bandwidth pulses drive both conjugate interferometers simultaneously with nearly equal contrast, allowing for state selective detection of the summed interferometer signal. Optical pumping to a magnetically-insensitive state suppresses magnetic dephasing and extends coherence time. Sensitivity comparable to interferometers using large momentum transfer pulses can be attained at interrogation times on the order of 10-ms due to lithiums high recoil frequency and the increased available atom number. At this time scale, vibration noise is converted to amplitude noise and does not perturb the determination of the recoil frequency from the summed interference signal. In addition to simplifying cooling, increasing atom number and reducing cycle time for faster integration, these techniques broaden the applicability of recoil-sensitive interferometry to particles that remain difficult to trap and cool, like electrons.

Large momentum transfer atomic interferometer gyroscope. ROBERT COMPTON, JOSHUA DORR, KARL NELSON, Honeywell, RICHARD PARKER, BRIAN ESTEY, HOLGER MULLER, UC Berkeley — Atom interferometry holds out significant promise as the basis for compact, low cost, high performance inertial sensing. Some light pulse atom interferometers are based on an atomic beam-splitter in which the interferometer paths separate at the velocity imparted by a two-photon (Raman) recoil event, resulting in narrow path separation and a corresponding high aspect ratio between the length and width of the interferometer. In contrast, proposals for large momentum transfer (LMT) offer paths to larger separation between interferometer arms, and aspect ratios approaching 1. Here, we demonstrate an LMT gyroscope based on a combination of Bragg and Bloch atomic transitions adding up to a total of 8 photons of momentum transfer. We discuss prospects for scalability to larger photon numbers where angular random walk (ARW) can be better than navigation-grade.

Large momentum transfer for atom interferometry with BECs. SVEN ABEND, Institut fuer Quantenoptik, Leibniz Uni Hannover, MARTINA GEBBE, ZARM, Uni Bremen, MATTHIAS GERSEMANN, ERNST M. RASEL, Institut fuer Quantenoptik, Leibniz Uni Hannover, QUANTUS COLLABORATION — We develop and demonstrate a novel scheme for a symmetric large momentum transfer beam splitter for interferometry with Bose-Einstein condensates. Large momentum transfer beam splitters are a key technique to enhance the scaling factor and sensitivity of an atom interferometer and to create largely delocalized superposition states. To realize the beam splitter, double Bragg diffraction is used to create a superposition of two symmetric momentum states. Afterwards both momentum states are loaded into a retro-reflected optical lattice and accelerated by Bloch oscillations on opposite directions, keeping the initial symmetry. The favorable scaling behavior of this symmetric acceleration, allows to transfer more than 1000/μK of total differential splitting in a single acceleration sequence of 6 ms duration while we still maintain a fraction of approx. 25% of the initial atom number. As proof of the coherence of this beam splitter, contrast in a closed Mach-Zehnder atom interferometer has been observed with up to 200/μK of momentum separation, which equals a differential wave-packet velocity of approx. 1.1 m/s for ^{87}Rb.

The presented work is supported by the CBC 1128 geo-Q and the DLR with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) due to an enactment of the German Bundestag under Grant No. DLR 50WM1552-1557 (QUANTUS-IV-Fallturm).
3:00PM P9.00006 Techniques for Macroscopic Scale Atom Interferometry. TIM KOVACHY, PETER ASENBAUM, CHRIS OVERSTREET, JASON HOGAN, MARK KASEVICH, Stanford University — Atom interferometers that cover macroscopic scales in space and in time have a high intrinsic sensitivity to inertial forces, making them a valuable tool for a wide range of applications. We have used such interferometers in a 10 meter atomic fountain apparatus for precision gravity gradiometry, measurements of phase shifts associated with spacetime curvature across a single quantum system, and differential acceleration measurements between Rb-85 and Rb-87 for a test of the weak equivalence principle. This talk will focus on the techniques that enable these large scale interferometers, with path separations of tens of centimeters and durations of more than a second. As the path separation and duration are increased, the interferometer becomes more susceptible to experimental imperfections that degrade the interference signal. We will describe how this challenge can be overcome through the use of large momentum transfer atom optics based on sequential two-photon Bragg transitions, high power atom optics lasers with a spectrum that compensates unwanted light shifts, and magnetic/optical-dipole lensing to produce a well-collimated atom source.

3:12PM P9.00007 Opportunities for Maturing Precision Metrology with Ultracold Gas Studies Aboard the ISS1. JASON WILLIAMS, Jet Propulsion Lab, JOSE D’INCAO, JILA, NIST and University of Colorado, Boulder — Precision atom interferometers (AI) in space are expected to become an enabling technology for future fundamental physics research, with proposals including unprecedented tests of the validity of the weak equivalence principle, measurements of the fine structure and gravitational constants, and detection of gravity waves and dark matter/dark energy. We will discuss our preparation at JPL to use NASA’s Cold Atom Lab facility (CAL) to mature the technology of precision, space-based, Als. The focus of our flight project is three-fold: a) study the controlled dynamics of heteronuclear Feshbach molecules, at temperatures of nano-Kelvins or below, as a means to overcome uncontrolled density-profile-dependent shifts in differential Als, b) demonstrate unprecedented atom-photon coherence times with spatially constrained Als, c) use the imaging capabilities of CAL to detect and analyze spatial fringe patterns written onto the clouds after Al and thereby measure the rotational noise of the ISS. The impact from this work, and potential for follow-on studies, will also be reviewed in the context of future space-based fundamental physics missions.

3:24PM P9.00008 Competition between spin echo and spin self-rephasing in a trapped atom interferometer. XAVIER ALAUZE, ALEXIS BONNIN, FRANCK PEREIRA DOS SANTOS, SYRTE - Observatoire de Paris, CYRILLE SOLARO, Aarhus University, JEAN-NOEL FUCHS, Laboratoire de Physique Théorique de la Matière Condensée - LPTMC, FREDERIC COMBES, FREDERIC PICHON, Laboratoire de Physique des Solides - Universite Paris-Sud — The FORCA-G project aims to develop a quantum sensor to probe short range forces. We realize a trapped atom interferometer of 87Rb in a vertical optical lattice in which stimulated Raman transitions induce coherent coupling between adjacent lattice sites. We thus measure the Bloch frequency with agreement with a theoretical model. This method is a useful tool for atomic interferometry and other areas in ultracold atoms where a robust effective knife-edge, created by a potential barrier, begins to become “blunt” due to tunneling for thin barriers, and we obtain quantitative measurement for matter-waves, we have been able to characterize ultra-low momentum widths. We measured a momentum width corresponding to an effective temperature of 900 \( \pm \) 300 pK, only limited by our cooling performance. We show that this technique compares favourably with most traditional methods, which would require expensive equipment and focus on frequency stability of 1 ppm. Finally, we show that the effective knife-edge, created by a potential barrier, begins to become “blunt” due to tunneling for thin barriers, and we obtain quantitative agreement with a theoretical model. This method is a useful tool for atomic interferometry and other areas in ultracold atoms where a robust and precise technique for characterizing the momentum distribution is required.

3:36PM P9.00009 Decoherence in Ramsey Spectroscopy Due to Magnetic Field Gradients1. FRANK NARDUCCI, Naval Air Systems Command, ARVIND SRINIVASAN, St. Mary’s College of Maryland, JON P. DAVIS, AMPAC, MATTHIAS ZIMMERMANN, MAXIM EFREMOV, Universitat Ulm, ERNST RASEL, Leibnitz Universitat, WOLFGANG SCHLEICH, Universitat Ulm — Ramsey or spin-echo spectroscopy techniques are often used to interferometrically probe systems. Most experiments use the clock transition to suppress the sensitivity to magnetic fields. Magnetic Raman transitions will behave the same way as the clock transition, apart from a dependence of the resonance frequency on the value of the field for perfectly static and uniform magnetic fields. However, our current experiments require the presence of a magnetic field gradient. The magnetic field gradient causes a loss of contrast in the interference pattern in two ways. Due to the gradient and the spatial extent of the cloud, the resonance frequency of the transition differs between atoms such that they do not receive perfect \( \pi/2 \) pulses. Proper frequency chirping of the Raman fields can restore the peak Raman amplitude. Secondly, the decoherence rate differs between different atoms, which is not reversible by standard spin echo techniques. This dephasing can be interpreted as a result of the non-closure of the interferometer. A properly closed interferometer, such as the one we demonstrate with a four pulse sequence will restore the contrast. We apply our results to our experiments on the measurement of the T3 contribution to the phase of the interferometer.

3:48PM P9.00010 Atom-optics knife-edge: Measuring sub-nanokelvin momentum distributions. RAMON RAMOS, DAVID SPIERINGS, AEPHRAIM STEINBERG, Univ of Toronto — Temperatures below 1 nanokelvin can be overcome through the use of large momentum transfer atom optics based on sequential two-photon Bragg transitions, high power atom optics lasers with a spectrum that compensates unwanted light shifts, and magnetic/optical-dipole lensing to produce a well-collimated atom source. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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1This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Thursday, June 8, 2017 3:30PM - 4:30PM – Session P10 Tutorial for Authors and Referees 317-318 -

3:30PM P10.00001 Tutorial for Authors and Referees –
Q1.00001 ATOMIC MAGNETOMETERS AND SENSORS

Q1.00002 Atomic vapor spectroscopy in integrated photonic structures , TILMAN PFAU, RALF RITTER, Center for Integrated Quantum Science and Technology, Universitaet Stuttgart, NICO GRUHLER, WOLFRAM PERNICE, Institute of Physics, University of Muenster, Germany, HARALD KUEBLER, ROBERT LOEW, Center for Integrated Quantum Science and Technology, Universitaet Stuttgart — We investigate an integrated optical chip immersed in atomic vapor providing several waveguide geometries for spectroscopy applications [1]. This includes integrated ring resonators [2], Mach Zehnder interferometers, slot waveguides and counterpropagating coupling schemes. The narrow-band transmission through a silicon nitride waveguide and interferometer is altered when the guided light is coupled to a vapor of rubidium atoms via the evanescent tail of the waveguide mode. We use grating couplers to couple between the waveguide mode and the radiating wave, which allow for addressing arbitrary coupling positions on the chip surface. The evanescent atom-light interaction can be numerically simulated and shows excellent agreement with our experimental data. This work demonstrates a next step towards miniaturization and integration of alkali atom spectroscopy and provides a platform for further fundamental studies of strong atom-light coupling. Cooperativities on the order of 1 are within reach. In the future integrated optical and electronic circuits in atomic vapor cells will enable applications in quantum sensing and quantum networks. [1] R. Ritter, et al., Appl. Phys. Lett. 107, 041101 (2015) [2] R. Ritter, et al., New Journal of Physics 18, 103031 (2016)

Q1.00003 DC Magnetometry at the T2 limit , ASHOK AJAY, University of California Berkeley, CA, YIXIANG LIU, PAOLA CAPPELLARO, Research Lab of Electronics, MIT Cambridge, MA — Sensing static or slowly varying magnetic fields with high sensitivity and spatial resolution is critical to many applications in fundamental physics, bioimaging and materials science. Several versatile magnetometry platforms have emerged over the past decade, such as electronic spins associated with Nitrogen Vacancy (NV) centers in diamond. However, their high sensitivity to external fields also makes them poor sensors of DC fields. Indeed, the usual method of Ramsey magnetometry leaves them prone to environmental noise, limiting the allowable interrogation time to the short dephasing time T2. Here we introduce a hybrid magnetometry platform, consisting of a sensor and an ancillary qubit, that allows sensing static magnetic fields with interrogation times up to the much longer T2 coherence time, allowing significant potential gains in field sensitivity. We demonstrate the method for an electronic NV sensor and a nuclear ancillary qubit. It relies on frequency up-conversion of transverse DC fields through the ancillary qubit, allowing quantum lock-in detection with low-frequency noise rejection, and ushers in a compelling technique for sensitive DC magnetometry at the nanoscale.

Q1.00004 Sensitivity Limits of Rydberg Atom-Based Radio Frequency Electric Field Sensing1 , AKBAR J. JAHANGIRI, SANTOSH KUMAR, Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, 440 W. Brooks St. Norman, OK 73019, USA, HARALD KUEBLER, 5. Physikalisches Institut, Universitaet Stuttgart, Pfaffenwaldring 57 D-70550 Stuttgart, Germany, HAOQUAN FAN, JAMES P. SHAFFER, Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, 440 W. Brooks St. Norman, OK 73019, USA — We present progress on Rydberg atom-based RF electric field sensing using Rydberg atoms and electromagnetically induced transparency (EIT) in room temperature atomic vapor cells. In recent experiments on homodyne detection with a Mach-Zehnder interferometer and frequency modulation spectroscopy with active control of residual amplitude modulation we determined that photon shot noise on the probe laser detector limits the sensitivity. Another factor that limits the accuracy is residual Doppler broadening due to the wave-vector mismatch between the coupling and the probe lasers. The sensor as limited by project noise can be orders of magnitude better. A multi-photon scheme is presented that can eliminate the residual Doppler effect by matching the wave-vectors of three lasers and reduce the photon shot noise limit by correctly choosing the Rabi frequencies of the first two steps of the EIT scheme. Using density matrix calculations, we predict that the three-photon approach can improve the detection sensitivity to below 200 nV cm\(^{-1}\) Hz\(^{-1/2}\) and expand the Butler-Townes regime which improves the accuracy.

1This work is supported by DARPA and the NRO.

Q1.00005 Theoretical analysis of the oscillating frequency in spin-exchange optically pumped spin oscillators,1 , ZHI GUO WANG, Interdisciplinary Center of Quantum Information, National University of Defense Technology — The atomic spin precesses continually when a positive feedback magnetic field is applied. The characteristics of this behaviour depend not only on the parameters of the spin ensemble but also on the feedback loop. We theoretically analyzed direct feedback and phase-lock feedback modes. We also compared the oscillating frequency of the spin oscillators driven by rotating and linear magnetic fields. In the direct feedback mode, the spin oscillator has a characteristic time of approximately twice the longitudinal relaxation time T1, whereas in the phase lock feedback mode, the characteristic time is approximately the transverse relaxation time T2 when T2<<T1. When the spin ensemble is driven by the rotating field, its oscillating frequency is \(\omega = \omega_0 + \tan^2 \phi \omega_2 / T_2\), regardless of the feedback type. Here, \(\omega_0\) is the free Larmour frequency, and \(\phi\) is the phase shift of the feedback loop. When the spin ensemble is driven by the linear field, its oscillating frequency is much more complicated. These findings will be useful to improve the accuracy of fundamental physical theory tests, such as the Lorentz-violation and EDM test, using spin oscillators.

1Natural Science Foundation of China (No. 61671458)

Q1.00006 Distribution of Rb atoms on the antirelaxation RbH coating. , YI ZHANG, ZHI GUO WANG, TAO XIA, Interdisciplinary Center of Quantum Information, National University of Defense Technology — We observe the extension of relaxation time of \(^{133}\)Xe with RbH coating, and compare the different depositions of Rb atoms on the inner surface of the vapor cell with and without RbH coating respectively to research the mechanism of coating prolongation. From the 5\(\times\)5\(\times\)5\(\mu\)m\(^2\) images of microscopy, we find that on the bare glass surface the Rb atoms form large random separated islands, and to the contrary they deposite as many regular longitudinal stripes with small islands on the RbH coating. We attribute these different distributions to the different molecular interactions between RbH coating and bare glass to Rb atom and build a simple rational physical model to explain this phenomenon. On the one hand, the small islands, or in other words, the relative uniform distribution on RbH coating may result from the relative stronger interaction of Rb to RbH than to the bare glass. On the other hand, the regular longitudinal stripe may stem from the grain boundaries which is related to the macroscopic shape of the vapor cell. And this longitudinal distribution can generate cylindrically electric gradient as used in some theoretically references before.
Q1.00007 A study of temperature control related factors in Vapor cell heating mechanism design for atomic sensor. TAO XIA, ZHIGUO WANG, YI ZHANG, Interdisciplinary Center of Quantum Information, National University of Defense Technology, RECIPROCAL SOCIETY TEAM — Atomic sensor has become a very promising field of study in developing low cost, high-precision quantum measurement in a compact volume. A vapor cell which contains the working substance is usually a key element for an atomic sensor. It is always necessary to maintain the working substance, such as alkali metal, in gas state with high density. The precision of the sensor is usually closely related to temperature stability and homogeneity of the working substance in the cell. This work studied different temperature control methods, heater band or heating power arrangements, and heating rate settings in the cell heating mechanism design. Our study firstly shows that the better heat preservation we have, the better temperature stability we will obtain. It also shows that an appropriate control of power distribution in different heater band is important in ensuring a cold point in the cell, so that the solid state alkali metal will condense near a fixed cold point. And in order to ensure the fixed cold point always has a lower temperature when powering off the system, we should carefully control the heating power decrease for different heater band around the cell. At last, based on our study, we designed an optimized heating mechanism for atomic sensor implementation in the future.

Q1.00008 Study of magnetic resonance with parametric modulation in a potassium vapor cell. RUI ZHANG, Peking University and National University of Defense Technology, ZHIGUO WANG, National University of Defense Technology, XUAN PENG, WENHAO LI, SONGJIAN LI, Peking University, HONG GUO, Peking University and National University of Defense Technology, CREAM TEAM — A typical magnetic-resonance scheme employs a static bias magnetic field and an orthogonal driving magnetic field oscillating at the Larmor frequency, at which the atomic polarization precesses around the static magnetic field. We demonstrate in a potassium vapor cell the variations of the resonance condition and the spin precession dynamics resulting from the parametric modulation of the bias field, which are in well agreement with theoretical predictions from the Bloch equation. We show that, the driving magnetic field with the frequency detuned by different harmonics of the parametric modulation frequency can lead to resonance as well. Also, a series of frequency sidebands centered at the driving frequency and spaced by the parametric modulation frequency can be observed in the precession of the atomic polarization. These effects could be used in different atomic magnetometry applications.

Q1.00009 An NV-Diamond Magnetic Imager for Neuroscience. MATTHEW TURNER, Harvard University, JENNIFER SCHLOSS, Massachusetts Institute of Technology, ERIK BAUCH, CONNOR HART, RONALD WALSWORTH, Harvard University — We present recent progress towards imaging time-varying magnetic fields from neurons using nitrogen-vacancy centers in diamond. The diamond neuron imager is noninvasive, label-free, and achieves single-cell resolution and state-of-the-art broadband sensitivity. By imaging magnetic fields from injected currents in mammalian neurons, we will map functional neuronal network connections and illuminate biophysical properties of neurons invisible to traditional electrophysiology. Furthermore, through enhancing magnetometer sensitivity, we aim to demonstrate real-time imaging of action potentials from networks of mammalian neurons.

Q1.00010 Detecting Magnetic Monopoles in Spin Ice with NV-magnetometry. FELIX FICKLER, University of California, Berkeley, FRANZISKA KIRCHNER, Oxford University, NORMAN YAO, University of California, Berkeley, STEPHEN UNDELL, Oxford University — Magnetic monopoles, isolated north and south poles, appear not to exist as fundamental particles in our universe. Nevertheless, it has been proposed that they may emerge as quasiparticles in certain materials: the geometrically-frustrated ‘spin ice’ pyrochlores dysprosium and holmium titanate. Despite a great deal of experimental and theoretical work, the smoking gun signature of magnetic monopoles in spin ice remains to be discovered. A promising candidate for the detection of individual magnetic monopoles comes in the form of Nitrogen-Vacancy (NV) defects in diamond, which act as very sensitive probes of vector magnetic fields on the nanometre scale. We present recent progress towards imaging time-varying magnetic fields from neurons using nitrogen-vacancy centers in diamond. The diamond neuron imager is noninvasive, label-free, and achieves single-cell resolution and state-of-the-art broadband sensitivity. By imaging magnetic fields from injected currents in mammalian neurons, we will map functional neuronal network connections and illuminate biophysical properties of neurons invisible to traditional electrophysiology. Furthermore, through enhancing magnetometer sensitivity, we aim to demonstrate real-time imaging of action potentials from networks of mammalian neurons.

Q1.00011 SQCRAMscope imaging of transport in an iron-pnictide superconductor. FAN YANG, ALICIA KOLLAR, STEPHEN TAYLOR, JOHANNA PALMSTROM, Stanford University, JIUN-HAW CHU, Stanford University and University of Washington, IAN FISHER, BENJAMIN LEV, Stanford University — Microscopic imaging of local magnetic fields provides a window into the organizing principles of complex and technologically relevant condensed matter materials. However, a wide variety of intriguing strongly correlated and topologically non trivial materials exist poorly understood phenomena outside the detection capability of state-of-the-art high-sensitivity, high-resolution scanning probe magnetometers. We have recently introduced a quantum-noise-limited scanning probe magnetometer that can operate from room- to cryogenic temperatures with unprecedented DC-field sensitivity and micron-scale resolution. The Scanning Quantum Cryogenic Atom Microscope (SQCRAMscope) employs a magnetically levitated atomic Bose-Einstein condensate (BEC), thereby providing immunity to conductive and blackbody radiative heating. We will report on the first use of the SQCRAMscope for imaging a strongly correlated material. Specifically, we will present measurements of electron transport in iron-pnictide superconductors across the electron nematic phase transition at T = 135 K.

Q1.00012 Optical Magnetometry using Multipass Cells with overlapping beams. NATHANIEL DAVID MCDONOUGH, VITO GIOVANNI LUCIVERO, NEZIH DURAL, MICHAEL ROMALIS, Princeton Univ — In recent years, multipass cells with cylindrical mirrors have proven to be a successful way of making highly sensitive atomic magnetometers. In such a cell, a small laser beam makes 40 to 100 passes within the cell with significant overlap with itself. Here we describe a new multi-pass geometry which uses spherical mirrors to reflect the probe beam from one side of the cell to the other and back again, thereby reducing optical losses while preserving the advantages of multi-pass cells over standing-wave cavities, namely a deterministic number of passes and absence of interference. We have fabricated several cells with this geometry and obtained good agreement between the measured and calculated levels of quantum spin noise. We will report on our effort to characterize the diffusion spin-correlation function in these cells and operation of the cell as a magnetometer.

Q1.00013 Electrometry and Quantum Memory With Rydberg Atoms. DAVID MEYER, U. of Maryland — College Park, KEVIN COX, FREDRIK FATemi, PAUL KUNZ, U.S. Army Research Laboratory — Rydberg states of atoms with large principle quantum number n have extreme sensitivity to electric fields with dipole moments that scale as n^2. These states are proposed for applications in precision measurement of microwave electric fields and open new possibilities in quantum information science. First we present an experiment that uses thermal Rydberg atoms to measure amplitude-modulated (AM) RF fields. Amplitude modulation can improve state-of-the-art sensitivities already achieved using Rydberg atoms, and through AM we demonstrate a phase-shift-keying communication protocol. In addition, we present progress on a new experiment to trap laser-cooled Rydberg atoms in an optical cavity where the Rydberg blockade may allow a deterministic and high fidelity quantum memory for a high entanglement rate quantum repeater.
Q1.00014 Progress towards a primary, ultracold-atom-based pressure standard in the XHV regime. DANIEL S. BARKER, JULIA K. SCHERSCHLIGT, NIKOLAI N. KLIMOVI, JAMES A. FEDCHAK, STEPHEN ECKEL, Sensor Science Division, National Institute of Standards and Technology, Gaithersburg, MD 20899 — Preparation and evaluation of ultra-high-vacuum (UHV) and extreme-high-vacuum (XHV) environments is critical for high-quality semiconductor fabrication and emerging quantum technologies. Vacuum sensors for these pressure ranges, such as ion-gauges, are not primary (i.e., they require calibration themselves) and have large, poorly-understood uncertainties. We present our progress towards a primary standard for vacuum measurement in the XHV using a gas of ultra-cold atoms confined in a magnetic trap. Our apparatus will allow high-accuracy measurements of atom-molecule collision cross-sections that are necessary to extract the vacuum pressure from the observed background-gas-limited lifetime of the trapped atoms. We are also developing a chip-scale atom trap that integrates all the optics and electromagnets required to create magnetically-trapped, ultra-cold gases. This nano-fabricated atom-trapping chip will form the basis for a deployable, primary vacuum sensor with embedded traceability that can replace an ion gauge.

Q1.00015 Magnetic imaging of magnetotactic bacteria using NV centers in diamond. CHENCHEN LUO, Massachusetts Institute of Technology, PAULI KEHAYIAS, Harvard University, MATTHIEU AMOR, University of California, Berkeley, DAVID GLENN, Harvard University, ARASH KOMEILI, University of California, Berkeley, RONALD WALSWORTH, Harvard University — Nitrogen-vacancy (NV) centers in diamond can be used for room-temperature magnetometry with high spatial resolution (~1 micron). We use NV magnetic microscopy to image the magnetic fields produced by magnetotactic bacteria (MTB), which produce intracellular chains of 50 nm ferromagnetic particles to orient themselves in the Earth’s magnetic field. We will present recent advances on using this magnetic imaging tool to further understand how these particles are formed, how different genes and proteins influence particle formation, and other biomagnetism questions.

Q1.00016 Paleomagnetism studies with NV widefield magnetic microscopy. DAVID GLENN, Harvard University, ROGER FU, Columbia University, PAULI KEHAYIAS, Harvard University, EDUARDO LIMA, CHENCHEN LUO, BENJAMIN WEISS, Massachusetts Institute of Technology, RONALD WALSWORTH, Harvard University — We will discuss using nitrogen-vacancy (NV) defect centers in diamond to measure the magnetic field of rock samples for paleomagnetism analysis. NV magnetic microscopy achieves micron-scale spatial resolution that is otherwise inaccessible for rock paleomagnetism studies. This enables us to spatially distinguish between different ferromagnetic minerals and isolate high-coercivity magnetic inclusions from possible contamination. In addition to presenting continuing sensitivity and instrumentation improvements, we will describe ongoing paleomagnetism measurements, including constraining the magnetic field strength of the early Earth and assessing whether meteorite parent bodies had magnetic dynamo activity.

Q1.00017 Towards NV-based magnetic sensing in the time domain.1 ELANA URBACH, TAMÁRA SUMARAC, IGOR LOVCHINSKY, RENATE LANDIG, JAVIER SANCHEZ-YAMAGISHI, TROND ANDERSEN, HONGKUN PARK, MIKHAIL LUKIN, Harvard Univ — The study of protein folding dynamics is an outstanding problem in the biological sciences. We show that nitrogen-vacancy (NV) centers in diamond can be used to dynamically sense the conformational states of individual proteins under ambient conditions. We present preliminary data on time-domain detection of electronic spin labels which were chemically attached to the proteins, as well as label-free detection of native hydrogen nuclear spins within the protein. In addition, we discuss work towards polarizing boron-11 spins in atomically-thin hexagonal boron nitride using Hartmann-Hahn double resonance, with the ultimate goal of studying many-body spin dynamics and performing quantum simulation.

1This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE1144152.

Q1.00018 Imaging strain gradients inside a diamond anvil cell using Nitrogen-Vacancy Centers in Diamond. SATCHER HSIEH, THOMAS MITTIGA, CHONG ZU, Department of Physics, University of California, Berkeley, CA 94720, USA, THOMAS SMART, Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA, BRYCE KOBRIIN, Department of Physics, University of California, Berkeley, CA 94720, USA, VIKTOR STRUZHKIN, Geophysical Laboratory, Carnegie Institution of Washington, Washington DC 20015, USA, RAYMOND JEANLOZ, Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA, NORMAN YAO, Department of Physics, University of California, Berkeley, CA 94720, USA — Since their introduction, diamond anvil cells have become the most versatile approach to generating sustained high pressures inside the laboratory. By compressing a thin sample between two opposing diamonds, pressures over hundreds of gigapascals can be achieved. Despite their ubiquity, little is known about the internal mechanical response of the diamond anvil at such high pressures. By imaging ensembles of nitrogen-vacancy centers, we perform experimental measurements of strain gradients over a millimeter-size volume under gigapascal pressures. Our results inform the optimization of high pressure cell designs and demonstrate the integration of nitrogen-vacancy centers as atomic scale sensors in high pressure research.

Q1.00019 Study of Harmful Algae Blooms Using UAS Imagery. ILEANA DUMITRU, Hobart & William Smith Colleges, PETER SPACHER, Rochester Institute of Technology, JOHN HALFMAN, Hobart & William Smith Colleges — Harmful Algal Blooms (HABs) occurrence has increased in recent decades. The transient nature of HABs in both space and time result in monitoring challenges, which add to the difficulty in understanding the criteria that trigger HABs. Traditional monitoring programs are expensive and time consuming. The use of UAS (Unmanned Aerial Systems) assures high-resolution space and time monitoring for HABs, and is economical for small bodies of water. By using UAS (Matrice100 and Phantom3) we obtained aerial photographs of eight Finger Lakes which span the oligotrophic to eutrophic spectrum of algal productivity. Water samples were collected and analyzed simultaneously. The Green/Blue (G/B) ratio extracted from the aerial photos was proportional to chlorophyll-a abundance. The algal pigments are also characterized by unique light absorbance and reflectance features, and spectral images obtained from two up-down visible spectrometers revealed a prominent feature ~790 nm which correlates to the concentration of algae in the water.

Q1.00020 PRECISION MEASUREMENT —
Q1.0021 Testing the Rotation Stage in the ARIADNE Axion Experiment

JORDAN DARGERT, CHLOE LOHMeyer, MINDY HARKNESS, MARk CUNNINGHAM, University of Nevada, Reno, HARRY FOSBINDER-ELKINS, Princeton University, ANDREW GERACI, University of Nevada, Reno, ARIADNE COLLABORATION — The Axion Resonant InterAction Detection Experiment (ARIADNE) will search for the Peccei-Quinn (PQ) axion, a hypothetical particle that is a dark matter candidate. Using a new technique based on Nuclear Magnetic Resonance, this new method can probe well into the allowed PQ axion mass range \( M_\text{P} \leq 1 \). Additionally, it does not rely on cosmological assumptions, meaning that the PQ Axion would be sourced locally. Our project relies on the stability of a rotating segmented source mass and superconducting magnetic shielding. Superconducting shielding is essential for limiting magnetic noise, thus allowing a feasible level of sensitivity required for PQ Axion detection. Progress on testing the stability of the rotary mechanism will be reported, and the design for the superconducting shielding in the experiment will be discussed, along with plans for moving the experiment forward. \([1]\) A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014)

Q1.0022 Measurement of parity non-conservation in cesium using two-pathway coherent control

YAO DE GEORGE TOH, JUNGU Choi, DANIEL ELLIOTT, Purdue Univ — Atomic parity violation measurements provide a way to probe physics beyond the Standard Model. They can provide constraints on conjectures of a massive \( Z^0 \) boson or a light boson, or searches of dark energy. Using the two-pathway coherent control techniques developed by our group, we plan a new measurement of \( \Delta B_{2s} \) far above the detection threshold for Earth-like planets. Here, we use the Sun as a test case to better understand RV variations due to sunspots, convection, and other types of stellar activity. The HARPS-N spectrograph on La Palma has enabled such observations. Planet Search for the Northern Hemisphere (HARPS-N) provides a method to search for the Peccei-Quinn (PQ) axion, a hypothetical particle that is a dark matter candidate. Using a new technique based on Nuclear Magnetic Resonance, this new method can probe well into the allowed PQ axion mass range \( M_\text{P} \leq 1 \). Additionally, it does not rely on cosmological assumptions, meaning that the PQ Axion would be sourced locally. Our project relies on the stability of a rotating segmented source mass and superconducting magnetic shielding. Superconducting shielding is essential for limiting magnetic noise, thus allowing a feasible level of sensitivity required for PQ Axion detection. Progress on testing the stability of the rotary mechanism will be reported, and the design for the superconducting shielding in the experiment will be discussed, along with plans for moving the experiment forward. \([1]\) A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014)

1 NSF grant # PHY-1509176

Q1.0023 Using Global Network Precision Measurements to Search for Exotic Physics

ALEX ROLLINGS, BENJAMIN ROBERTS, GEOFFREY BLEWITT, CONNER DAILEY, University of Nevada, Reno, MAXIM POPOLEV, University of Victoria, Canada, TIMOTHY MILBOURNE, University of Nevada, Reno, Google DM COLLABORATION — The Global Positioning System (GPS) comprises of a constellation of approximately 30 Medium-Earth Orbit satellites equipped with Cs or Rubidium atomic clocks, as well as a number of Earth-based receiver stations, many of which employ highly-stable H-maser clocks. More than a decade’s worth of high accuracy GPS timing data is currently available. Such a constellation provides a unique opportunity; by analyzing the satellite and terrestrial atomic clock data, it is possible to search for transient signatures of exotic physics, such as dark matter and dark energy. In effect, we utilize the GPS constellation as a 50,000 km aperture dark matter detector. In this poster, we outline some of the details and challenges involved in employing such a network for fundamental physics research, in particular the Bayesian analysis methods that we use for the search. These methods do not only apply to the GPS atomic clocks. Similar approaches can be used for networks of ground-based atomic clocks, magnetometers, gravimeters, and any other precision measurement tools. A. Derevianko and M. Pospelov, Nat. Phys. 10, 933 (2014)

1 Supported by the NSF

Q1.0024 Progress towards measuring the Rydberg constant with circular Rydberg atoms

ANDIRA RAMES, KAITLIN MOORE, GEORG RAITHHEL, University of Michigan — An experiment to measure the Rydberg constant independently of nuclear-charge effects, such as the currently ambiguous proton-size puzzle, is underway. Cooled and trapped circular Rydberg atoms will be utilized for the measurement. These states, obtained by using the adiabatic rapid passage method (ARP), have the advantages of having lifetimes in the order of milliseconds, small QED corrections, and no ionic-core and nuclear-charge overlaps. The transition of interest will be driven via amplitude modulation of a three-dimensional standing-wave light field the atoms are immersed in, which results in a Doppler-free spectroscopic signal. In this poster, we discuss the design and construction of the circularization, field control and lattice schemes for this experiment.

Q1.0025 Quantum measurement and control of rapidly rotating single qubits in diamond

ALEXANDER WOOD, EMMANUEL LILETTE, YAAKOV FEIN, School of Physics, University of Melbourne, LIAM MCGUINNESS, Institute for Quantum optics, Ulm University, Germany, DAVID SIMPSON, ALASTAIR STACEY, JEAN-PHILLIPE TETIENNE, LLOYD HELLRIGL, EMMANUEL LILETTE, University of Melbourne and QCQCT, University of Melbourne, ROBERT SCHOLTEN, ANDY MARTIN, School of Physics, University of Melbourne — Internal state rotations are a ubiquitous feature of quantum mechanics, but the effects of physical rotation on a qubit are less widely understood. Rotation induces interesting physics, such as geometric phase accumulation in a rotating qubit, as well as concomitant challenges. The nitrogen-vacancy (NV) center in diamond is a highly versatile quantum sensor, capable of probing magnetic fields, electric fields, crystal strain and temperature in real-world sensing environments. The NV is a propitious candidate for observing the effects of physical rotation on a single qubit, for example as a nanoscale gyroscope. In this work we demonstrate optical addressing and quantum state manipulation of single NV centers within a diamond mechanically rotated with a period comparable to the spin dephasing time \( T_2^\ast \). Our results demonstrate measurements of single qubits rotating with high angular velocities, and establish the experimental techniques required to control and extract quantum information from rapidly moving NV centers.

Q1.0026 Atomic Spectroscopy of the Solar Atmosphere to Enable Earth-like Exoplanet Detection

TIMOTHY MILBOURNE, NICHOLAS LANGELLIER, AAKASH RAVI, CHRISTIAN DOLLIFF, Physics Department, Harvard University, DAVID PHILLIPS, Harvard-Smithsonian Center for Astrophysics, RONALD WALSWORTH, Physics Department, Harvard University, DAVID PHILLIPS, Harvard-Smithsonian Center for Astrophysics — The radial velocity (RV) method has proved to be one of the most prolific means of exoplanet detection. This technique uses measurements of periodic Doppler shifts of the stellar spectrum to deduce the mass and semi-major axis of orbiting exoplanets. The detection an Earth-like exoplanet orbiting a Sun-like star requires RV sensitivity below 10 cm/s (corresponding to kHz shifts of GHz-wide spectral lines). The installation of a laser-frequency “astro-comb” at the High Accuracy Radial velocity Planet Search for the Northern Hemisphere (HARPS-N) spectrograph on La Palma has enabled such observations. Exoplanet measurements is now limited by the noise of the stars themselves; sunspots, convection, and other types of stellar activity produce RV variations on the order of m/s, far above the detection threshold for Earth-like planets. Here, we use the Sun as a test case to better understand RV variations due to stellar activity. By comparing solar spectra taken by a purpose-built Solar Telescope on La Palma with images taken by the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO), we hope to identify feature in the solar spectrum which are correlated with solar activity. Such correlates will allow us to build more sophisticated models of stellar activity, and will enable more precise measurements of Earth-like exoplanets.
Q1.00027 High-precision atomic structure measurements in lead. ELI HOENIG, P.M. RUPASINGHE, P.K. MAJUMDER, Williams College — Two high-precision measurements of atomic parity nonconservation in lead were completed more than two decades ago. The ability of these tests to the Electroweak Standard Model was limited, however, by the poor accuracy of lead atomic structure calculations. Very recently, significantly improved wavefunction calculations in lead suggest that a new, precise electroweak test in this system may be possible. We have undertaken new measurements of atomic structure properties of lead to test the new calculations and guide their further refinement. Our direct absorption and Faraday optical rotation techniques, we are measuring isotope shifts and $^{207}$Pb hyperfine structure splittings in ground-state transitions. In particular we are measuring the electric quadrupole $6\Sigma_3 \rightarrow 6\Pi_1$ transition amplitude relative to the more-easily-calculable $6\Pi_1 \rightarrow 6\Pi_1$ magnetic dipole amplitude. The high sensitivity of our optical rotation technique allows the E2 and M1 absorptivities to be measured simultaneously in the same cell, even though the E2 transition strength is approximately two orders of magnitude smaller. Current experimental results will be presented.

1Work supported by NSF grant 1404206

Q1.00028 All-Optical Nanoscale Thermometry using Silicon-Vacancy Centers in Diamond, CHRISTIAN NGUYEN, RUFFIN EVANS, ALP SIAPIHALI, MIHIR BHASKAR, DENIS SUKACHEV, MIKHAIL LUKIN, Harvard University — Accurate thermometry at the nanoscale is a difficult challenge, but building such a thermometer would be a powerful tool for discovering and understanding new processes in biology, chemistry and physics. Applications include cell-selective treatment of disease, engineering of more efficient integrated circuits, or even the development of new chemical and biological reactions. In this work, we study how the bulk properties of the Silicon Vacancy center (SiV) in diamond depend on temperature, and use them to measure temperature with 100mK accuracy. Using SiVs in 200nm nanodiamonds, we measure the temperature with 100nm spatial resolution over a 10µm area.

Q1.00029 High-precision polarizability measurements in excited states of indium using two-step spectroscopy in an atomic beam, NATHANIEL VILAS, P.M. RUPASINGHE, P.K. MAJUMDER, Williams College — Recent measurements in our group of indium scalar polarization within two low-lying transitions showed excellent agreement with ab initio atomic theory at the 1-2% level. We are now completing measurements of the polarizability within the $6\Sigma_{1/2} \rightarrow 7\Pi_{1/2,3/2}$ excited-state transitions. In our experiment, two external cavity semiconductor diode lasers interact transversely with a collimated indium atomic beam. We tune a 410 nm laser to the $6\Sigma_{1/2} \rightarrow 6\Pi_{1/2}$ transition, keeping the laser locked to the exact Stark-shifted resonance frequency. We overlap a second (685 or 690 nm) laser to reach the $7\Pi_{3/2}$ excited states, using lock-in detection to observe its very small absorption in the atomic beam. Monitoring the two-step excitation signal in a field-free supplemental vapor cell provides frequency reference and calibration. Scalar polarizabilities for the $7\Pi$ states are 1-2 orders of magnitude larger than in previously measured transitions, so that application of modest, precisely calibrated electric fields of a few kV/cm produce Stark shifts of order 100 MHz. Fields of order 15 kV/cm can also be applied in order to extract the tensor polarizability of the $7\Pi_{1/2}$ state. Experimental details and latest results will be presented.

1Work supported by NSF grant 1404206

Q1.00030 Atomic Spectroscopy and Gaussian Processes to Enable Earth-like Exoplanet Detection, NICHOLAS LANGELIER, TIMOTHY MILBOURNE, AAKASH RAVI, CHRISTIAN DOLLIFF, Harvard Physics, DAVID PHILLIPS, Harvard Smithsonian Center for Astrophysics, RONALD WALSWORTH, Harvard Smithsonian Center for Astrophysics, Harvard Physics — Precision radial velocity (PRV) exoplanet astronomy has reached a critical sensitivity barrier in the detection of Earth-like planets. We describe techniques to overcome this barrier. We have developed a small solar telescope located in the Canary Islands, which we use to observe the Sun as a point source of light, i.e., as if it was a distant star. We are employing methods from atomic spectroscopy and Gaussian processes to analyze the Sun-as-a-star data, and thereby to understand systematic effects on PRV signals arising from “stellar jitter” (oscillations, sunspots, etc.).

Q1.00031 Proposal for Two-Photon Doppler-Free Extreme Ultraviolet Direct Frequency Comb Spectroscopy of the Helium Ground State, GIL PORAT, CHRISTOPH M. HEYL, STEPHEN B. SCHOUN, JUN YE, JILLA, NIST and the University of Colorado — Tests of quantum electrodynamics (QED) are part of the search for physics beyond the standard model. QED calculations are most precise in simple systems, e.g., few-electron atoms. Hydrogen spectroscopy yielded the most stringent test so far, however QED effects are stronger in helium ground state transitions. Furthermore, experimental results disagree on the $3\Sigma^+ - 1\Sigma^+$ nuclear charge radius difference, measured using excited state transitions. This discrepancy might be related to the proton radius puzzle, and could potentially be resolved by measuring a helium ground state transition, where the effect of the nucleus is greatest. However, such transitions are in the extreme ultraviolet (XUV), where the only available stabilized laser is a frequency comb, which has so far lacked sufficient power for direct spectroscopy. We propose to perform direct two-photon frequency comb spectroscopy of the 20.6eV $1\Sigma^+ - 2\Sigma^+$ transition in helium, using a cell of cryogenic helium. This approach just became available, due to our success in scaling the power of our XUV frequency comb. The use of cold (~4K) helium gas significantly reduces transit-time broadening and also allows for high gas densities. We expect to achieve the first spectroscopic measurement in the XUV with sub-MHz precision.

1We acknowledge support for this work from NIST, AFOSR, and NSF.

Q1.00032 Development of a position sensitive detector for Rydberg atom experiments, MELINA FUENTES-GARCIA, ADRIC JONES, JEREMY MOXOM, DANIEL ADAMS, GABRIEL CECCHINI, HARRIS RUTBECK-GOLDMAN, KEVIN OSORNO, ROD GREAVES, HARRY TOM, ALLEN MILLS, Univ of California - Riverside — Since their invention, resistive anodes have played an important role in the imaging systems of many experiments. They are commonly used in conjunction with micro-channel plate detectors, which can greatly enhance the positional sensitivity. It is well known that the use of a square anode results in significant distortion in the positional mapping, which can be resolved by careful shaping of the anode. Here we utilize a square anode and correct the position data in post-analysis. We describe the development of such a paired system for use in our positronium (Ps) beam line, designed specifically for the detection of Rydberg Ps atoms. The first experimental results obtained with the detector demonstrated the focusing of a beam of Rydberg Ps by means of an electrostatic mirror. By employing a larger scale version of this apparatus, it should be possible to measure the gravitational deflection of Rydberg Ps atoms in Earth’s field to high precision.

1Work supported by NSF grants PHY 1404576 and PHY 1505903.
Q1.00033 Fetal Magnetocardiography with an Atomic Magnetometer Array. Michael Bulatowicz, Zack Deland, Lena Zhivun, Alec Hryciuk, Ron Wakai, Thad Walker, University of Wisconsin - Madison — We present the results of fetal magnetocardiography utilizing an array of four atomic magnetometers with simultaneous two-vector-component detection of magnetic fields resulting from a fetal heartbeat. Each magnetometer in the array contains an individual cell with 87Rb and buffer gas, operated in a SERF regime using orthogonal pump and probe beams, combined with parametric modulation along the pump beam for simultaneous two-vector-component detection of magnetic fields with a noise floor around 5 fT/rtHz. This work is supported by the National Institutes of Health.

Q1.00034 Ionization potentials of superheavy elements No, Lr, and Rf and their ions. Marianna SafroNova, University of Delaware, Vladimir Dzuba, School of Physics, UNSW, Australia, Ulyana SafroNova, University of Nevada, Reno, Alexander Kramida, National Institute of Standards and Technology, Gaithersburg — We predict ionization potentials of superheavy elements No, Lr, and Rf and their ions using a relativistic hybrid method that combines configuration interaction (CI) with the linearized coupled-cluster approach. We expect these values to be accurate to about 350 cm⁻¹. Extensive study of the completeness of the four-electron Cl calculations for Hf and Rf was carried out. As a test of theoretical accuracy, we also calculated ionization potential of Yb, Lu, Hf, and their ions, which are homologues of the superheavy elements of this study. The test demonstrated that the CI + all-order method is capable of predicting ionization potentials of ions with 1 to 4 valence electron to a very good precision, which may be used to provide improved recommended data.

Q1.00035 Precision Measurements with a Dual Species NMR Oscillator. Susan Sorensen, Daniel Thrasher, Joshua Weber, Anna Korver, Thad Walker, University of Wisconsin - Madison — We present progress towards a dual species nuclear magnetic oscillator using synchronous optical pumping. By applying the bias field as a sequence of alkali 2πn pulses, we generate alkali polarization transverse to the bias field. The alkali polarization is then modulated at the noble gas resonance so that through spin exchange collisions the noble gas becomes polarized. This novel method of NMR suppresses the alkali field frequency shift by at least a factor of 2500 as compared to longitudinal NMR. We will present a detailed noise analysis of the apparatus as well as plans for measuring earths rotation.

Q1.00036 Ultralight dark matter signatures in precision measurements. Andrei Derevianko, University of Nevada, Reno — Virialized Ultra-Light Fields (VULFs) while being viable cold dark matter candidates can in a certain parameter space also solve the standard model hierarchy problem. Direct searches for VULFs due to their non-particle nature require low-energy precision measurement tools. While the previous proposals have focused on detecting coherent oscillations of the measured signals at the VULF Compton frequencies, here we exploit the fact that VULFs are essentially dark matter waves and as such they carry both temporal and spatial phase information. Thereby the discovery reach can be improved by using distributed networks of precision measurement tools. We find the expected dark-matter signal by deriving the spatio-temporal two-point VULF correlation function. Based on the developed understanding of coherence properties of dark-matter fields, we propose several experiments for dark matter wave detection. In the most basic version, the modifications to already running experiments are minor and only require GPS-assisted time-stamping of data. We also derive the expected dark matter line profile for individual detectors.

Q1.00037 Constraining dark energy scalar fields using atom interferometry. Victoria Xu, Matt Jaffe, Philipp Haslinger, Univ of California - Berkeley, Paul Hamilton, Univ of California - Los Angeles, Amol Upadhye, University of Wisconsin - Madison, Benjamin Elder, Justin Khoury, Univ of Pennsylvania, Holger Mueller, Univ of California - Berkeley — Atom interferometry has proven to be a technique capable of making precise gravitational measurements. Typically, however, these measurements probe the gravitational forces of large source masses, such as the Earth. We perform atom interferometry in an optical cavity near a centimeter-sized, in-vacuum source mass. By observing the gravitational attraction between a 190 gram miniature source mass and atoms for the first time, our measurement is sensitive to a wide class of screened scalar fields which would manifest as a fifth-force with a matter coupling as weak as gravity, a natural lower bound for fundamental forces. In particular, we improve our previous limits on “screened” scalar field theories which can reproduce the observed cosmic acceleration by over two orders of magnitude.

Q1.00038 Ionization potentials of superheavy elements No, Lr, and Rf and their ions, Marianna SafroNova, University of Delaware, Vladimir Dzuba, School of Physics, UNSW, Australia, Ulyana SafroNova, University of Nevada, Reno, Alexander Kramida, National Institute of Standards and Technology, Gaithersburg — We predict ionization potentials of superheavy elements No, Lr, and Rf and their ions using a relativistic hybrid method that combines configuration interaction (CI) with the linearized coupled-cluster approach. We expect these values to be accurate to about 350 cm⁻¹. Extensive study of the completeness of the four-electron CI calculations for Hf and Rf was carried out. As a test of theoretical accuracy, we also calculated ionization potential of Yb, Lu, Hf, and their ions, which are homologues of the superheavy elements of this study. The test demonstrated that the CI + all-order method is capable of predicting ionization potentials of ions with 1 to 4 valence electron to a very good precision, which may be used to provide improved recommended data.

Q1.00039 Exactly solvable interacting number-conserving models with Majorana-like ground states. Zhiyuan Wang, Youjiang Xu, Han Pu, Kaden Hazzard, Rice University — Majorana fermions have sparked interest in condensed matter and cold atoms as emergent quasiparticles with fundamentally new properties, in particular non-Abelian statistics. However, most theoretical calculations start with a Bogoliubov mean-field approximation from which it is shown that the resulting model supports Majorana states. It then remains an open question whether and when this mean-field approximation is valid. We make progress towards this question in two ways. First, we demonstrate a model in which mean-field theory incorrectly predicts a gapped phase with Majorana ground states, whereas an unbiased DMRG calculation predicts a gapless phase instead. Second, we construct new families of exactly solvable interacting models, including a one-dimensional double wire lattice model and a two dimensional p+ip superconducting model. Significantly, these models are number-conserving but nevertheless can be shown to host robust Majorana-like degenerate ground states in the presence of edges and vortices. These results give a deeper conceptual understanding of how Majorana fermions can be realized in practice.
Q1.00040 Topology transfer from interacting systems to free lattice fermions, RUI LI, Univ. of Kaiserslautern, DOMINIK LINZNER, Univ. of Darmstadt, MICHAEL FLEISCHHAUER, Univ. of Kaiserslautern — We show that the topological properties of an interacting, one-dimensional lattice system can be transferred to non-interacting lattice fermions by proximity coupling. A cyclic variation of parameters in the interacting system, corresponding to a topological Thouless pump, is shown to result in a quantized fractional charge transport of the free fermions. We argue that this transfer of topological properties can be used to detect topological invariants of interacting systems with the potential advantage of being insensitive to topological excitations, which limit interferometric schemes [1]. We discuss in particular the extended superlattice Bose-Hubbard model (SLBHM) in one spatial dimension at quarter filling which has a degenerate ground state and fractional topological phases. Proximity coupling to a one-dimensional lattice of non-interacting fermions leads to the formation of an incompressible phase of the fermions at quarter filling. Performing a Thouless pump in the SLBHM system would result in a quantized charge transport in the fermionic system. We analyze the robustness of the induced charge pump and argue that it allows to detect the fractional Chern number associated with the SLBHM even in the presence of defects. [1] F. Grusdt et. al. Nature Comm. 7, 11994 (2016)

Q1.00041 Disordered wires and quantum chaos in a momentum-space lattice, ERIC MEIER, FANGZHAO AN, JACKSON ANGONGA, BRYCE GADWAY, Univ of Illinois - Urbana — We present two topics: topological wires subjected to disorder and quantum chaos in a spin-J model. These studies are experimentally realized through the use of a momentum-space lattice, in which the dynamics of $^{87}$Rb atoms are recorded. In topological wires, a transition to a trivial phase is seen when disorder is applied to either the tunneling strengths or site energies. This transition is detected using both charge-pumping and Hamiltonian-quenching techniques. In the spin-J study we observe the effects of both linear and non-linear spin operations by measuring the linear entropy of the system as well as the out-of-time order correlation function. We further probe the chaotic signatures of the paradigmatic kicked top model.

Q1.00042 Ultracold atom dynamics in tailored disorder and synthetic gauge fields, FANGZHAO AN, ERIC MEIER, BRYCE GADWAY, Univ of Illinois - Urbana — Ultracold atoms in optical lattices have shown to be a versatile and useful platform for investigating a wide range of transport phenomena. Here we extend the range of cold atom quantum simulation with key advances in the study of both disordered and topological systems. By controlling laser-driven dynamics of a $^{87}$Rb condensate in a momentum-space lattice, we demonstrate and apply our ability to engineer arbitrary patterns of disorder and flux (and thus field strength). We compare the dynamical responses to static tunneling phase disorder, dynamically-varying phase disorder akin to coupling with a thermal bath, and quasiperiodic site energy disorder. We study synthetic gauge fields in both a two-leg square ladder geometry and a zig-zag ladder geometry. We present measurements of chiral edge states in a uniform flux ladder, and of quantum reflection in the presence of an effective magnetic defect. We show similar flux-dependent dynamics in the zig-zag ladder, and further observe a flux-dependent metal-insulator transition in the presence of quasiperiodic disorder.

Q1.00043 Topological states of photons in coupled microwave cavities, JOHN OWENS, AMAN LACHAPELLE, RUICHAO MA, BRENDAH SAXBERG, JONATHAN SIMON, DAVID SCHUSTER, University of Chicago — We present recent results in using coupled cavity arrays to explore quantum many-body phenomena. We create tight binding lattices with arrays of evanescently coupled three-dimensional coaxial microwave cavities. Topologically non-trivial band structures are engineered by utilizing the chiral coupling of the cavity modes to ferrite spheres in a magnetic field. Using screws made of different dielectric material, we can control every lattice site frequency, loss, and coupling strength to its neighbors. We then can probe each lattice site and measure the band structure, the edge dispersion, and time-resolved dynamics of pulses we inject at a particular site. These lattices can be cooled to superconducting temperatures to realize low disorder, long-coherence, topological tight binding models that are compatible with effective onsite photon-photon interactions by coupling lattice sites to superconducting qubits. This will allow us to explore the interplay between topology and coherent interaction in these artificial strongly-correlated photonic quantum materials.

Q1.00044 Symmetry-based dissipative preparation of matrix product states, LEO ZHOU, SOONWON CHOI, MIKHAIL LUKIN, Harvard University — Matrix product states (MPS) are a powerful class of many-body entangled states capable of describing a variety of quantum systems in 1D, including all symmetry-protected topological (SPT) phases. The symmetry of an MPS can be exploited for a simple scheme that prepares the state dissipatively. As an example, we provide an explicit scheme to prepare the Affleck-Kennedy-Lieb-Tasaki (AKLT) states, which exhibit spin-1 SPT order characterized by string order parameters and spin-1/2 degrees of freedom on the boundary. In our scheme, we harness the symmetry of the AKLT parent Hamiltonian to design a simple driven-dissipative dynamics requiring only global control, under which an arbitrary initial state deterministically evolves into one of the ground states. The use of symmetry allows for robust experimental implementation where no fine-tuning of control parameters is required while still leading to an exact steady state. We demonstrate our scheme via numerical simulations, and propose an efficient method using parallelization to prepare the quantum state even in large system sizes. A concrete protocol for implementation in an array of trapped neutral atoms is also presented.

Q1.00045 Holographic driving and probing of a twisted optical resonator for exploration of topological physics, NATHAN SCHINE, MICHELLE CHALUPNIK, JONATHAN SIMON, Univ of Chicago — Nontrivial topology is at the heart of a host of intriguing phenomena in condensed matter physics. Synthetic materials consisting of a quantum gas of photons or ultracold atoms have established themselves as ideal systems to explore these phenomena. As experiments push into the strongly-interacting, strongly-correlated regime, characterizing topological many-body states through measurements of topological quantum numbers becomes critical. We present a real-space Chern number measurement in a photonic integer quantum Hall system, produced in a degenerate topological model of a multimode ring resonator. We will present how we control the spatial excitation of the resonator and perform holographic reconstruction of the resulting modes. From this, we measure arbitrary ‘band projectors’ from which the Chern number is calculated. This system and measurement technique is compatible with strong interactions via cavity Rydberg electromagnetically induced transparency, enabling the preparation and characterization of novel manybody quantum states.

Q1.00046 DYNAMICS OF COLD ATOMS IN OPTICAL LATTICES –
Q1.00047 Quench-induced resonant tunneling mechanisms of bosons in an optical lattice with harmonic confinement. The non-equilibrium dynamics of small boson ensembles in one-dimensional optical lattices is explored upon a sudden quench of an additional harmonic trap from strong to weak confinement. We find that the competition between the initial localization and the repulsive interaction leads to a resonant response of the system for intermediate quench amplitudes, corresponding to avoided crossings in the many-body eigenspectrum with varying final trap frequency. In particular, we show that these avoided crossings can be utilized to prepare the system in a desired state. The dynamical response is shown to depend on both the interaction strength as well as the number of atoms manifesting the many-body nature of the tunneling dynamics.

Q1.00048 Multipulse interaction quenched ultracold few-bosonic ensembles in finite optical lattices. The correlated non-equilibrium dynamics following a multipulse interaction quench protocol in few-bosonic ensembles confined in finite optical lattices is investigated. The multipulse interaction quench gives rise to the cradle [1,2] and a global breathing mode. These modes are generated during the interaction pulse and persist also after the pulse. The corresponding tunneling dynamics consists of several energy channels accompanying the dynamics. The majority of the tunneling channels persist after the pulse, while only a few occur during the pulse. The induced excitation dynamics is also explored and a strong non-linear dependence on the delayed time of the multipulse protocol is observed. Moreover, the character of the excitation dynamics is also manifested by the periodic population of higher-lying lattice momenta. The above mentioned findings pave the way for future investigations on the direct control of the excitation dynamics. [1] S.I. Mistakidis, L. Cao, and P. Schmelcher, J. Phys. B: At. Mol. and Opt. Phys., 47, 225303 (2014). [2] S.I. Mistakidis, L. Cao, and P. Schmelcher, Phys. Rev. A, 91, 033611 (2015).

Q1.00049 Quantum walks assisted by particle number fluctuations. We consider quantum walks of particles governed by lattice Hamiltonians with particle-number changing interactions. We show that such interactions, even if weak, accelerate quantum walks at short times due to Rabi oscillations between different particle number subspaces. We examine the dynamics of quantum walks governed by Hamiltonians arising in the context of D-wave quantum annealing experiments and experiments with excitations of ultracold molecules in optical lattices. The same Hamiltonians describe excitations in ensembles of highly magnetic atoms, such as Dy.

Q1.00050 Studying matter-wave emission with ultracold atoms in an optical lattice. We report experimental and theoretical progress on the implementation of the Weisskopf-Wigner Hamiltonian in an optical lattice scenario. In our system, lattice-trapped atoms are coupled to a continuum of freely moving, untrapped states via an internal state transition. This fully tunable system allows for studies of a plethora of effects including the transition from Markovian to non-Markovian decay and evanescently bound matter-waves. Recent technological advancements in our laboratory, including the development of a blue-detuned optical lattice and a method to measure magnetic fields to high accuracy, will allow for the exploration of new regimes in these models, especially many-body effects such as superradiant dynamics and extended range (tunneling) Hubbard models.

Q1.00051 Experimental realization of a subwavelength optical potential based on atomic dark state. We report on progress towards controlling single strontium atoms in large, defect-free arrays of optical tweezers. Strontium has both bosonic and fermionic species with narrow optical transitions and magic wavelengths, which enable robust cooling, trapping, and coherent manipulation. By using state of the art light shaping technologies and long vacuum-limited lifetimes, we expect to create defect-free arrays of several hundred atoms. We also explore strategies for sideband cooling and non-destructive imaging in optical dipole traps.
Q1.00053 1D array of dark spot traps formed by counter-propagating nested Gaussian laser beams for trapping and moving atomic qubits. KATHARINA GILLEN-CHRISTANDL, California Polytechnic State University, Anais Luís Osbopo, TRAVIS D. FRAZER, JILA, University of Colorado, Boulder — The standing wave of two identical counter-propagating Gaussian laser beams constitutes a 1D array of bright spots that can serve as traps for single neutral atoms for quantum information operations [1]. Detuning the frequency of one of the beams causes the array to start moving, effectively forming a conveyor belt for the qubits [1]. Using a pair of nested Gaussian laser beams with different beam waists, however, forms a standing wave with a 1D array of dark spot traps confined in all dimensions [2]. We have computationally explored the trap properties and limitations of this configuration and, trading off trap depth and frequencies with the number of traps and trap photon scattering rates, we determined the laser powers and beam waists needed for useful 1D arrays of dark spot traps for trapping and transporting atomic qubits in neutral atom quantum computing platforms. [1] D. Schrader et al., Appl. Phys. B 73, 819 (2001); [2] P. Zemánek, C. J. Foot, Opt. Comm. 146, 119 (1998).

Q1.00054 Superfluid in a shaken optical lattice: quantum critical dynamics and topological defect engineering. ANITA GAJ, LEI FENG, LOGAN W. CLARK, CHENG CHIN, University of Chicago — We present our recent studies of non-equilibrium dynamics in Bose-Einstein condensates using the shaken optical lattice. By increasing the shaking amplitude we observe a quantum phase transition from an ordinary superfluid to an effectively ferromagnetic superfluid composed of discrete domains with different quasi-momentum. We investigate the critical dynamics during which the domain structure remains stable and walls emerge. We demonstrate the use of a digital micro-mirror device to deterministically create desired domain structure. Using this technique we develop a clearer picture of the quantum critical dynamics at early times and its impact on the domain structure long after the transition.

Q1.00055 Quantum many-body dynamics of strongly interacting atom arrays. HANNE BERNIER, ALEXANDER KEELING, HARRY LEVINE, SYLVAIN SCHWARTZ, AHMED OMRAH, ERIC ANSCHUETZ, Harvard University, MANUEL ENDRÈS, Caltech, VLADAN VULETIC, Massachusetts Institute of Technology, MARKUS GREINER, MHIKAIL LUKIN, Harvard University — The coherent interaction between large numbers of particles gives rise to fascinating quantum many-body effects and lies at the heart of quantum simulations and quantum information processing. The development of systems consisting of many, well-controlled particles with tunable interactions is an outstanding challenge. Here we present a new platform based on large, reconfigurable arrays of individually trapped atoms[1]. Strong interactions between these atoms are enabled by exciting them to Rydberg states. This flexible approach allows access to vastly different regimes with interactions tunable over several orders of magnitude. We study the coherent many-body dynamics in varying array geometries and observe the formation of Rydberg crystals. [1] Science 354, 1024 (2016)

Q1.00056 Observation of quantum thermalization and progress towards the many-body localized regime. ADAM KAUFMAN, ERIC TAI, ALEX LUKIN, MATTHEW RISPOLI, ROBERT SCHITTOKO, TIM MENKE, Harvard University, PHILIPP PREISS, University of Heidelberg, MARKUS GREINER, Harvard University — In classical thermodynamics entropy plays a crucial role. A classical many-body system equilibrates to a maximally entropic state, and will quickly re-thermalize when perturbed. In contrast, the total entropy of an isolated quantum many-body system does not change following a global or local quantum quench. Nevertheless, sufficient local observables quickly thermalize to steady state values which are well described by entropic thermal ensembles. Surprisingly, this thermalization is absent in the presence of sufficiently high disorder. In this regime, the system can retain memory of its initial state even at infinite times. We explore these phenomena in a 1D Bose-Hubbard system of ultracold rubidium atoms under a quantum gas microscope. Our microscope gives us unique access to local observables as well as the ability to measure entanglement entropy both locally and globally. We observe a fast growth in subsystems' entanglement entropy after the quench and describe how it provides thermalization for local observables. We have now added disorder to our system to study the breakdown of thermalization in the many-body localized regime; we will present our progress towards these measurements.

Q1.00057 Effective three-body interactions of ultracold bosons in anharmonic traps. PHILIP JOHNSON, Department of Physics, American University, Washington DC, EITE TIESINGA, Joint Quantum Institute, NIST and University of Maryland — The influence of elastic effective three- and higher-body interactions, induced by virtual excitations of ground-state bosons to excited vibrational states (higher bands in the case of periodic potentials), are seen in a number of experiments with trapped ultracold atoms in optical lattices. One of the most intriguing signatures, revealed in collapse-and-revival experiments, is a significant modification of the phase dynamics of superfluid bosons. We find, however, a significant deviation between the experimental data for atoms in optical lattices, and theoretical calculations based on harmonic trapping potentials. Using a number of model potentials with varying degrees and types of anharmonicity, we show that effective interaction strengths are highly sensitive to trap shape and anharmonic corrections must be taken into account when analyzing this physics.

Q1.00058 An apparatus for simulating lattice spin models with Rydberg-dressed cesium atoms. OGNJEN MARKOVIC, VICTORIA BORISH, JACOB HINES, MONIKA SCHLEIER-SMITH, Stanford University — Rydberg-dressed cesium atoms provide a versatile platform for engineering lattice spin models for studies of frustrated magnetism and quantum many-body dynamics. We present the design of an experiment that is optimized for achieving highly coherent and dynamically controllable interactions. Cesium atoms will be pinned in a two-dimensional optical lattice of 1–2 μm spacing and coupled to the Rydberg manifold with a single ultraviolet photon. A flexible experimental chamber design will permit close optical access for trapping, imaging and addressing, while simultaneously enabling control of the electric field to enhance the strength of interactions or switch their sign. The large interatomic spacing will facilitate single-spin-resolved detection for detailed characterization of many-body quantum states.

Q1.00059 LASER COOLING AND TRAPPING —

Q1.00060 Reducing photoassociation and light assisted collisions in tightly confined geometries. ALBAN URVOY, JIAZHONG HU, ZACHARY VENDEIRO, WENLAN CHEN, VLADAN VULETIC, Massachusetts Institute of Technology — Light-induced binary loss mechanisms have dramatic consequences for the manipulation of cold atoms with light fields, limiting the performance of optical cooling schemes at high atomic densities, as well as the in-situ observation of atoms in quantum gas microscopes. Here we present our results on several methods for reducing such loss mechanisms for atoms tightly confined in optical lattices. First we show that using light that is far detuned to the red of the atomic transition significantly reduces light-induced binary losses, as predicted by theory. Then we discuss how these loss mechanisms are modified by light scattering effects in low dimension and tightly-confined gases, based on our observation of anomalously low light-induced loss rates.
Q1.00061 Laser cooling and compression of an atomic beam for use in a focused ion beam, STEINAR T.W. WOUTERS, GUS TEN HAAF, TIM C.H. DE RAADT, PETER H.A. MUTSAERS, EDGAR J.D. VREDENBREGT, Eindhoven University of Technology — Magneto-optical compression is performed on a thermal beam of rubidium atoms effusing from a collimated Knudsen source with the aim of generating a high density, low temperature atomic beam that can be ionized into a high brightness ion beam. Such an ion beam can be used in a focused ion beam system (FIB) that is widely used in science and industry to image and modify structures at the nanoscale. Simulations of the proposed setup including the compact magneto-optical compressor, photo-ionization and ion beam focusing have shown that a 1 nm resolution can be achieved, for rubidium at a beam current of 1 pA and 30 keV energy. This will be a major improvement over commercial offerings. A collimated Knudsen source for rubidium has been constructed and characterized. The resulting atomic beam is loaded into a compact (70 mm long) magneto-optical compressor (MOC). Behind the MOC sub-Doppler cooling is applied to lower the transverse temperature even further. The resulting beam flux is equivalent to 0.6 nA and the brightness of the beam reads $6 \times 10^7$ A/m$^2$/sr/eV which is an order of magnitude higher than conventional ion sources promising a higher resolution. This contribution reports about the experimental characterization of the Knudsen source, MOC and sub-Doppler cooler.

Q1.00062 Dipole Trapping under Microgravity, CHRISTIAN VOGT, MARIAN WOLTMANN, SVEN HERMANN, CLAUS LMMERZAHL, ZARM, University of Bremen, PRIMUS TEAM — The PRIMUS-Project will be testing the weak equivalence principle (WEP) with a two species (Rb and K) atom interferometer under microgravity. Microgravity offers the benefit of largely extended free evolution times of the atomic ensembles, which significantly enhances the sensitivity. As microgravity platform we chose the drop tower in Bremen, a free fall tower with a height of 110m, which allows for a free fall time of 4.7s and excellent microgravity quality. Contrary to similar projects using an atomic chip (e.g. CAL or QUANTUS), the cold atomic ensembles will be prepared in a dipole trap with a wavelength of about 2m and a maximum Power of about 10W directly loaded from a 3D-MOT. Dipole Traps have several advantages like a symmetric trap shape and the availability of Feshbach Resonances. They are well established in ground based experiments and will most likely play a major role in space born cold atom experiments. In this manner our project also serves as a pathfinder experiment for further cold atom tests of fundamental physics. Within this work we were just recently able to produce the first dipole trap under microgravity. The talk will be about the current status of the project.

1We acknowledge support by the German Space Agency DLR with funds provided by the Federal Ministry of Technology (BMWi) under grant number DLR 50 WM1642.

Q1.00063 Achieving Translationally Invariant Trapped Ion Rings, ERIK URBAN, HAO-KUN LI, CRYSTAL NOEL, BOERGE HEMLING, XIANG ZHANG, HARTMUT HAEFFNER, UC Berkeley — We present the design and implementation of a novel surface ion trap design in a ring configuration. By eliminating the need for wire bonds through the use of electrical vias and using a rotationally invariant electrode configuration, we have realized a trap that is able to trap up to 20 ions in a ring geometry 45um in diameter, 400um above the trap surface. This large trapping height to ring diameter ratio allows for global addressing of the ring with both lasers and electric fields in the chamber, thereby increasing our ability to control the ring as a whole. Applying compensating electric fields, we measure very low tangential trap frequencies (less than 20kHz) corresponding to rotational barriers down to 4mK. This measurement is currently limited by the temperature of the ions but extrapolation indicates the barrier can be reduced much further with more advanced cooling techniques. Finally, we show that we are able to reduce this energy barrier sufficiently such that the ions are able to overcome it either through thermal motion or rotational motion and delocalize over the full extent of the ring.

1This work was funded by the Keck Foundation and the NSF

Q1.00064 Entrainment of lithium atoms into a supersonic beam and magnetic deceleration, YU LU, LUKAS GRADL, LICHUNG HA, LOGAN HILLBERRY, KEVIN MELIN, PAVEL NAGORNYKH, JORDAN ZESCH, MARK RAIZEN, UT Austin — We report our progress on the development of an alternative to laser cooling of neutral atoms, using all atomic physics as the benchmark for a direct comparison. The first step is optimization of entrainment of lithium into a supersonic beam followed by magnetic deceleration. We create a supersonic beam of cold helium gas by pulsing on an Even-Lavie valve, which then crosses lithium vapor generated by a directional oven. The resulting entrainment number and temperature of the lithium atoms are measured downstream with a hot-wire detector. In order to further optimize entrainment, we developed a pulsed atomic source that is synchronized with the supersonic valve with an appropriate delay time. Lithium atoms from the directional oven accumulate on a thin metallic ribbon and are quickly evaporated as a hot-wire detector. In order to further optimize entrainment, we developed a pulsed atomic source that is synchronized with the supersonic valve with an appropriate delay time. Lithium atoms from the directional oven accumulate on a thin metallic ribbon and are quickly evaporated as a hot-wire detector. In order to further optimize entrainment, we developed a pulsed atomic source that is synchronized with the supersonic valve with an appropriate delay time. Lithium atoms from the directional oven accumulate on a thin metallic ribbon and are quickly evaporated as a hot-wire detector. In order to further optimize entrainment, we developed a pulsed atomic source that is synchronized with the supersonic valve with an appropriate delay time. Lithium atoms from the directional oven accumulate on a thin metallic ribbon and are quickly evaporated as a hot-wire detector. In order to further optimize entrainment, we developed a pulsed atomic source that is synchronized with the supersonic valve with an appropriate delay time. Lithium atoms from the directional oven accumulate on a thin metallic ribbon and are quickly evaporated as a hot-wire detector.

1W.M. Keck Foundation

Q1.00065 Narrow-line cooling of neutral Holmium, WILLIAM MILNER, CHRISTOPHER YIP, DONALD BOOTH, MARK SAFFMAN, University of Wisconsin-Madison — Neutral Holmiums 128 ground hyperfine states, the most of any non-radioactive element, is a testbed for quantum control of a very high dimensional Hilbert space, and offers a promising platform for quantum computing. BOOTH, MARK SAFFMAN, University of Wisconsin-Madison — Neutral Holmiums 128 ground hyperfine states, the most of any non-radioactive element, is a testbed for quantum control of a very high dimensional Hilbert space, and offers a promising platform for quantum computing. Previously, we have cooled Holmium atoms in a MOT on a 410.5 nm transition with a Doppler temperature of 780 $\mu$K and characterized its Rydberg spectra. Following these past results, we are currently working towards narrow-line cooling on a 412 nm line with a Doppler temperature of 35 $\mu$K, allowing colder MOT temperatures. We have experimentally determined the excited state hyperfine constants of this transition and will present progress towards cooling on the F = 11 to F' = 12 hyperfine transition of the 412 nm line.

1This work was supported by NSF award PHY-1404357.

Q1.00066 Toward Measurements With Sympathetically Cooled State-Selected Molecular Ions, RYAN A. CAROLLO, DAVID A. LANE, ALEXANDER FRENETT, DAVID HANNEKE, Amherst College — Deeply bound diatomic molecular ions are of interest for a variety of studies, such as precision measurements, quantum control of rotational states, or quantum memory. We are particularly interested in homonuclear systems, which show promise at suppressing certain systematic effects. We present an apparatus capable of controllably leaking O$_2$ into ionizing and sympathetically cooling trapped O$_2^+$, and performing state-selective photionization. We report on progress toward initial measurements with oxygen, and discuss a proposed precision measurement of the time variation of the proton-to-electron mass ratio using trapped O$_2^+$.
Q1.00067 Progress towards a high temperature inductive oven for an ultracold Er+Na mixture experiment, NEIL ANDERSON, SWARNAV BANIK, MONICA GUTIERREZ, AVINASH KUMAR, HECTOR SOSA, Joint Quantum Institute, NIST and University of Maryland — One of the major challenges in an ultracold atom experiment is the production of the atomic beam for laser cooling. Atomic species of recent interest such as Er, Dy, Cr present a particular challenge in that they require very high temperatures (upwards of 1000 C) to produce vapor pressures suitable for the generation of a thermal atomic beam. In recent experiments, this challenge has been addressed by using a commercial oven in conjunction with a Zeeman slower. Here we present progress towards an inductive oven for Er. Inductive heating, as opposed to resistive heating, offers the distinct advantage of heating the sample directly, eliminating the need for bulky water cooling stages of conventional high temperature ovens. Additionally, the inductive oven’s compact design enables it to serve as a transverse source in a two species 2D MOT setup.

Q1.00068 In situ sensing of position and temperature of a single trapped atom via resonance fluorescence, RICHARD WAGNER, WES ERICKSON, DAN STECK, University of Oregon — Temperature measurements of ultra-cold atoms have either required releasing of the atomic cloud or have taken advantage of relatively weak confining forces to observe center-of-mass motion of the cloud. However, tight confinement forces required for single-atom trapping limit temperature measurements to destructive release-recapture methods. We present an alternative temperature measurement for single atoms in a MOT. A small oscillation in the magnetic field of a MOT imposes a position-dependent oscillation in the fluorescence of a single atom. Measuring this fluorescence oscillation provides information about the spatial distribution of the atom in the trap, and therefore its temperature. This is done without the need to release the atom, allowing for additional experiments on the atom with a known temperature.

Q1.00069 Towards trapping and laser cooling Ba and La ions, JESSIE HANKES, AMANDA NELSON, PATRICK BANNER, STEVEN OLMSCHEK, Denison University — Trapped atomic ions are one of the leading candidates for applications in quantum information. We are currently working with barium ions (Ba II), directly loaded by laser ablation of a barium titanium oxide target, and laser cooled using visible laser light (650 nm and 494 nm). Motivated by applications of quantum networks, we also present progress towards laser cooling and trapping lanthanum ions (La III), which should enable quantum information protocols at telecom wavelengths for long-distance applications.

Q1.00070 Simulation of a 3D MOT-Optical Molasses Hybrid for Potassium-41 Atoms, W. A. PETERSON, JONATHAN WRUBEL, Creighton University — We report a design and numerical model for a 3D magneto-optical trap (MOT)-optical molasses hybrid for potassium-41 atoms. In this arrangement, the usual quadrupole magnetic field is replaced by an octupole field. The octupole field has a central region of very low magnetic field where our simulations show that the atoms experience an optical molasses, resulting in sub-doppler cooling not possible in a quadrupole MOT. The simulations also show that the presence of the magneto-optical trapping force at the edge of the cooling beams provides a restoring force which cycles atoms through the molasses region. We plan to use this hybrid trap to directly load a far off-resonance optical dipole trap. Because the atoms are recycled for multiple passes through the molasses, we expect a higher phase-space density of atoms loaded into the dipole trap. Similar hybrid cooling schemes should be relevant for lithium-6 and lithium-7, which also have poorly resolved D2 hyperfine structure.

Q1.00071 Investigation of magic wavelengths for Francium atom with linearly, circularly and elliptically polarized light, SUKHJIT SINGH, BINDIYA ARORA, Department of Physics, Guru Nanak Dev University, Amritsar, Punjab, India, B. K. SAHOO, Atomic, Molecular and Optical Physics Division, Physical Research Laboratory, Navrangpura, Ahmedabad, India — Various techniques for laser cooling of atoms have recently become of much interest and are immensely used in modern experiments for carrying out very high precision measurements. In a remarkable work, Katori et. al. in 1999 had explored the use of magic wavelengths (λ_magic) for Sr atoms, at which the investigated transition of the trapped atoms observes null Stark shifts, to reduce the systematics in the measurements. We intend to investigate λ_magic for D1 and D2 lines of Francium(Fr) atom with linearly, circularly and elliptically polarized light. Use of circularly polarized light can be advantageous in increasing the number of λ_magic and using elliptically polarized light can lead to identify λ_magic independent of magnetic sublevels and hyperfine levels.

Q1.00072 Progress toward simultaneous sub-Doppler cooling of 6Li and 7Li using a single laser frequency, YANPING CAI, DANIEL ALLMAN, KEVIN WRIGHT, Dartmouth College — We have built an experimental system for simultaneous cooling and trapping of 6Li and 7Li. The cold atomic beam originates from a dual-species 2D MOT with angled effusive sources. Atoms from the 2D MOT are captured in a 3D MOT, and must undergo further cooling for effective loading into a crossed-beam dipole trap. Standard sub-Doppler cooling techniques cannot be used with lithium, however, a Sisyphus cooling technique was recently demonstrated with 6Li [1] that uses a single laser frequency at relatively large detuning (several GHz) from the D lines. We have applied this cooling technique to 4Li, and measured the cooling efficiency as a function of different parameters including power, detuning, and beam geometry. Because the isotope shift for lithium is only 10 GHz, it should be possible to perform Sisyphus cooling on both isotopes simultaneously with a single laser frequency. We will report on progress toward achieving that goal.

Q1.00073 Apparatus for creating quantum degenerate gas of Lithium-6, VINOD GAIRE, LEVI SALLYARDS, CAMERON CALIGAN, COLIN PARKER, Georgia Inst of Tech — We describe our apparatus for generation of quantum degenerate gas of lithium-6, a fermion, for further study and simulation of quantum and condensed matter systems. We designed and constructed a modified Bitter type electromagnet and control system which can provide both homogeneous and quadrupole magnetic fields in different current configurations. We are assembling an ultra-high vacuum system for trapping and cooling the lithium atoms and performing experiments. Unique features of the system include an internal radiofrequency antenna and 21-directional optical access to the main chamber. The laser system will be described separately. Progress and a roadmap to degenerate Fermi gases will be outlined.
Doppler cooling with performance similar to more complex CW systems. We have demonstrated control of a single 174 Yb$^+$ intensities, can be frequency multiplied to deep UV efficiently without the need for the complex machinery of CW frequency multiplication transitions in the UV that are difficult to access with continuous wave (CW) lasers. Mode locked (ML) lasers, due to their high instantaneous indispensability tools in a host of atomic clocks and quantum information systems. The vast majority of these ion species, however, have cooling would show the trapped particles to have less kinetic energy than those injected. a FR state for storage. The process repeats, building the trapped number and density. A simple consideration of potential and kinetic energies now in the FS state, the particles sees the decreasing field as a potential hill to climb. Before it comes to a halt, the particle is switched back to pumping: A FR particle approaches the trap and climbs to the top of the confining potential with a finite velocity. There, it is switched to a field oscillating about its minimum. After laser-cooling our particles and before entering the trap, we employ the non-hamiltonian process of optical—governed by Hamilton's equations. We have built an accumulator by a simple magneto-static cusp trap formed from two ring shaped permanent field. We are primarily interested in characterizing magnetic Feshbach resonances and determine scattering properties of interest for sympathetic magnetic field values. Our study is aimed at guiding future experiments with cold Ca$^+$ Ca$^+$ are expected be insufficiently accurate to agree with experiments. We account for this by exploring the dependence of positions and widths of$eta^-$ to increase statistics at low energy in our$eta$-asymmetry measurement where possible new physics could exist, while simultaneously improving our momentum resolution. Improved momentum resolution on the$eta^-$ will aid in constraining our recoil ion detector response function for an eventual measurement of the recoil asymmetry in polarized$^{37}\text{K}$. Supported by NSERC and NRC through TRIUMF.


Q1.00075 Development of High Reflectivity Pellicle Mirrors for Polarized$^{37}\text{K}$ Beta Decay Asymmetry Studies$^1$, JAMES MCNEIL, Department of Physics and Astronomy, UBC, 2329 West Mall, Vancouver, BC V6T 1Z4, Canada, ALEXANDRE GORELOV, BEN SHELDMAN, MELISSA ANHOLM, LIAM LAWRENCE, JOHN BEHR, TRIUMF, 4004 Wesbrook Mall Vancouver, BC V6T 2A3, Canada, TRINAT COLLABORATION — Precision low energy$\beta$-decay experiments utilize the maximal parity violating standard model property of its charged weak couplings in powerful decay asymmetry studies to probe for new physics up to several TeV in mass. The TRIUMF Neutral Atom Trap (TRINAT) investigates the decay asymmetries in optically cooled, polarized$^{37}\text{K}$. Following trapping using a magneto-optic trap, optical pumping of$^{37}\text{K}$ produces highly polarized initial nuclear spin states along the$z$-axis from which$\beta^-$ decay takes place. Thin 12 µm high reflector pellicle mirrors are developed for our in-vacuum mirror system along the$z$-axis to simultaneously supply circularly polarized light to optically pump the cooled$^{37}\text{K}$, while minimizing the MeV$\beta$-scattering and energy loss as it punches through the mirrors before detection. The goal of using the pellicles is to reduce the threshold energy on our event selection to increase statistics at low energy in our$\beta$-asymmetry measurement where possible new physics could exist, while simultaneously improving our momentum resolution. Improved momentum resolution on the$\beta^-$ will aid in constraining our recoil ion detector response function for an eventual measurement of the recoil asymmetry in polarized$^{37}\text{K}$.$^1$Los Alamos National Laboratory's Office of Laboratory Directed Research and Development

Q1.00076 Accumulator for Low-Energy Laser-Cooled Particles$^1$, KEVIN MERTES, PETER WALSTROM, MICHAEL DI ROSA, Los Alamos National Laboratory, LANL COLLABORATION — An accumulator builds phase-space density by use of a non-Hamiltonian process, thereby circumventing Liouville's theorem, which states that phase-space density is preserved in processes governed by Hamilton's equations. We have built an accumulator by a simple magneto-static cusp trap formed from two ring shaped permanent magnets. In traps with a central minimum of |B|, the stored particles are in a field-repelled (FR) Zeeman state, pushed away by |B| and oscillating about its minimum. After laser-cooling our particles and before entering the trap, we employ the non-hamiltonian process of optical pumping: A FR particle approaches the trap and climbs to the top of the confining potential with a finite velocity. There, it is switched to a field seeking (FS) state. As the switch does not change the velocity, the particle proceeds into the trap but continues to lose momentum because, now in the FS state, the particles sees the decreasing field as a potential hill to climb. Before it comes to a halt, the particle is switched back to a FR state for storage. The process repeats, building the trapped number and density. A simple consideration of potential and kinetic energies would show the trapped particles to have less kinetic energy than those injected.$^1$Supported by NSERC and NRC through TRIUMF.

Q1.00077 Cooling single ions with an optical frequency comb$^1$, ANTHONY RANSFORD, MICHAEL IP, XUEPING LONG, CONRAD ROMAN, UCLA, ANDREW JAYICH, UCSB, WESLEY CAMPBELL, UCLA — Laser cooled ions have become indispensable tools in a host of atomic clocks and quantum information systems. The vast majority of these ion species, however, have cooling transitions in the UV that are difficult to access with continuous wave (CW) lasers. Mode locked (ML) lasers, due to their high instantaneous intensities, can be frequency multiplied to deep UV efficiently without the need for the complex machinery of CW frequency multiplication systems. While large bandwidth is the hallmark of ML lasers, their spectra also have sufficiently narrow features to make them useful for laser Doppler cooling with performance similar to more complex CW systems. We have demonstrated control of a single 174 Yb$^+$ ion's temperature with a frequency doubled optical frequency comb, including single and multiple comb tooth effects, with a scattering rate high enough to rival the performance of CW systems. This work is supported by the US Army Research Office.$^1$Partially supported by the NASA Postdoctoral Program at the NASA Ames Research Center, administered by USRA and the MURI US Army Research Office Grant No.W911NF-14-1-0378 (MG), and by the PIF program of the National Science Foundation Grant No. PHY-141556

Q1.00079 ULTRACOLD COLLISIONS AND PHOTOASSOCIATION PROCESSES

Q1.00080 Ultracold collisions of Ca + Ca$^+$, MARKO GACESA, NASA Ames Research Center, ROBIN CÔTÉ, University of Connecticut — We report the results of our study of Ca + Ca$^+$ collisions at ultracold temperatures in the presence of a magnetic field. We are primarily interested in characterizing magnetic Feshbach resonances and determine scattering properties of interest for sympathetic cooling of Ca$^+$ ions. Our investigation is based on potential energy curves obtained by recent ab-initio electronic structure calculations that are expected be insufficiently accurate to agree with experiments. We account for this by exploring the dependence of positions and widths of Feshbach resonances on variation of potential energy curves in an effort to determine their shared properties that could be detected at certain magnetic field values. Our study is aimed at guiding future experiments with cold Ca + Ca$^+$ mixtures.
Q1.00081 Geometric phase effects in ultracold hydrogen exchange reactions1, BALAKRISHNAN NADUVALATH, JAMES F. E. CROFT, JISHA HAZRA, University of Nevada, Las Vegas, NV 89154, BRIAN K. KENDRICK, Theoretical Division (T-1, MS B221), Los Alamos National Laboratory, Los Alamos, NM 87545 — Electronically non-adiabatic effects play an important role in many chemical reactions. The geometric phase, also known as the Berry’s phase, arises from the adiabatic transport of the electronic wave function around a conical intersection between two electronic potential energy surfaces. It is shown that in ultracold collisions of H and D atoms with vibrationally excited HD, inclusion of the geometric phase leads to constructive and destructive interferences between non-reactive and exchange components of the wave function. This results in strong enhancement or suppression of reactivity depending on the final rovibrational levels of the scattered HD molecules. The effect is illustrated for non-rotating and rotationally excited HD molecules in the v = 4 vibrational level for which the H+HD and D+HD reactions occur through a barrierless path.

1This work was supported in part by NSF grant PHY-1505557 (N.B.), ARO MURI grant No. W911NF-12-1-0476 (N.B.), and DOE LDRD grant No. 20170221ER (B.K.).

Q1.00082 Observation of broad p-wave Feshbach resonances in an 85Rb-87Rb mixture, SHEN DONG, YUE CUI, CHUYANG SHEN, YEWEI WU, XIAOBIN MA, State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, BO GAO, Department of Physics and Astronomy, University of Toledo, MENG KHOON TEE, LI YOU, State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University; Collaborative Innovation Center of Quantum Matter — We observe new Feshbach resonances in ultracold mixtures of 85Rb and 87Rb atoms in the 85Rb(2, -2) + 87Rb(1, -1) and 85Rb(2, +2) + 87Rb(1, +1) scattering channels. The positions and properties of the resonances are predicted and characterized using the semi-analytic multichannel quantum-defect theory by Gao [1]. Of particular interest, a number of broad entrance-channel dominated p-wave resonances are identified, implicating exciting opportunities for studying a variety of p-wave interaction dominated physics of superfluid bosons mixtures, such as three-body recombination decay and formation of p-wave heteronuclear molecules.


Q1.00083 Reduced dimensional model of ultracold molecule-molecule scattering . CHRISTOPHER TICKNOR, BRIAN KENDRICK, LEIDING, Los Alamos Natl Lab — We study a reduced dimensional molecule-molecule scattering system. This work is an intermediate step in performing the complete scattering calculations as we develop tools to bring together the long range, ultracold 2-body scattering problem and the short range 4-body quantum chemistry problem. We use accurate ab initio electronic calculations to construct the Born Oppenheimer potentials for the nuclear motion. We focus on studying how vibrationally states are excited by the potential. We also present a first set of scattering calculations on these potentials.

Q1.00084 Efimov-van-der-Waals universality for ultracold atoms with positive scattering lengths1, JOSE D’INCAO, JILA, Dept. of Physics, Univ of Colorado, Boulder and NIST, PAUL MESTROM, Eindhoven University of Technology, JIA WANG, Centre for Quantum and Optical Science, Swinburne University of Technology, CHRIS GREENE, Department of Physics and Astronomy, Purdue University — We study the universality of the three-body parameters for systems relevant for ultracold quantum gases with positive s-wave two-body scattering lengths. Our results account for finite-range van-der-Waals effects and their universality is tested by changing the number of deeply bound diatomic states supported by our interaction model. We find that the physics controlling the values of the three-body parameters associated with the ground and excited Efimov states is constrained by a variational principle and can be strongly affected by d-wave interactions that prevent both trimer states from merging into the atom-dimer continuum. Our results enable comparisons to current experimental data and suggest tests of universality for atomic systems with positive scattering lengths.

1This work was supported by the U. S. National Science Foundation.

Q1.00085 Theoretical studies of association and dissociation of Feshbach molecules in a microgravity environment1, JOSE D’INCAO, JILA, Dept. of Physics, Univ of Colorado, Boulder, and NIST, JASON WILLIAMS, Jet Propulsion Laboratory, California Institute of Technology — NASA’s Cold Atom Laboratory (CAL) is a multi-user facility scheduled for launch to the ISS in 2017. Our flight experiments with CAL will characterize and mitigate leading-order systematics in dual-atomic-species atom interferometers in microgravity relevant for future fundamental physics missions in space. As part of the initial state preparation for interferometry studies, here, we study the RF association and dissociation of weakly bound heteronuclear Feshbach molecules for expected parameters relevant for the microgravity environment of CAL. This includes temperatures on the pico-Kelvin range and atomic densities as low as $10^9$/cm$^3$. We show that under such conditions, thermal and loss effects can be greatly suppressed, resulting in high efficiency in both association and dissociation of extremely weakly bound Feshbach molecules and allowing for high accuracy determination coherent properties of such processes. In addition we study the possibility to implement delta-kick cooling techniques for weakly bound heteronuclear molecules and explore numerically other methods for molecular association and dissociation including the effects of three-body interactions.

1This research is supported by the National Aeronautics and Space Administration.

Q1.00086 Coupled square well model and Fano-phase correspondence, BIN YAN, CHRIS GREENE, Department of Physics and Astronomy, Purdue University — This work investigates the Fano-Feshbach resonance with a two-channel coupled-square-well model in both the frequency and time domains. This systems is shown to exhibit Fano lineshape profiles in the energy absorption spectrum. The associated time-dependent dipole response has a phase shift that has recently been understood to be related to the Fano lineshape asymmetric q parameter by $\varphi = 2 \text{arg}(q - i)$. The present study demonstrates that the phase-q correspondence is general for any Fano resonance in the weak coupling regime, independent of the transition mechanism.
Q1.00087 Universality and chaotic dynamics in reactive scattering of ultracold KRb molecules with K atoms\textsuperscript{1}. MING LI, Temple University, CONSTANTINOS MAKRIDES, JQI and NIST Gaithersburg, ALEXANDER PETROV, SVETLANA KOTCHIGOVA, Temple University, JAMES F. E. CROFT, NADUVALATH BALAKRISHNAN, University of Nevada, Las Vegas, BRIAN K. KENDRICK, Los Alamos National Laboratory — We study the benchmark reaction between the most-celebrated ultracold polar molecule, KRb, with an ultracold K atom. For the first time we map out an accurate \textit{ab initio} ground potential energy surface of the K\textsubscript{2}Rb complex in full dimensionality and performed a numerically exact quantum-mechanical calculation of reaction dynamics based on coupled-channels approach in hyperspherical coordinates. An analysis of the adiabatic hyperspherical potentials reveals a chaotic distribution for the short-range complex that plays a key role in governing the reaction outcome. The equivalent distribution for a lighter collisional system with a smaller density of states (here the Li\textsubscript{2}Yb trimer) only shows random behavior. We find an extreme sensitivity of our chaotic system to a small perturbation associated with the weak non-additive three-body potential contribution that does not affect the total reaction rate coefficient but leads to the rotational distribution in the product molecule. In both cases the distribution of these rates is random or Poissonian.

\textsuperscript{1}This work was supported in part by NSF grant PHY-1505557 (N.B.) and PHY-1619788 (S.K.), ARO MURI grant No. W911NF-12-1-0476 (N.B. & S.K.), and DOE LDRD grant No. 20170221ER (B.K.).

Q1.00088 Universal Behavior of Spin Dipolar Relaxation in Atomic Condensates . YUANGANG DENG, YIQUAN ZHOU, MIN DENG, QI LIU, MENGKHOON TEY, State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing 100084, China, BO GAO, Department of Physics and Astronomy, University of Toledo, Malis top 111, Toledo, Ohio 43606, USA, LI YOUNG, State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing 100084, China — The dipolar relaxation of atomic spinor condensates is studied in terms of the semi-analytical scattering wave functions by utilizing the quantum-defect theory. At nonzero magnetic fields, inelastic dipolar relaxation of exothermic reaction leads to loss of the atomic population. By tuning the bias field, we find that the dipolar relaxation rate exhibits a universal behavior involving a unique dip and peak structure, different from the commonly referenced result based on the Born or the distorted-wave Born approximations. The positions for the dip and the peak are shown to be determined dominantly by the short-range s-wave scattering length and the Van der Waals radius, independent of the dipolar interaction strength of ultracold atoms. This is confirmed by the precision measured dipolar relaxation decay rate for both spin-polarized atomic coherent spin states and twin-Fock states of \( F = 1 \) \textsuperscript{87}Rb Bose-Einstein condensates. We observe the dipolar relaxation suppression as predicted by our theory for the large bias field, a feature not previously studied experimentally. Our results imply the possibility of extracting the short-range scattering length and the Van der Waals dispersion coefficient from spin dipolar decay measurements.

Q1.00089 COLD ATOMS, MOLECULES AND PLASMAS –

Q1.00090 Diffusion of Single Cs Atoms in a Bath . DANIEL MAYER, MICHAEL HOHMANN, FARINA KINDERMANN, TOBIAS LAUSCH, FELIX SCHMIDT, ARTUR WIDERA, University of Kaiserslautern — Studying the dynamics of single impurities in a many-body system of ultracold gases allows deducing insights on diffusion processes and non-equilibrium behavior at a microscopic level in a broad parameter range. First, we experimentally observe the non-equilibrium dynamics of single Cs atoms impinging on an ultracold Rb cloud and detect the effect of individual collisions. We render the friction coefficient of a modified Langevin equation velocity dependent and thereby extend the validity range to light impurities which yields excellent agreement with our data without free parameters. We further show that the gas temperature can be retained from the Cs atoms, suggesting their use as local, non-destructive probes for a quantum many-body system. Finally, we couple single Cs atoms in a periodic potential to a bath of near-resonant photons and study the ensuing diffusion. Analyzing diffusion traces of single atoms we observe marked non-Brownian features not detectable in standard ensemble properties and find a surprisingly slow timescale on which ergodicity is established in the system. Our results might shed light on the interpretation of similar phenomena in single-particle tracking experiments in life science.

Q1.00091 Index guiding by optically trapped ultracold atoms measured via optical pumping . JON GILBERT, JACOB ROBERTS, Colorado State University — The spatial density variation of optically trapped ultracold atoms is calculated to be sufficient to guide near-resonant red-detuned light through the gas in a manner reminiscent of a graded index fiber for experimentally achievable conditions. We present measurements of light propagating through such an optically trapped gas made via optical pumping by the light. This allows us to measure the light intensity in the gas as a function of propagation distance along the axial direction of the gas in a straightforward fashion. Comparisons between measurements and theoretical expectations based on Maxwells equations will be presented.

Q1.00092 Construction of a Quantum Matter Synthesizer . JONATHAN TRISNADI, MICKEY McDONALD, CHENG CHIN, James Franck Institute, Enrico Fermi Institute, and Department of Physics, University of Chicago — We report progress on the construction of a new platform to manipulate ultracold atoms. The Quantum Matter Synthesizer (QMS) will have the capability of deterministically preparing large 2D arrays of atoms with single site addressability. Cesium atoms are first transferred into a science cell (specially textured to reduce reflectance to 0.1\% across a wide range of wavelengths and incident angles) via a moving 1D lattice, where they are loaded into a magic-wavelength, far-detuned 2D optical lattice. Two NA=0.8 microscope objectives surround the science cell from above and below. The lower objective will be used to project an array of optical tweezers created via a digital micromirror device (DMD) onto the atom-trapping plane, which will be used to rearrange atoms into a desired configuration after first taking a site-resolved fluorescence image. We provide updates on our magnetic-optical trap and Raman-sideband cooling performance, characterization of the resolution of our microscope objectives, and stability tests for the objective mounting structure.

Q1.00093 Measurements of Collective Mode Frequencies in a Multicomponent Quantum Gas . JOSHUA HILL, JAMES AMAN, THOMAS KILLIAN, Rice Univ — The frequencies of collective modes provide a powerful probe of many-body physics in ultracold atom gases. We will describe our characterization of the collective modes in mixtures of atomic species using ultracold strontium, which has a wide assortement of isotopes to work with. A cold thermal-gas of Strontium atoms is prepared in a succession of magneto-optical trap (MOT) stages before being evaporatively cooled in an optical dipole trap (ODT). Additional confinement is then introduced by ramping on a second laser beam, the potential minimum of which is overlapped with the ODT. While maintaining the ODT, the second beam is rapidly turned off, and the gas undergoes collective-mode oscillations. These oscillations are clearly visible in the calculated temperature of the gas after time-of-flight absorption imaging. We identify both center of mass (sloshing) and quadrupole modes.
Q1.00094 Optical Phase Coherence in the Adiabatic Rapid Passage (ARP) Force¹,
BRIAN ARNOLD, TAICHI INAKI, YIFAN FANG, HAROLD METCALF, Physics Dept., Stony Brook University, Stony Brook NY 11794-3800 —
The huge optical force on atoms implemented using ARP results from coherent exchange of momentum between atoms and the light field. This is done with counterpropagating beams of chirped, pulsed light that alternately produce absorption followed by stimulated emission, and has been demonstrated for atoms at rest. How does the ARP force depend on atomic velocities $v_a$? Atomic motion in the lab frame corresponds to Doppler-shifted frequencies in the atomic frame, so we use oppositely detuned laser beams to simulate $v_a$. For large $v_a$ this uses two different lasers, but the coherent momentum exchange requires phase locking them. This has been implemented and the first results show that the force is nearly constant at low $v_a$ but decreases at higher $v_a$. For an ARP frequency sweep range of $\pm \delta_0/k$, one intuitively expects a range of $v_a$ between $1/4$ and $1/2$ of $\pm \delta_0/k$, and our initial measurements corroborate this. Our new tools enable further exploration of the dependence of the ARP force on $v_a$ as well as the role of phase noise that can be inserted experimentally.

1Supported by ONR and Dept of Educ.

Q1.00095 Efimov Resonances and Quantum Degeneracy in a Strongly Mass-Imbalanced Fermi-Bose Mixture, KRUTIK PATEL, B.J. DESALVO, JACOB JOHANSEN, CHENG CHIN, James Franck Institute, Enrico Fermi Institute, Department of Physics, University of Chicago — We present observations of Efimov resonances in a $^6\text{Li} ^{133}\text{Cs}$ mixture near one broad ($s_{\text{res}} = 0.71$) and one narrow ($s_{\text{res}} = 0.02$) interspecies Feshbach resonance near 890 G. These Feshbach resonances have nearly equal intraspecies scattering lengths, yet we find a substantial difference in the absolute interspecies scattering length at which the Efimov features occur. Our observation confirms the predicted departure from universal physics near the narrow resonance. Additionally, we report the realization of a stable Bose-Einstein condensate of Cs overlapped with a degenerate Fermi gas of Li in a dual color optical dipole trap. Such a system provides a platform for the study of Fermi-Bose quantum mixtures in the ground state with widely tunable interspecies interactions.

Q1.00096 Scale Invariant Quantum Dynamics in Ultracold¹, JEFF MAKI, FEI ZHOU, Univ of British Columbia — We examine the effects of scale invariance on the far from equilibrium dynamics of cold atom systems. Such far from equilibrium scale invariant dynamics can be observed in non-interacting Fermi gases in three spatial dimensions. We examine and categorize not only the features of scale invariant far from equilibrium dynamics but the deviations that can arise when one breaks the scale invariance. We show that the long time deviations is related to the beta function of the system, which describes the changes in the correlation length near these two scale invariant points.

1CIFAR (Canadian Institute for Advanced Research), NSERC (National Science and Engineering Research Council)

Q1.00097 Experiments with bosonic atoms for quantum gas assembly¹, MARK BROWN, YIHENG LIN, BRIAN LESTER, ADAM KAUFMAN, RANDALL BALL, LUDOVIC BROSSARD, LEONID ISAEV, TOBIAS THIELE, ROBERT LEWIS-SWAN, KAI-NIKLAS SCHYMIK, ANA MARIA REY, CINDY REGAL, JILA / University of Colorado at Boulder — Quantum gas assembly is a promising platform for preparing and observing neutral atom systems on the single-atom level. We have developed a toolbox that includes ground-state laser cooling, high-fidelity loading techniques, addressable spin control, and dynamic spatial control and coupling of atoms. Already, this platform has enabled us to pursue a number of experiments studying entanglement and interference of pairs of bosonic atoms. We discuss our recent work in probabilistically entangling neutral atoms via interference, measurement, and post-selection as well as our future pursuits of interesting spin-motion dynamics of larger arrays of atoms.

1This work was supported by the David and Lucile Packard Foundation, National Science Foundation Physics Frontier Centers, and the National Defense Science and Engineering Graduate Fellowships program

Q1.00098 BOSE-EINSTEIN CONDENSATES —

Q1.00099 Dark-bright soliton interactions beyond the integrable limit¹, GARYFALLIA KATSIMIGA, JAN STOCKHOFE, Center for Optical Quantum Technologies, University of Hamburg, PAÑAGIOTIS KEVREKIDIS, Department of Mathematics and Statistics, University of Massachusetts, Amherst; PETER SCHMELCHER, Center for Optical Quantum Technologies, University of Hamburg, THEORY GROUP OF FUNDAMENTAL PROCESSES IN QUANTUM PHYSICS TEAM — In this work we present a systematic theoretical analysis regarding dark-bright solitons and their interactions, motivated by recent advances in atomic two-component repulsively interacting Bose-Einstein condensates. In particular, we study analytically via a two-soliton ansatz adopted within a variational formulation the interaction between two dark-bright solitons in a homogeneous environment beyond the integrable regime, by considering general inter- and intra-atomic interaction coefficients. We retrieve the possibility of a fixed point in the case where the bright solitons are out of phase. As the intercomponent interaction is increased, we also identify an exponential instability of the two-soliton state, associated with a subcritical pitchfork bifurcation. The latter gives rise to an asymmetric partition of the bright soliton mass and dynamically leads to spontaneous splitting of the bound pair. In the case of the in-phase bright solitons, we explain via parsing the analytical approximations and monitoring the direct dynamics why no such pair is identified, despite its prediction by the variational analysis.

¹Deutsche Forschungsgemeinschaft in the framework of the grant SCHM 885/26-1
Q1.00100 Dark-Bright Soliton Dynamics Beyond the Mean-Field Approximation\textsuperscript{1}. GARYFALLIA KATSIMIGA, GEORGIOS KOUTENTAKIS, ŠIMEON MISTAKIDIS, University of Hamburg, PANAGIOTIS KEVREKIDIS, University of Massachusetts, PETER SCHMELCHER, University of Hamburg, THEORY GROUP OF FUNDAMENTAL PROCESSES IN QUANTUM PHYSICS TEAM — The dynamics of dark bright solitons beyond the mean-field approximation is investigated. We first examine the case of a single dark-bright soliton and its oscillations within a parabolic trap. Subsequently, we move to the setting of collisions, comparing the mean-field approximation to that involving multiple orbitals in both the dark and the bright component. Fragmentation is present and significantly affects the dynamics, especially in the case of slower solitons and in that of lower atom numbers. It is shown that the presence of fragmentation allows for bipartite entanglement between the distinguishable species. % to be also generically observed. Most importantly the interplay between fragmentation and entanglement leads to the decay of each of the initial mean-field dark-bright solitons into fast and slow fragmented dark-bright structures. A variety of excitations including dark-bright solitons in multiple (concurrently populated) orbitals is observed. Dark-antidark states and domain-wall-bright soliton complexes can also be observed to arise spontaneously in the beyond mean-field dynamics.\textsuperscript{1}

\textsuperscript{1Deutsche Forschungsgemeinschaft (DFG) in the framework of the SFB 925 “Light induced dynamics and control of correlated quantum systems”}

Q1.00101 Adiabatically tuning quantized supercurrents and superfluid hysteresis in spin-orbit coupled Bose-Einstein condensates\textsuperscript{1}. JUNPENG HOU, XIWANG LUO, KUEI SUN, CHUANWEI ZHANG, Department of Physics, The University of Texas at Dallas — The ability to generate and manipulate quantized persistent currents is crucial for building atomtronic devices with novel functionality. Previous schemes for generating quantized supercurrents, such as rotating laser barriers, rely on dynamical process and thus are not accurate and stable. Here we show that arbitrary quantized circulation states can be adiabatically prepared and tuned as the ground state of a BEC confined on a ring by utilizing spin-orbital angular momentum coupling and an external trapping potential. We show that there exists superfluid hysteresis for the process of tuning supercurrents between different quantization values. Our work provides a powerful platform for building and exploring novel superfluid atomtronic circuits.

\textsuperscript{1}NSF, NASA, NIST

Q1.00102 Probing many-body physics with a resonantly interacting Bose gas\textsuperscript{1}. CATHERINE KLAUSS, XIN XIE, CARLOS LOPEZ-ABADIA, JOSE D’INCAO, ERIC CORNELL, University of Colorado, Boulder and JILA — By sweeping a resonantly interacting Bose-Einstein Condensate (BEC) onto weak interactions, we are able to create a mixture of atoms and molecules. We realize a mixture of free atoms, Feshbach molecules and Efimov molecules, using loss rate measurements to distinguish these components. In particular, the creation of Efimov molecules suggests the presence of three-body correlations in the resonantly interacting BEC, revealing opportunities to study few- and many-body phenomena in a controlled system. We present further investigation into this possibility by studying the overall loss of the resonantly interacting BEC over two orders of magnitude in density.

\textsuperscript{1}NSF, NASA, NIST

Q1.00103 Results from the Cold Atom Laboratory’s ground test bed\textsuperscript{1}. ETHAN ELLIOTT, Jet Propulsion Laboratory, CAL TEAM — We describe validation and development of critical technologies in the Cold Atom Laboratory’s (CAL) ground test bed, including the demonstration of the first microwave evaporation and generation of dual-species quantum gas mixtures on an atom chip. CAL is a multi-user facility developed by NASA’s Jet Propulsion Laboratory (JPL) to provide the first persistent quantum gas platform in the microgravity environment of space. The CAL instrument will be operated aboard the International Space Station (ISS) and utilize a compact atom chip trap formed by a dual-species magneto optical trap of rubidium and potassium. In the unique environment of microgravity, the confining potentials necessary to the process of cooling atoms can be arbitrarily relaxed, enabling production of gases down to picoKelvin temperatures and ultra-low densities. Complete removal of the confining potential allows for ultracold clouds that can float virtually fixed relative to the CAL apparatus. This new parameter regime enables ultracold atom research with broad applications in fundamental physics and inertial sensing.

\textsuperscript{1}Results from the Cold Atom Laboratory’s ground testbed

Q1.00104 Progress towards a Na+Er mixture experiment\textsuperscript{1}. AVINASH KUMAR, MONICA GUTIERREZ GALAN, NEIL ANDERSON, SWARNAV BANIK, HECTOR SOSA-MARTINEZ, Joint Quantum Institute, University of Maryland, STEPHEN ECKEL, NIST, Joint Quantum Institute, University of Maryland, TED JACOBSON, University of Maryland, IAN SPIELMAN, GRETCHEN CAMPBELL, NIST, Joint Quantum Institute, University of Maryland — Recent advances in the production of arbitrary trapping potentials for ultracold atoms have enabled the creation and study of analog physical systems using degenerate gases. Here we present an exploration of cosmic inflation realized using a supersonically expanding, toroidally trapped, $^{23}$Na BEC. We observe features of cosmic inflation such as the red-shifting of phonons, particle production, and spontaneous winding number generation. Our group is currently constructing a second-generation experimental apparatus for a Na+Er mixture. This novel setup features a dual species 2D MOT, an improved imaging system, a new locking system for the 583 nm narrow line transition of Er, and high magnetic field capabilities. These new capabilities open the possibility of studying lanthanide-alkali collisions and Feshbach spectra, as well as the realization of other quantum many-body systems.

\textsuperscript{1}NSF Grant PHY-1508300 and the ARO-MURI Non-equilibrium Many-body Dynamics Grant W9111NF-14-1-0003

Q1.00105 Dynamics of Bose-Einstein Condensation in Higher Bands\textsuperscript{1}. SAYAN CHAUDHURY, ERICH MUELLER, Cornell Univ — Motivated by recent experiments, we explore the kinetics of Bose-Einstein condensation in the upper band of a double well optical lattice. These experiments engineer a non-equilibrium situation in which the highest energy state in the band is macroscopically occupied. The system subsequently relaves and the condensate moves to the lowest energy state. We model this process. We argue that the condensate first evaporates and then recondense. We explain how this scenario can be verified through future experiments.

\textsuperscript{1}e NSF Grant PHY-1508300 and the ARO-MURI Non-equilibrium Many-body Dynamics Grant W9111NF-14-1-0003

Q1.00106 Design of a microgravity shell-geometry Bose-Einstein condensate experiment\textsuperscript{1}. NATHAN LUNDBLAD, THOMAS JARVIS, TIAGO CORREIA, Bates College — Notions of geometry, topology, and dimensionality have directed the historical development of quantum-gas physics. Here we review a planned microgravity flight experiment (NASA CAL, launching 2017) which will explore a trapping geometry for quantum gases that is both theoretically tantalizing and difficult to attain terrestrially: a trap forming a spherical or ellipsoidal shell. This trap could confine a Bose-Einstein condensate to the surface of an experimentally-controlled topologically-connected bubble. In particular we will review plans for observing shell condensates aboard CAL, and summarize some of the key technical challenges involved. Particular calculations of trap inhomogeneity (resulting in possible incomplete shell coverage) are presented, along with potential mitigation schemes.

\textsuperscript{1}NASA/JPL
Q1.00107 HYBRID QUANTUM SYSTEMS —

Q1.00108 A Hybrid Atom-Superconductor Interface for Quantum Networking¹, REMY LEGAIE, CRAIG PICKEN, JONATHAN PRITCHARD, University of Strathclyde — Quantum mechanics offers a revolutionary approach to how information is processed, with unprecedented levels of security through quantum encryption and exponential speed up with quantum computing. A key challenge to exploiting these benefits is the development of the next-generation hardware required for creating networks exploiting light at the single photon level. Hybrid quantum computation overcomes this challenge by combining the unique strengths of disparate quantum technologies, enabling realization of a scalable quantum device.

We present a new project using cold atoms trapped above superconducting microwave resonators to enable generation, storage and entanglement of optical photons on-chip. Strong Rydberg atom dipole-dipole interactions provide a mechanism for efficient single photon coupling to atomic ensembles, whilst entanglement is mediated via an off-resonant interaction with the superconducting microwave cavity to provide long distance (~mm scale) interaction lengths. This represents the first steps to the creation of a quantum analog of a router, an essential building block for quantum networking. Long term this can be integrated with superconducting qubits technologies to exploit fast on-chip processing power.

¹Funded by EPSRC Grant EP/N003527/1

Q1.00109 Rydberg Atom Quantum Hybrid Systems², YUANXI CHAO, JITENG SHENG, SANTOSH KUMAR, Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, OK 73019, USA, NICHOLAS P. BIGELOW, Department of Physics, The University of Rochester, NY 14627, USA, JAMES P. SHAFFER, Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, OK 73019, USA — We report on our recent experimental and theoretical work with Rydberg atom-cavity and Rydberg atom-surface hybrid quantum systems. In the atom-cavity system, Rb contained in a dipole trap is transported into a high-finesse optical cavity using a focus-tunable lens. Cavity assisted Rydberg EIT is observed in the cavity transmission and used to characterize the electric fields in the cavity. The electric fields are attributed to surface adsorbates adhering to the cavity mirrors. We also investigate the coupling of a Rydberg atom ensemble to surface phonon polaritons (SPhPs) propagating on piezoelectric superlattices made from thin film ferroelectric materials. Strong coupling between the atomic and surface excitations can be achieved, due to the large Rydberg transition dipole moments and the local field enhancement of the SPhP modes. The system has many advantages for information transport since the atoms need only be placed at distances on the order of mms from the surface and the SPhPs do not couple to free space electro-magnetic fields. Experimental progress will be discussed, including the fabrication of submicron-period periodically poled Lithium Niobate using the direct e-beam writing technique.

²This work is supported by AFOSR.

Q1.00110 Photonic and Phononic Entanglement with Hybrid Species Ion Chains¹, CLAYTON CROCKER, MARTIN LICHTMAN, KSENIA SOSNOVA, TUAN NGUYEN, ALLISON CARTER, Joint Quantum Institute and University of Maryland, VOLKAN INLEK, Duke University, HANNA RUTH, CHRISTOPHER MONROE, Joint Quantum Institute and University of Maryland — Trapped atomic ions represent a leading platform for quantum information networks due to their long coherence times and diversity of entangling operations. External fields can drive strong local entangling interactions via phonons, and remote qubits can be entangled via emitted photons. Unfortunately, resonant light from the photonic entanglement process can disrupt nearby qubits. We resolve this crosstalk by introducing a separate atomic species to the trap for use as a photonic entanglement qubit. We report successful demonstration of both entangling gates between the mixed species qubit pair through their collective motion, and entanglement between our remote entanglement qubit and emitted visible photons. We additionally report our progress on a new trapping apparatus that was implemented to improve these operations to a level required for scaling up the system size.

¹This work is supported by the ARO with funding from the DARPA LogiQ program, the AFOSR, the ARO MURI on Modular Quantum Circuits, the AFOSR MURI on Quantum Transduction, and the ARL Center for Distributed Quantum Information.

Q1.00111 Spin-mediated optomechanics: A hybrid quantum system for quantum sensing and transduction, HIL F H CHEUNG, YOGESH S PATIL, JIALUN LUO, MUKUND VENGALATTORE, Cornell University — We describe our realization of a hybrid quantum system consisting of a mesoscopic mechanical resonator optically interfaced to an ultracold spin ensemble. Combining ultrahigh quality factor resonators with the strong optical interactions and low decoherence rates of the ultracold gas, we show that the parameters of our system ensure the operation of this hybrid quantum system in the strong coupling regime. We demonstrate that the optical coupling between the resonator and the quantum spins realizes a powerful "spin-photon-phonon" interface for applications to quantum sensing and quantum state preparation. Furthermore, we show that the ultracold spin ensemble can enhance and dynamically tune the optomechanical coupling to create effective nonlinear interactions between the resonator and the quantum spins.

Q1.00112 A novel nanophotonic platform for optomechanics in the strong coupling regime, ADITYA G DATE, California Institute of Technology, M M TORUNBALCI, Purdue University, JIALUN LUO, CLAIRE WARNER, HIL F H CHEUNG, YOGESH S PATIL, Cornell University, SUNIL BHAVE, Purdue University, MUKUND VENGALATTORE, Cornell University — We describe the realization of a novel microtoroidal resonator for optomechanics in the strong coupling regime. Owing to its design and material properties, the microresonator exhibits low mechanical and optical dissipation leading to strong interactions between its mechanical and optical whispering gallery modes. In addition to the conventional optomechanical control via a nanofiber interface, this device also enables strong local entangling between the collective spin of an ultracold atomic gas and the microwave transition of the ultracold gas.

Q1.00113 Towards Long Range Spin-Spin Interactions via Mechanical Resonators, JAN GIESELER, ARTHUR SAFIRA, AARON KABCENELL, Department of Physics, Harvard University, JACK HARRIS, Departments of Physics and Applied Physics, Yale University, MIKHAIL LUKIN, Department of Physics, Harvard University — Nitrogen vacancy centers (NVs) are promising candidates for quantum computation, with room temperature optical spin read-out and initialization, microwave manipulability, and weak coupling to the environment resulting in long spin coherence times. The major outstanding challenge involves engineering coherent interactions between the spin states of spatially separated NV centers. To address this challenge, we are working towards the experimental realization of mechanical spin transducers. We have successfully fabricated magnetized high quality factor (Q > 10⁷), doubly-clamped silicon nitride mechanical resonators integrated close to a diamond surface, and report on experimental progress towards achieving the coherent coupling of the motion of these resonators with the electronic spin states of individual NV centers under cryogenic conditions. Such a system is expected to provide a scalable platform for mediating effective interactions between isolated spin qubits.
Q1.00114 Nanophotonic cavity QED with individually trapped atoms, TAMARA DORDEVIC, POLNÖP SAMUTPRAPHOÖT, HANNES BERNEIÑ, PALOMA OCOLA, SYLVAIN SCHWÄRTZ, Department of Physics, Harvard University, VLADAN VULETIC, Department of Physics, MIT, CRYSTAL SENKO, Department of Physics and Astronomy, University of Waterloo, MIKHAIL LUKIN, Department of Physics, Harvard University — The realization of strong interactions between single photons and single atoms is a central theme in quantum optics and an essential prerequisite for future quantum applications such as quantum networks. We achieve such interactions by using a hybrid approach in which we couple independently trapped atoms to nanophotonic crystal cavities [1]. Here we present our methods for trapping and cooling two atoms near a nanophotonic cavity and our progress towards preparing entangled state of two atoms mediated by the cavity photons. Our experiment aims at demonstrating scalable and efficient quantum gates [2] with applications in integrated quantum networks. [1] J. D. Thompson, T. G. Tiecke, N. P. de Leon, J. Feist, A. V. Akimov, M. Gullans, A. S. Zibrov, V. Vuletic, and M. D. Lukin, Science 340, 1202 (2013) [2] T. G. Tiecke, J. D. Thompson, N. P. de Leon, L. R. Liu, V. Vuletic and M. D. Lukin, Nature 508, 241 (2014)

Q1.00115 Exploring photon-mediated long-range interaction in a cold atom array trapped on a nanophotonic resonator , MAY KIM, TZU-HAN CHANG, BRIAN FIELDS, CHEN-LUNG HUNG, Purdue University — Recent experimental demonstrations of trapped atoms near nanoscale photonic waveguides and cavities have proven that such hybrid platforms can offer unprecedentedly strong radiative coupling between single atoms and single photons, capable of mediating long-range interactions. The small size of the entangled nanophotonic system makes it difficult to achieve in cold atom experiments. In addition, with the coherent long-range atom-atom interactions mediated by photons with intermediate to high cooperativity, we can explore novel physics arising from few to many-photon induced self-organization. We expect rich physics arising from strong coupling between the atomic and photonic fields, which cannot be described by simple mean-field theory. We report on the design and experimental progress toward realizing such a novel system, using laser cooled cesium atoms localized near the surface of a high quality nanophotonic resonator, and discuss our schemes to control atom-atom interactions as well as ways to probe the resulting quantum states.

Q1.00116 Radiation enhanced antiferromagnetic exchange between spins in a superconducting host, KAMPHOL AKKARAVARAWONG, Univ of California - Berkeley, JUKKA VÄYRYNEN, Yale University, JAY SAU, University of Maryland, LEONID GLAZMAN, Yale University, NORMAN YAO, Univ of California - Berkeley — A magnetic impurity on a conventional superconductor can host a localized bound state whose energy lies inside the superconducting gap. If the distance between two such impurities is smaller than the coherence length, the presence of these so-called Yu-Shiba-Rusinov (YSR) bound states can induce an antiferromagnetic exchange interaction between the impurities, falling off as $1/r^2$. Although the YSR interaction exhibits a slower decay than conventional RKKY interactions, its strength is significantly weaker, making it extremely challenging to experimentally observe. We demonstrate that the strength of the YSR interaction can be enhanced via radiation assisted virtual occupation, and that the signature of this coupling can naturally be observed through spectroscopy.

Q1.00117 New Diamond Color Center for Quantum Communication , DING HUANG, BRENDON ROSE, ALEXEI TYRYSHKIN, SORAWIS SANGTAWESIN, SRIKANTH SRINIVASAN, Department of Electrical Engineering, Princeton University, DANIEL TWITCHEN, MATTHEW MARKHAM, ANDREW EDMONDS, Element Six, UK, ADAM GALI, Department of Atomic Physics, Budapest University of Technology and Economics, ALASTAIR STACEY, Department of Physics, University of Melbourne , WU-YI WANG, ULRIKA DHAENENS-JOHANSSON, Gemological Institute of America, NY, ALEXANDRE ZAITSEV, Department of Engineering Science and Physics, CUNY College of Staten Island, STEPHEN LYON, NATHALIE DE LEON, Department of Electrical Engineering, Princeton University — Color centers in diamond are attractive for quantum communication applications because of their long electron spin coherence times and efficient optical transitions. Previous demonstrations of color centers as solid-state spin qubits were primarily focused on centers that exhibit either long coherence times or highly efficient optical interfaces. Recently, we developed a method to stabilize the neutral charge state of silicon-vacancy center in diamond ($^{11}B$) with high conversion efficiency. We observe spin relaxation times exceeding 1 minute and spin coherence times of 1ms for $^{19}F$ centers. Additionally, the $^{19}F$ center also has > 90% of its emission into its zero-phonon line and a narrow inhomogeneous optical linewidth. The combination of a long spin coherence time and efficient optical interface make the $^{19}F$ center a promising candidate for applications in long distance quantum communication.

Q1.00118 Strongly Interacting mm-Wave and Optical Photons with Rydberg Atoms , MARK STONE, AZIZA SULEYMANZADE, SCOTT EUSTICE, JONATHAN SIMÓN, DAVID SCHUSTER, Univ of Chicago — We describe progress towards a hybrid experimental system for engineering strong interactions between single optical and mm-wave photons using Rydberg atoms as an interface. Entanglement between photons with gigahertz and optical frequencies creates a new platform to access exotic photonic quantum states as well as powerful new techniques in quantum computing and simulation. We will present recent experimental developments including trapping and cooling atoms in a cryogenic MOT, measuring high-Q superconducting cavities at 100 GHz and coupling atoms to an optical cavity inside a cryostat at 3 Kelvin.

Q1.00119 MATTER WAVE INTERFEROMETRY —

Q1.00120 Measuring the fine structure constant with Bragg diffraction and Bloch oscillations , WEICHENG ZHONG, RICHARD PARKER, CHENGHUI YU, BRIAN ESTEY, HOLGER MÜLLER, Univ of California - Berkeley — We have demonstrated a new scheme for atom interferometry based on large-momentum-transfer Bragg beam splitters and Bloch oscillations. In this new scheme, we have achieved a resolution of $\delta\alpha/\alpha = 0.29\mathrm{ppb}$ in the fine structure constant measurement, which gives over 10 times the previous scheme. This improvement is realized by suppressed macroscopic effects in the interferometers with Raman beam splitters such as light shift, Zeeman effect shift as well as vibration. We have also simulated multi-atom Bragg diffraction to understand sub-ppb systematic effects, and implemented spatial filtering to further suppress systematic.

Q1.00121 Spatial variation of interference fringes in a cold atom Sagnac interferometer based on a single large Raman beam , SANGKYUNG LEE, TAE HYUN KIM, SIN HYUK YIM, KYU MIN SHIM, Agency for Defense Development — We have developed a cold atom Sagnac interferometer where a $\pi/2 - \pi$ $\pi/2$ Raman pulse sequence is realized by a single large Raman beam. Because the launched atomic cloud is crossing the Raman beam along the radial direction, the sides of the atomic cloud do not satisfy the $\pi/2$ pulse condition and that leads the variation in spatial contrast in the atomic cloud. The time-of-flight measurement performed by the thin probe beams, whose widths are 4 times smaller than the size of the atomic cloud enables analysis of the variation in spatial contrast. We analyzed the contrast as a function of the radial positions and the widths of the spatial selection. With a help of the spatial selection, we achieved the 1.3 times contrast enhancement with respect to the fully integrated contrast. We also discuss the effect of the spatial selection in the angular sensitivity.
Q1.00122 Surface-sensitive molecular interferometry: beyond $^3$He spin echo experiments$^1$. JOSHUA T CANTIN, ROMAN V KREMS, Univ of British Columbia, ODED GODSI, TSOFAR MANIV, GIL ALEXANDROWICZ, Technion - Israel Institute of Technology — $^3$He atoms can be used as surface-sensitive atomic interferometers in $^3$He spin echo experiments to measure surface morphology, molecular and atomic surface diffusion dynamics, and surface vibrations. However, using the hyperfine states of molecules gives experiments the potential to be less expensive, be more sensitive, and include angle-dependent interactions. The manifold of hyperfine states of molecules is large in comparison to the two nuclear spin states used in $^3$He spin echo experiments and allows for increased precision, while simultaneously complicating experimental interpretation. Here, we present the theoretical formulation required to interpret these experiments. In particular, we show how to determine the effect of magnetic lensing on the molecular hyperfine states and use a modified form of the transfer matrix method to quantum mechanically describe molecular propagation throughout the experiment. We also discuss how to determine the scattering matrix from the experimental observables via machine learning techniques. As an example, we perform numerical calculations using nine hyperfine states of ortho-hydrogen and compare the results to experiment.

$^1$This work was funded by NSERC of Canada and the European Research Council under the European Union’s seventh framework program (FP/2007-2013)/ERC grant 307207.

Q1.00123 Continuous Rotation and Acceleration Sensing in a Dual Atom Interferometer. FRANK NARDUCCI, MARY LOCKE, RAGHAV SIMHA, JON DAVIS, AARON MELDRUM, Naval Air Systems Command, Patuxent River, MD, GEORGE WELCH, Texas A&M University, College Station, TX, NAVAL AIR SYSTEMS COMMAND, PATUXENT RIVER, MD TEAM, TEXAS A&M UNIVERSITY, COLLEGE STATION, TX COLLABORATION — The theoretical model and progress of achieving pure acceleration and rotation measurements using atom interferometry is presented. We source our interferometer with a high flux (10$^8$ 1/atom) atom beam derived from a 2D MOT without the use of co-propagating optical beams. With the aim of circumventing complications and measurement discontinuities arising from pulsed Raman fields, we utilize continuous Raman fields with the transverse velocity of the atom beam determining our $\pi/2$-$\pi$-$\pi/2$ “pulse” condition. Along with the sensitivity benefits of matter wave interferometry as compared to optical interferometry, the continuous nature of our apparatus makes it beneficial for inertial navigation.

Q1.00124 Implementing large momentum transfer in an Ytterbium BEC contrast interferometer for photon recoil and $\alpha$.$^1$. DANIEL GOCHNAUER, BENJAMIN PLOTKIN-SWING, KATIE MCALPINE, SUBHADEEP GUPTA, Univ of Washington — We operate an ytterbium (Yb) Bose-Einstein condensate (BEC) contrast interferometer designed to make a precision measurement of the fine structure constant, $\alpha$, via a measurement of $h/m$, where $h$ is Planck’s constant and $m$ is the mass of Yb [1]. Our interferometer is insensitive to both magnetic fields, due to the electronic structure of bosonic Yb, and physical vibrations, due to the symmetry of the interferometer geometry. In this geometry the total phase accumulation and therefore measurement sensitivity scales as $N^2$, where $N$ is the number of photon pairs which accelerate one of the interfering paths. We have observed contrast interferometer fringes after imparting $2N\hbar k$ momentum from photon recoils for $N>1$. We have also separately demonstrated Yb BEC acceleration by up to 200 km/s by using Bloch oscillations. The laser pulses for these atom-optics are precisely controlled with analog intensity stabilization and direct digital synthesis generation of frequencies. We are working on implementing acceleration to high $N$ values within the interferometer, and will report on our work towards demonstrating quadratic increase with recoil number in the total phase accumulation and thus interferometer sensitivity.


Funding: National Science Foundation

Q1.00125 TIME-RESOLVED ELECTRON DYNAMICS AND ATTOSECOND SPECTROSCOPY –

Q1.00126 Time-dependent local density approximation study of iodine photoionization delay.$^1$. MAIA MAGRAKVELIDZE, University of Mary Washington, Fredericksburg, USA, HIMADRI CHAKRABORTY, Northwest Missouri State University, Maryville, USA — We investigate dipole quantum phases and Wigner-Smith (WS) time delays in the photoionization of iodine using Kohn-Sham time-dependent local density approximation (TDLDA) [1] with the Leeuwen and Baerends exchange-correlation functional [2]. Study of the effects of electron correlations on the absolute as well as relative delays in emissions from both valence 5p and 5s, and core 4d, 4p and 4s levels has been carried out. Particular emphasis is paid to unravel the role of correlations to induce structures in the delay as a function of energy at resonances and Cooper minima. The results should encourage attosecond measurements of iodine photoemission and probe the WS-temporal landscape of an open-shell atomic system. [1] Magrakvelidze et al, Phys. Rev. A 91, 063415 (2015). [2] van Leeuwen et al, Phys. Rev. A 49, 2421 (1994).

$^1$This work was supported by the U.S. National Science Foundation.


$^1$This work was supported by the U.S. National Science Foundation.
Q1.00128 Attosecond coherence control of Helium ions ensemble1, SAAD MEHMOOD, Phys. Dept., University of Central Florida, Orlando, FL. EVA LINDROTH, Phys. Dept., Stockholm University, Sweden (EU), LUCA ARGENTI, Phys. Dept., University of Central Florida, Orlando, FL — Attosecond extreme ultraviolet (XUV) pulses trigger the release of a photoelectron from an atom or molecule in a coherent ionization process. As soon as the electron is emitted, however, part of the coherence in the residual parent-ion is lost, and so is the chance of guiding any subsequent transformations of the target in a reproducible way. To influence the parent-ion coherence, the system must be perturbed with additional light pulses before the ionization process is over. Here we present a theoretical study of the attosecond XUV-pump IR-probe ionization of the Helium atom to the 2s and 2p He2+ states. In electrostatic approximation, these states are degenerate, and hence their coherent superposition gives rise to a parent ion with a permanent dipole moment. We show that the magnitude of the polarization can be controlled by altering the time delay between the XUV and IR pulses on a timescale of few femtoseconds, which is comparable to the beating between the autoionizing states populated by the XUV pulse. Furthermore, on a timescale of few picoseconds, the dipole moment fluctuates even in absence of external fields, due to spin orbit interaction. Our results show how the slow dynamics of such polarized-ion ensemble can be controlled with attosecond precision.

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Q1.00132 Modeling fast photoemission from GaAs1, EVAN BRUNKOW, NATHAN CLAYBURN, MARIA BECKER, ERIC JONES, HERMAN BATELAAN, TIMOTHY GAY, University of Nebraska- Lincoln — We present a model that enables us to determine if multi-photon electron photoemission is “fast,” i.e., has a time duration comparable to the laser pulses that produce it. In femtosecond pump-probe experiments performed at 775 nm and 100 MHz, laser-induced field emission of electrons from metallic nanotips is considered fast when the emission process is nonlinear in intensity and additive. This means that the emission rate from the source with both pulses present is equal to the sum of the emission rates generated from the pump and probe pulses alone at sufficient delays. [1]. For a GaAs tip source, the emission is instead sub-additive for delays less than a nanosecond, meaning that the emission rate with both pulses present is less than the sum of the pump and probe beams alone [2]. Our model and preliminary data supports the conclusion that the emission from GaAs is fast, and we conclude any material with a non-linear emission process and sub-additivity also has fast emission. This model predicts that the presence of electrons in the conduction band of GaAs causes a decrease in emission due to the second laser pulse. [1] B. Barwick et al., New J. Phys., 9, 142 [2] E. Brunkow et al., B.A.P.S., 61, No. 8, 53

1 Funded by NSF PHY-1505794, NSF EPSCoR Grant IIA-1430519, and NSF PHY-1306565
Q1.00133 Energy-dependent phases more fundamental than “attosecond time delays”? GREG ARMSTRONG, B. D. ESRY, J. R. Macdonald Laboratory, Kansas State University — The time delay in photoionization from neighboring atomic valence sub-shells has become an area of considerable recent interest, with delays of tens of attoseconds reported in experiments for a number of atomic targets. The assumption that such delays are particular to electronic dynamics is questionable, given our recent calculation of “attosecond delays” in nuclear motion. Moreover, in both cases, the connection of such delays to physical delays in wavepacket creation or detection is inherently ambiguous, for example, due to gauge-dependence. Previous atomic studies using the RABBIT technique have extracted time delays from phase differences in the energy spectra for different sub-shells as a function of delay between harmonics. We will argue, however, that the more fundamental physical information lies in the energy dependence, which may be related to quantities such as the scattering phase shift. A molecular target such as HeH$^+$ provides a convenient analog of atomic systems, allowing the investigation of energy-dependent phases in dissociation from adjacent vibrational states. Using a RABBIT-like combination of laser pulses, and applying the photon-phase formalism, we extract information on energy-dependent phases and their relation to scattering phase shifts.

1 This work is supported by the Chemical Science, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U. S. Department of Energy Under Contract No. DE-FG02-86ER13191

Q1.00135 Ultrafast laser control of autoionizing resonances observed in attosecond transient absorption†1, CHENTING LIAO, NATHAN HARKEMA, ARVINDER SANDHU, University of Arizona — Attosecond and femtosecond extreme ultraviolet (XUV) pulses can be used to probe electron dynamics in high-lying excited states that autoionize on a femtosecond timescale, thus providing information on the process of Auger decay and its interference with the continua. Here we utilize XUV pulses in connection with infrared (IR) pulses to perform attosecond transient absorption spectroscopy of the impulsive response of argon autoionizing Rydberg states in the vicinity of the 3$s^{-1}$1$^4p$ resonance. We show that by tuning the time delay and field polarization of IR pulse, it is possible to control the dipolar coupling between neighboring states and hence the spectral line shape of the resonance, such as the transition between Breit-Wigner to Beutler-Fano profiles.

1 NSF Grant No. PHY-1505556


1 Wigner time delay in photodetachment of Tm- and in photoionization of Yb: A comparative study

Q1.00139 A self-referencing attosecond interferometer1, JAN TROSS, GEORGIOS KOLIOPOULOS, CARLOS A. TRALLERO-HERRERO, James R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, KS 66506 — We demonstrate an experimental tool for the controlled interferometric measurement of two beating trains of attosecond pulses with 13 attoseconds in resolution and hundreds of zeptoseconds in precision. The attosecond pulse train is generated by higher order harmonics from two sources in a gas medium. By controlling the offset phase between the two trains of attosecond pulses we are able to measure the phase difference of the harmonics, emanated from the two distinct sources, relative to the offset phase of the fundamental f0. We find that the phase difference evolution for all the measured harmonics follows the linear relation Δφ_n = (2n+1)f_0, n being the harmonic order. This represents an ideal source for homodyne spectroscopic measurements in the XUV regime. Phase measurements were performed with a resolution of 12.5 attoseconds or half of the atomic unit of time. The precision of the measurement is in the hundreds of zeptoseconds which can be enhanced in further experiments. Finally, no carrier envelope phase stabilization nor generation of isolated attosecond pulses is required for the presented measurements, thus reducing the complexity of future experiments.

1Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy (DOE) under Grant No. DE-FG02-86ER13491

Q1.00140 ELECTRON-MOLECULE COLLISIONS —

Q1.00141 N(2P) Production in electron-N_2 Collisions.1, J WILLIAM MCCONKEY, WLADEK KEDZIERSKI, JEFFERY DECH, University of Windsor — A unique detector which is selectively sensitive to low energy metastable atoms, is used to study the production of ground configuration N(2P) atoms following collisions of low energy (0-300 eV) electrons with molecular nitrogen. Time-of-flight detection has allowed identification of at least two dissociation channels with significant differences in released kinetic energy of the fragments. Excitation probability measurements will be presented as a function of incident electron energy and near-threshold data will be used to help identify possible excitation channels.

1Support of NSERC and CFI, Canada, is gratefully acknowledged.

Q1.00142 HCl+, H_2Cl+, DCl+, D_2Cl+ dissociative recombination, 300-500 K.1, THOMAS M. MILLER, JUSTIN P. WIENS, NICHOLAS S. SHUMAN, ALBERT A. VIGGIANO, Air Force Research Laboratory, Kirtland AFB, NM — We have used a flowing afterglow Langmuir probe apparatus to measure dissociative recombination (DR) rate coefficients at 300-500 K for HCl+, H_2Cl+, DCl+, and D_2Cl+. For 300 K, we find 7.7 x 10^{-8} cm^3/s (HCl+), 2.6 x 10^{-7} cm^3/s (H_2Cl+), and 1.1 x 10^{-7} cm^3/s (DCl+) and (D_2Cl+), each with about 35% accuracy. The DR rate coefficient for DCl+ is too slow for us to measure, especially in the face of dealing with mixed H/D species formed in apparatus feedlines when introducing DCl. DR rate coefficients are needed in modeling chlorinated species in diffuse interstellar molecular clouds,1 though at much lower temperatures than we can reach. Cl+ exists in diffuse clouds because IE(Cl+) < IE(H), so Cl is not shielded from starlight UV by the abundant H. Cl+ is exothermic to form HCl+ in collision with H_2, and a second collision is exothermic to yield HCl. Storage ring experiments should yield product branching for the DR reactions. The reaction cycle is repeated from Cl neutrals produced in the DR process. 1. D. A. Neufeld and M. G. Wolffe, Astrophys. J. 706, 1594 (2009). 2. O. Novotny, et al., Astrophys. J. 777, 54 (2013).

1Supported by Air Force Office of Scientific Research (AFOSR-2303EP).

Q1.00143 Long-lived metastable anions in fullerene molecules.1, ALFRED MSEZANE, ZINEB FELFIFI, Clark Atlanta University — The Regge pole method is benchmarked on the measured electron affinities of C_{60}, C_{70}, C_{76}, C_{82} and C_{92} through the calculated electron elastic scattering total cross sections in the electron energy range 0.02 ≤ E ≤ 10.0 eV. The method is then used to explore core-polarization induced long-lived metastable negative ions formation as resonances in these fullerenes. Indeed, the calculated total elastic cross sections for these fullerenes have been found to behave very much like those of their ground states. They are characterized generally by Ramsauer-Townsend (R-T) minima, shape resonances and dramatically sharp resonances manifesting long-lived metastable negative ion formation at 1.86 eV, 1.77 eV, 2.20 eV, 1.72 eV and 2.35 eV for C_{60}, C_{70}, C_{76}, C_{82} and C_{92}, respectively. These core polarization-induced long-lived metastable cross sections, with their second R-T minima and resonance positions close to those of their respective ground states, demonstrate the importance of identifying and delineating the resonance structures in low-energy electron scattering from fullerenes in general.

1This work was supported by U.S. DOE, Basic Energy Sciences, Office of Energy Research.
Q1.00144 Simple method for determining binding energies of fullerene and complex atomic negative ions.\textsuperscript{1}, ZINEB FELFLI, ALFRED MSEZANE, Clark Atlanta University — A robust potential which embeds fully the vital core polarization interaction has been used in the Regge pole method to explore low-energy electron scattering from C\textsubscript{60}, Eu and Nb through the total cross sections (TCs) calculations. From the characteristic dramatically sharp resonances in the TCs manifesting negative ion formation in these systems, we extracted the binding energies for the C\textsubscript{60}, Eu and Nb anions; they are found to be in outstanding agreement with the measured electron affinities of C\textsubscript{60}\textsuperscript{−}, Eu\textsuperscript{2−} and Nb\textsuperscript{4−}. Common among these considered systems, including the standard atomic Au is the formation of their ground state negative ions at the second Ramsauer-Townsend (R-T) minima of their TCs. Indeed, this is a signature of all the fullerenes and complex atoms considered thus far. Shape resonances, R-T minima and binding energies of the resultant anions are presented.\textsuperscript{[1]} D. –L. Huang et al. J. Chem. Phys. 140, 224315 (2014) \textsuperscript{[2]} S. –B. Cheng and A.W. Castleman, Jr., Sci. Rep. 5, 12414 (2015) \textsuperscript{[3]} V. T. Davis and J. S. Thompson, J. Phys. B 37, 1961 (2004) \textsuperscript{[4]} Z. Luo et al. Phys. Rev. A 93, 020501(R) (2016)

\textsuperscript{1}This work was supported by U.S. DOE, Basic Energy Sciences, Office of Energy Research

Q1.00145 Resonances in low-energy electron elastic scattering from Fullerenes C\textsubscript{60} through C\textsubscript{70}\textsuperscript{−}. ZINEB FELFLI, ALFRED MSEZANE, Clark Atlanta University — The electron affinity (EA) provides a stringent test of theory when the calculated and measured EAs are compared. A strong motivation for the fundamental investigations of low-energy electron elastic scattering from the selected fullerenes C\textsubscript{60}, C\textsubscript{70}, C\textsubscript{84}, C\textsubscript{86}, C\textsubscript{88} and C\textsubscript{90} is the availability of high quality measured EAs\textsuperscript{[1, 2]}. The Regge pole calculated electron total cross sections for these fullerenes are found to be characterized generally by Ramsauer-Townsend (R-T) minima, shape resonances and dramatically sharp resonances manifesting stable negative ion formation. The extracted binding energies for the resultant anions agree excellently with the measured EAs of the fullerenes listed above, giving great credence to the Regge pole method and confirming that fullerenes behave like “big atoms”\textsuperscript{[3]}. Common among all these fullerenes is the appearance of their ground state negative ions at their second R-T minima, similarly to the atomic Au case. 1. D.-L. Huang et al, J. Chem. Phys. 140, 224315 (2014) 2. O. V. Boltalina et al, Rapid Commun. Mass Spectrom. 7, 1009 (1993) 3. M. Ya Amusia, Chem. Phys. 414, 168 (2013)

\textsuperscript{1}This work was supported by U.S. DOE, Basic Energy Sciences, Office of Energy Research

Q1.00146 Rydberg scattering in K(12p)-CH\textsubscript{3}NO\textsubscript{2} collisions: role of transient ion pair states\textsuperscript{1}. M. KELLEY, S. BUATHONG, F. B. DUNNING, Rice University — Studies of heavy-Rydberg ion pair formation through non-dissociative electron transfer between Rydberg atoms and attaching targets have focused on targets that form valence-bound anions. Collisions with CH\textsubscript{3}NO\textsubscript{2}, lead to formation of dipole-bound anions which can, through internal couplings, result in creation of valence-bound anions. Our measurements, however, provide no evidence for formation of long-lived ion pair states. Rather, the data show that collisions lead to strong Rydberg atom scattering with collision cross sections comparable to the geometrical size of the Rydberg atom. This scattering is attributed to creation of transient K\textsuperscript{+}-CH\textsubscript{3}NO\textsubscript{2} ion-pair states with lifetimes sufficient to allow significant scattering of the K\textsuperscript{+} and CH\textsubscript{3}NO\textsubscript{2} ions but which, on time scales > 10 ps, are destroyed by field-induced detachment from the anion due to the field of the K\textsuperscript{+} ion. Following detachment, the electron remains bound to the K\textsuperscript{+} ion in a Rydberg state.

\textsuperscript{1}Research supported by the Robert A. Welch Foundation

Q1.00147 Dissociative recombination of HCN\textsuperscript{+} and HNC\textsuperscript{+}, a simplified approach. ERIN MCBROOM, NICOLAS DOUGUET, SAMANTHA FONSECA, Drake Univ, ASA LARSON, Stockholm University, ANN OREL, UCDavis — We present the study of the Dissociative Recombination (DR) of the HCN\textsuperscript{+} and HNC\textsuperscript{+} molecular ions. Our calculations are based on a simplified theoretical model that captures the essence of indirectly driven DR process. We use normal modes to represent the vibrational states and the non-adiabatic couplings between them are obtained simply by computing the scattering matrix elements in this vibrational space. Electronic structure calculations, as well as scattering calculations, were carried out entirely from ab initio principles and we compare our results to available data on the literature.

Q1.00148 Dissociative Excitation of Adenine by Electron Impact.\textsuperscript{1}, J WILLIAM MCCONKEY, JOSHUAH TROCCHI, JEFFERY DECH, WLADEK KEDZIERSKI, University of Windsor — Dissociative excitation of adenine (C\textsubscript{12}H\textsubscript{14}N\textsubscript{2}H\textsubscript{2}) into excited atomic fragments has been studied in the electron impact energy range from threshold to 300 eV. A crossed beam system coupled to a vacuum ultraviolet (VUV) monochromator is used to study emissions in the wavelength range from 110 to 200 nm. The beam of adenine vapor from a stainless steel oven is crossed at right angles by the electron beam and the resultant UV radiation is detected in a mutually orthogonal direction. The strongest feature in the spectrum is H Lyman-\alpha.

\textsuperscript{1}Financial support from NSERC and CFI, Canada, is gratefully acknowledged

Q1.00149 Momentum imaging of the dissociation dynamics for dissociative electron attachment to CF\textsubscript{4} and dipolar dissociation of O\textsubscript{2}\textsuperscript{+}. D. REEDY, University of Nevada, Reno, A. NEMER, R. STROM, A. EDMONDS, Auburn University, T. J. GAY, University of Nebraska, E. MILIORDOS, A. L. LANDERS, M. FOGLE. Auburn University — We present experimental results for dissociative electron attachment (DEA) to CF\textsubscript{4} and dipolar dissociation of O\textsubscript{2}. From our ion-momentum imaging results we extract anion fragment kinetic energies and angular distributions with respect to the incoming electron beam. From these we can directly observe the dissociation dynamics associated to the formation of transitory negative ions. For the DEA to CF\textsubscript{4}, we have measured both dissociation pathways which lead to CF\textsubscript{3} and F\textsuperscript{−} anions. For the CF\textsubscript{3}\textsuperscript{−} pathway, we have investigated the kinetic energy release (KER) as a function of incident electron energy and find a result that is contrary to previous experimental observations. For the F\textsuperscript{−} dissociation channel, we observe both high and low KER channels. We have made detailed investigations of these channels in terms of angular distributions, which suggest the state symmetries involved. For the dipolar dissociation of O\textsubscript{2}, we investigate the formation of positive and negative ion pair production due to electron-impact excitation. We will compare theoretical calculations with the momentum imaging results.

\textsuperscript{1}Work at Auburn University was supported by the National Science Foundation under contract nsf-phys1404366

Q1.00150 ATOMIC AND MOLECULAR STRUCTURE AND PROPERTIES –
Q1.00151 Van der Waals pentamers. JIANING HAN, University of South Alabama — We report on the five-body repulsive van der Waals interactions in the strongly dipole–dipole coupled Rydberg states. Compared to three-body and four-body interactions, five-body van der Waals interactions show more energy levels and more potential wells caused by avoided crossings. This research bridges the few-body physics and many-body physics. Other disciplines, such as chemistry, biology, and medical field, will also benefit from better understanding van der Waals interactions.  

Q1.00152 Closed-channel fraction of a strongly interacting Fermi Gas. XIANG-PEI LIU, HAO-ZE CHEN, XING-CAN YAO, XIAO-QIONG WANG, YU-XUAN WANG, YU-PING WU, University of Science and Technology of China, QI-JIN CHEN, ZHEJIANG University, YU-AO CHEN, JIAN-WEI PAN, University of Science and Technology of China — Near Feshbach resonance, the many-body state of paired atoms is the so-called dressed molecule which can be understood as a linear combination of open-channel atom pairs and closed-channel bare molecules. The closed-channel fraction plays a crucial role in the description of the BEC-BCS crossover since it quantifies the mixing between the atom pairs and the bare molecules. In this presentation, I will first show the experimental procedure for producing of large degenerate Fermi gas. With advanced laser cooling and sympathetic cooling, we are able to obtain a maximum molecule number of $3 \times 10^{16}$ at $T/T_F \sim 0.06$. The low temperature and large atom number allow us to study the closed-channel fraction over a wide parametric range (scattering length, fermi momentum and temperature). With a molecule probe laser, we are able to extract the closed-channel fraction in the BEC-BCS crossover. Experimental results shows a good agreement with the prediction of two-channel model. 

Q1.00153 Calculations of long-range three-body interactions for Li(2S)-Li(2S)-Li$^+$ (1S) PEI-GEN YAN, U. New Brunswick, LI-YAN TANG, WIPM, CAS, ZONG-CHAO YAN, U. New Brunswick & WIPM, CAS, JAMES F BABB, ITAMP, Harvard-Smithsonian CfA, — We theoretically investigate long-range interactions between a ground state Li$^+$ ion and two ground state neutral Li atoms with highly accurate variationally-generated wave functions in Hylleraas coordinates. Using perturbation theory for the energies up to third-order, we evaluate the coefficients $C_4$, $C_6$ and $C_8$ of the second order dispersion interactions and the coefficients $C_9$ and $C_{10}$ of the third-order additive and nonadditive interactions. The nonadditive interactions coefficients depend on the geometrical configurations of this three-body system and on the different positions of the ion for each configuration. Our calculations may be of interest for the study of three-body recombination and for constructing potential energy surfaces. 

Q1.00154 ABSTRACT WITHDRAWN

Q1.00155 Breaking Into the Nuclear and Nucleosynthesis Codes EUGENE PAMFILOFF, Retired — In 1964, astrophysicists John N. Bahcall showed that there was no evidence in support of the stellar model regarding the fusion of plasma protons into helium nuclei and provided a plan to measure the neutrino emission from the sun for that proof of concept. For every four protons that would fuse into helium, two e-neutrinos should be emitted. But sadly the tests failed, as only 25% of the predicted flux was discerned. Subsequent attempts to modify the stellar and particle models to account for the missing neutrinos left inconclusive results. To find that supportive evidence, a study of the reverse of fusion comprising 2753 unstable isotopes was undertaken. This provided an archive of new information. That data disclosed both confirmations of many contemporary theories and assumptions for which no factual basis existed, as well as contradictions of several models and other universally accepted conclusions. These confirmations and contradictions are expressed in three formats under the above title. They include a point-source presentation, a paper that briefly describes some notable results, and the sum of the findings are detailed in a recent book. One of the primary topics of this work is in reference to the methods by which positively charged particles assemble into multi-particle nuclei, specifically those containing the highest quantity of nucleons. Although it is subject to peer review, nevertheless several persistent problems in stellar and nuclear physics have been unraveled by this research. For additional information, contact the author.

Q1.00156 Piezoelectricity Enhancement and Band Structure Modification of Single Atomic Shift in MoS$_{2}$ Supercell Monolayer FELIX JAETAE SEO, SHENG YU, QUINTON RICE, SHOPAN HAFIZ, BAGHER TABIBI, Hampton University, QILIANG LI, George Mason University, HAMPTON UNIVERSITY TEAM, GEORGE MASON UNIVERSITY COLLABORATION — A monolayer of transition metal dichalcogenides (TMDCs, TM: Mo, W; DC: S, Se, Te) has second-order nonlinearpiezoelectricity responding to an external field due to spatial inversion asymmetry. The intrinsic piezoelectric coefficient ($e_{11}$) of MoS$_2$ without any atomic shift has $298$ pC/m, where $e_{11}$ indicates the sum of ion and electronic polarizations along the armchair direction responding to the uniaxial atomic shift along the armchair direction. The piezoelectric coefficients ($e_{11}$) of MoS$_2$ supercell with a single atomic shift of Mo- and S-ions positively (20%) along the armchair direction were increased to $350$ pC/m and $305$ pC/m, respectively. Meanwhile, the piezoelectric coefficients ($e_{11}$) of MoS$_2$ supercell with a single atomic shift of Mo- and S-ions positively (20%) along the zigzag direction have $350$ pC/m. The bandgap energy at the K point in the first Brillouin zone of a single atomic shift either Mo- and S-ions positively (20%) along the armchair direction in the MoS$_2$ atomic cell is largely reduced to $0.06$ eV compared to the intrinsic bandgap (1.96 eV) of MoS$_2$ without atomic shift. The large piezoelectricity enhancement and bandgap modification due to a single atomic shift in TMDCs may open astonishing scientific research and applications including quantum information processing and optomechanics in the pico-scale atomic layer. 

Q1.00157 Paschen-Back effects and Rydberg-state diamagnetism in vapor-cell electromagnetically induced transparency LU MA, University of Michigan, DAVID ANDERSON, Rydberg Technologies LLC, GEORG RAITHEL, University of Michigan — We report on a rubidium vapor-cell Rydberg electromagnetically induced transparency (EIT) experiment in a 0.7 T magnetic field where all involved levels are in the hyperfine Paschen-Back regime, and the Rydberg state exhibits a strong diamagnetic interaction with the magnetic field. Signals from both $^{85}$Rb and $^{87}$Rb are present in the EIT spectra. This feature of isotope-mixed Rb cells allows us to measure the strength of strong magnetic fields to within a 0.2% relative uncertainty. The measured spectra are in excellent agreement with the results of a Monte Carlo calculation. Line shifts and broadenings due to small inhomogeneities of the magnetic field are included in the model. The method can be extended to even higher fields.
Q1.00158 Harmonic Vibrational Frequencies: Approximate Global Scaling Factors for TPSS, M06, and M11 functional families using several common basis sets.\textsuperscript{1} D. O. KASHINSKI, R. C. NELSON, G. M. CHASE, O. E. DI NALLO, United States Military Academy, E. F. C. BYRMD, Army Research Laboratory — We propose new approximate global multiplicative scaling factors for the DFT calculation of harmonic vibrational frequencies using functionals from the TPSS, M06, and M11 functional families with standard Correlation Consistent cc-pV\(x\)Z and aug-cc-pV\(x\)Z \((x = D, T\) and Q\) basis sets. A total of 99 harmonic frequencies are being calculated for 26 gas phase organic and non-organic molecules typically found in detonated solid propellant residue. The approximate multiplicative scaling factors and associated uncertainties are being determined using a least squares approach comparing the computed harmonic frequencies to experimental counterparts well established in the scientific literature. A comparison of our work to previously published global scaling factors will be made to verify method reliability and an applicability of our molecular test set. An update on the progress of this work will be given at the meeting.

\textsuperscript{1}work supported by the ARL, DoD-HPCMP, and USMA

Q1.00159 Enhancement of Rb 5P fine-structure collisional transfer rates in dense inert buffer gas mixtures , ALINA GEARBA, JEREMIAH WELLS, RANDY KNIZE, JERRY SELL, US Air Force Academy — Measurements of collisional fine-structure mixing rates between Rb 5P states in Rb-He and Rb-He-Xe gas mixtures will be presented. We have found that the Rb-He mixing rates are significantly increased by the addition of Ar or Xe, even though the Rb-Ar or Rb-Xe mixing cross sections are orders of magnitude smaller than that of Rb-He. Using Rb-inert gas interatomic potentials we have developed a model to explain our experimental results. Our model takes into account the decrease in Rb 5P fine-structure splitting at small internuclear distances which occurs at high buffer gas pressures. This results in an effective increase in the collisional excitation transfer cross section with buffer gas pressure. We will compare our experimental results to these simulated results and model what this effect would be in K and Cs with inert buffer gas mixtures.

Q1.00160 Single photoionization cross section measurements of Au\(^+\) ions and first determinations of excited state levels in Au\(^{2+}\), DAVID MACALUSO, University of Montana, ALFRED MUELLER, STEFAN SCHIPPERS, Justus Liebig University, Giessen, A.L. DAVID KILCÔYNE, The Advanced Light Source, LBNL — Single photoionization cross-section measurements of Au\(^+\) ions were performed using synchrotron radiation and a-beam-technique at the Advanced Light Source at Lawrence Berkeley National Laboratory. Measurements were made at a photon energy resolution of 18 meV from 18.06 to 25.57 eV spanning the \(^1\)S\(_0\) ground state and \(^1\)D\(_{3}\) metastable state ionization thresholds. Multiple autoionizing resonance series are identified using quantum defect theory. These series identifications were used to make preliminary determinations of low-lying excited state energy levels in the product Au\(^{2+}\) ion, representing the first experimental determination of these levels.

Q1.00161 Single photoionization cross section measurements of Au\(^+\) ions and first determinations of excited state levels in Au\(^{2+}\), DAVID MACALUSO, University of Montana, ALFRED MUELLER, STEFAN SCHIPPERS, Justus Liebig University, Giessen, A.L. DAVID KILCÔYNE, The Advanced Light Source, LBNL — Single photoionization cross-section measurements of Au\(^+\) ions were performed using synchrotron radiation and a-beam-technique at the Advanced Light Source at Lawrence Berkeley National Laboratory. Measurements were made at a photon energy resolution of 18 meV from 18.06 to 25.57 eV spanning the \(^1\)S\(_0\) ground state and \(^1\)D\(_{3}\) metastable state ionization thresholds. Multiple autoionizing resonance series are identified using quantum defect theory. These series identifications were used to make preliminary determinations of low-lying excited state energy levels in the product Au\(^{2+}\) ion, representing the first experimental determination of these levels.

Q1.00162 The spectrum of doubly ionized silver: Ag III\textsuperscript{1}, ANKITA SAXENA, TAUHEED AHMAD, Alligarh Muslim University, India — Doubly ionized silver, isoelectronic with Rh I, has ground configuration 4p\(^8\)4d\(^3\) and the excited configurations are of the type 4d\(^n\)l\(_n\) (n>3) and 4p\(^4\)d\(^4\)l\(_n\). The spectrum of Ag III has been studied in the wavelength region 350-2074 ˚A. The spectra needed for the analysis were recorded on 3-m normal incidence vacuum spectrograph at Antigonish Laboratory, Canada. The analysis of this spectrum was started by Gibbs and White establishing the ground doublet followed by Gilbert, Shadmi and lastly by Benschop et al. At present only two excited configurations 4d\(^5\)5p and 4d\(^5\)5s have been studied apart from the ground doublets. In the present work we have undertaken the study of two major configurations 4d\(^3\)(5d+6s) which comprising of 83 energy levels, with the aid of Relativistic Hartree-Fock (HRF) method and least square fitted parametric calculations using Cowan Code. All the previously reported values for 4d\(^5\)5p and 4d\(^5\)5s have been confirmed except the two levels of 4d\(^2\)5p configuration. J value of one of the level at 135626.7 cm\(^{-1}\) has been changed from J=0.5 to J=1.5 and new level for J=0.5 is established at 135778.4 cm\(^{-1}\). The work is still in progress and the new findings will be presented.

\textsuperscript{1}Ankita Saxena would like to acknowledge the financial support through Inspire Fellowship Scheme through Department of Science and Technology (DST), India.

Q1.00163 Bound and Quasibound States of the Negative Ion of Lanthanum (La\(^-\)) Studied by Photodetachment Spectroscopy\textsuperscript{1}, C.W. WALTER, N.D. GIBSON, N.B. LYMAN, J. WANG, Denison University, Granville, OH — The negative ion of lanthanum, La\(^-\), has the richest bound state spectrum ever observed for an atomic negative ion \textsuperscript{[1]} and it has been proposed as perhaps the best candidate for laser cooling of a negative ion \textsuperscript{[2,3]}. In the present experiments, La\(^-\) is investigated using tunable infrared spectroscopy. The relative signal for neutral atom production was measured with a crossed ion-beam–laser-beam apparatus over the photon energy range 520-900 meV to probe the continuum region above the La neutral atom ground state. The spectrum shows multiple resonance peaks due to transitions to quasibound excited states of La\(^-\) which subsequently autodetach. In addition, photodetachment thresholds are observed to excited states of La. The measured spectrum is consistent with the recently reported revised electron affinity for lanthanum \textsuperscript{[4]}.}

\textsuperscript{1}This material is based on work supported by the National Science Foundation under Grant Nos. 1068308 and 1404109.

Q1.00164 Using coherent molecular motion to merge electron diffraction with x-ray spectroscopic results\(^1\), KAREEM HEGAZY, Stanford Univ, PULSE, MARKUS ILLCHEN, SLAC, DESY, JIE YANG, XIAOZHE SHEN, RENKAI LI, THEODORE VECCHIONE, JEFF CORBETT, ALAN FRANK, NICK HARTMANN, CARSTEN HAST, KEITH IOBE, IGOR MAKASYUK, JOSEPH ROBINSON, SHARON VETTER, STEPHEN WEATHERSBY, CHARLES YONEDA, XIJIE WANG, SLAC, RYAN COFFEE, SLAC, LCLS, SLAC UED TEAM, LCLS EXPERIMENT AM00314 COLLABORATION — Ultrafast electron diffraction (UED) has recently been shown to probe ultrafast time dependent molecular structure. If such structural measurements could be connected to spectroscopic measurements, one could study that fine balance between the electronic degrees of freedom. As a first step, we diffract MEV scale electrons, time-resolved, following repeated impulsive stimulated Raman excitation of an ensemble wide coherent rotational revival in N2O. An identical molecular alignment procedure was used in a previous soft x-ray spectroscopic experiment at the Linac Coherent Light Source (LCLS). Both experiments clearly reveal the molecular alignment signature which can be used to merge the data sets.

\(^1\)UED is supported in part by DOE BES Scientific User Facilities Division and SLAC UED/UEM program development: DE-AC02-05CH11231. LCLS is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences: DE-AC02-76SF00515.

Q1.00165 Laser cooling of BaF. , YAN BO, WENHAO BU, TAO CHEN, GUITAO LV, Zhejiang University — In this poster, we report our recently experimental progresses in laser cooling of BaF molecule. Our theoretic calculation shows BaF is a good candidate for laser cooling; quasi-cycling transitions, good wavelengths (around 900nm) for the main transitions. We have built a 4K cryogenic machine, laser ablate the target to make BaF molecules. The precise spectroscopy of BaF is measured and the laser cooling related transitions are identified. The collision between BaF and 4K He is carefully characterized. The quasi-cycling transition is demonstrated. And laser cooling experiment is going on.

Q1.00166 Fermion superuid with hybridized s- and p-wave pairings , LIHONG ZHOU, Institute of Physics, Chinese Academy of Sciences, WEI YI, University of Science and Technology of China, XIAOLING CUI, Institute of Physics, Chinese Academy of Sciences, UNIVERSITY OF SCIENCE AND TECHNOLOGY OF CHINA COLLABORATION — Ever since the pioneering work of Bardeen, Cooper and Schrieffer in the 1950s, exploring novel pair forming mechanisms for superconductors and superfluids has become one of the central tasks in modern physics. Here, we investigate a new type of fermion superuid with hybridized s- and p-wave pairings in an ultracold spin-1/2 Fermi gas. Its occurrence is facilitated by the co-existence of comparable s- and p-wave interactions, which is realizable in a two-component 40K Fermi gas with close-by s- and p-wave Feshbach resonances. The hybridized superfluid state is stable over a considerable parameter region on the phase diagram, and can lead to intriguing patterns of spin densities and pairing elds in momentum space. In particular, it can induce a phase-locked p-wave pairing in the fermion species that has no p-wave interactions. The hybridized nature of this novel superuid can also be confirmed by measuring the s-wave and p-wave contacts, which can be extracted from the high- momentum tail of the momentum distribution of each spin component. These results enrich our knowledge of pairing superuidity in Fermi systems, and open the avenue for achieving novel fermion superuidus with multiple partial-wave scatterings in cold atomic gases.

Q1.00167 Nonequilibrium Hall Response After a Topological Quench\(^1\), F. NUR UNAL, Max-Planck Institute PKS, ERICH MÜLLER, Cornell University, M. O. OKTEL, Bilkent University — We theoretically study the Hall response of a lattice system following a quench where the topology of a filled band is suddenly changed. In the limit where the physics is dominated by a single Dirac cone, we find that the change in the Hall conductivity is two-thirds of the quantum of conductivity. We explore this universal behavior in the Haldane model, and discuss cold-atom experiments for its observation. Beyond linear response, the Hall effect crosses over from fractional to integer values. We investigate finite-size effects, and the role of the harmonic confinement. Furthermore, we explore the magnetic field quenches in ladders formed in synthetic dimensions.

\(^1\)This work is supported by TUBITAK, NSFPHY-1508300, ARO-MURI W9111NF-14-1-0003.

Q1.00168 Characterizations of SiN and AlN microfabricated waveguides for evanescent-field atom-trap applications\(^1\), JONGMIN LEE, MATT EICHENFIELD, ERICA DOUGLAS, JOHN MUDRICK, GRANT BIEDERMANN, YUAN-YU JAU, Sandia National Laboratories — Trapping neutral atoms in the evanescent fields generated by microfabricated nano-waveguides will provide a new platform for neutral atom quantum controls via strong atom-photon interactions. At Sandia National Labs, we are aiming at developing the related technology that can enable the efficient optical coupling to the waveguide at multiple wavelengths, fabrication nano-waveguides to handle required optical power, more robust waveguide structure, and the new fabrication geometry to facilitate the cold-atom experiments. We will report our latest results on the related subjects.

\(^1\)Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

Q1.00169 ABSTRACT WITHDRAWN

Q1.00170 ABSTRACT WITHDRAWN

Q1.00171 High temperature superconducting surface ion traps. , KIRILL LAKHMANSKIY, PHILIP HOLZ, DOMINIC SCHRTL, Univ of Innsbruck, MUIR KUMPH, IBM Thomas J. Watson Research Center, USA, YVES COLOMBE, RAINER BLATT, Univ of Innsbruck — Traps are known to be a good tool to perform quantum simulations [1] and quantum computation [2]. Large scale quantum systems can be achieved by surface ion traps. However, the closeness of the ions to the trap’s surface leads to an increase of the heating rate of the motional state, which degrades the fidelity of quantum operations. The origin of this heating is not well understood [3]. We investigate finite-size effects, and the role of the harmonic confinement. Furthermore, we explore the magnetic field quenches in ladders formed in synthetic dimensions. Using coherent molecular motion to merge electron diffraction with x-ray spectroscopic results\(^1\), KAREEM HEGAZY, Stanford Univ, PULSE, MARKUS ILLCHEN, SLAC, DESY, JIE YANG, XIAOZHE SHEN, RENKAI LI, THEODORE VECCHIONE, JEFF CORBETT, ALAN FRANK, NICK HARTMANN, CARSTEN HAST, KEITH IOBE, IGOR MAKASYUK, JOSEPH ROBINSON, SHARON VETTER, STEPHEN WEATHERSBY, CHARLES YONEDA, XIJIE WANG, SLAC, RYAN COFFEE, SLAC, LCLS, SLAC UED TEAM, LCLS EXPERIMENT AM00314 COLLABORATION — Ultrafast electron diffraction (UED) has recently been shown to probe ultrafast time dependent molecular structure. If such structural measurements could be connected to spectroscopic measurements, one could study that fine balance between the electronic degrees of freedom. As a first step, we diffract MEV scale electrons, time-resolved, following repeated impulsive stimulated Raman excitation of an ensemble wide coherent rotational revival in N2O. An identical molecular alignment procedure was used in a previous soft x-ray spectroscopic experiment at the Linac Coherent Light Source (LCLS). Both experiments clearly reveal the molecular alignment signature which can be used to merge the data sets.

\(^1\)UED is supported in part by DOE BES Scientific User Facilities Division and SLAC UED/UEM program development: DE-AC02-05CH11231. LCLS is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences: DE-AC02-76SF00515.
Q1.00172 It may be possible to use Microscopic Black Holes as a Propulsion Beam.

RICHARD KRISKE, UM — Several years ago during the commissioning of the LHC, the question as to whether a miniature Black Hole would be formed, and what to do with it if it was, came up as a legitimate topic of discussion. It was calculated at that time that although it was possible, the possibility was extremely small, and it would evaporate quickly, and would be safely ejected into space, as its mass would be so great as to simply continue along its inertial path, out the end of the circular LHC accelerator. New improvements to the LHC are the increase in energy — to about 15 TEV. Linear accelerators, such as the ILC, claim to be able to produce much higher TEV, as they collide electrons and positrons, as opposed to Protons, as does the LHC. This author has heard incredible numbers, such as 250 TEV, with a beam current of 1 Amp. With this incredible increase in Energy and Current, one could turn the Black Hole investigation around, and try to determine how one could produce a steady stream of Microscopic Black Holes. A Black Hole machine. When the Black Holes evaporate do they expand, space in space time. Would the old theory of expanding space behind a craft warp space, and enable the craft to exceed the speed of light. The warp theory was proposed before Star Trek, is it now feasible to prove? 

Q1.00173 Near-threshold photodetachment spectroscopy and THz spectroscopy of NH$_2^-$

OLGA LAKHMANSKAYA, MALCOLM SIMPSON, SIMON MURAERU, ERIC ENDRES, University of Innsbruck, VIATCHESLAV KOKOULINE, University of Central Florida, ROLAND WESTER, University of Innsbruck — NH$_2^-$ ions are known to be interesting species for understanding interstellar nitrogen chemistry [1]. Recent astronomical observations showed that an unidentified absorption feature at 933.973-934.009 GHz might be associated to p-NH$_2^-$ [1]. We, therefore, present findings on near-threshold photodetachment spectroscopy of the amide anion NH$_2^-$ performed in a cold (10 K) 22-argon ion trap. The spectrum reveals step features which are associated with specific transitions between rotational levels of the ground vibrational state of NH$_2^-$ (X$^2$A$_1^-$ electronic state) and NH$_2$ (X$^2$B$_1^-$ electronic state). With this data we can significantly improve the determination of the electron affinity of amidogen NH$_2$ and access the fundamental rotational transition of p-NH$_2$. [1] C. M. Persson, M. Hajigholi, G. E. Hassel, A. O. H. Olofsson, J. H. Black, E. Herbst, H. S. P. Müller, J. Cernicharo, Wirstrom, M. Olberg, A. Hjalmarson, D. C. Lis, H. M. Cuppen, M. Gerin, and K. M. Menten 2014 Astronomy & Astrophysics

Q1.00174 A telecom-wavelength conversion from near-infrared light based on a cold Rubidium atomic ensemble

WEI CHANG, YUNFEI PU, NAN JIANG, CHANG LI, SHENG ZHANG, LUMING DUAN, Center for Quantum Information,IIIS, Tsinghua University, CENTER FOR QUANTUM INFORMATION LAB4,IIIS, TSINGHUA UNIVERSITY TEAM — Exponential photon transmission losses in fiber is a severe limitation to realize long-distance quantum communication. It’s helpful to use telecom-wavelength photon transmission to mitigate these absorption losses. However, typical atomic electronic transition from ground-level is in visible wavelengths or near-infrared wavelengths, such as transitions based on Rubidium. Here we report our progress in telecom-wavelength conversion from 780nm to 1475nm and from 795nm to 1530nm in a cold optically thick gas of Rubidium. Both these two conversions are using a diamond configuration transition that we use S$_{5/2}^{-3}$P$_{3/2}^{-1}$/2$^{-4}$D$_{3/2}^{-1}$/2 cascade transition for the 780nm to 1475nm route and S$_{5/2}^{-1}$/2$^{-3}$P$_{1/2}^{-1}$/2$^{-4}$D$_{3/2}^{-1}$/2 cascade transition for the 795nm to 1530nm route.

1This work was supported by the National Basic Research Program of China and the quantum information project from the Ministry of Education of China. LMD acknowledges in addition support from the IARPA MUSIQ program, the AFOSR and the ARO MURI program

Q1.00175 Highly polarized 1D Fermi gases near p-wave resonance

YINFENG MA, XIAOLING CUI, Institute of Physics Chinese Academy of Sciences (CAS) — Based on the recently developed interaction renormalization for 1D p-wave interaction, we study the polaron physics in the 1D spin-$1/2$ Fermi gas near p-wave resonance. We use the variational approach up to two particle-hole excitations on top of the unperturbed Fermi sea, and find good convergence to the attractive polaron energy. We show that the attractive polaron becomes energetically unstable to the molecule formation as increasing the interaction strength, while the repulsive polaron branch features a broadened spectral width as approaching resonance indicating the instability due to atom loss. These properties are distinct from the polaron physics in 1D s-wave interacting Fermi gases, but share essential similarity to the 3D fermion system across s-wave resonance.

Q1.00176 The Road to DLCZ Protocol in Rubidium Ensemble

CHANG LI, YUNFEI PU, NAN JIANG, WEI CHANG, SHENG ZHANG, Tsinghua Univ, CENTER FOR QUANTUM INFORMATION, INSTITUTE FOR INTERDISCIPLINARY INFORMATION SCIENCES, TSINGHUA UNIV TEAM — Quantum communication is the powerful approach achieving a fully secure information transferal. The DLCZ protocol ensures that photon linearly decays with transferring distance increasing, which improves the success potential and shortens the time to build up an entangled channel. Apart from that, it provides an advanced idea that building up a quantum internet based on different nodes connected to different sites and themselves. In our laboratory, three sets of laser-cooled Rubidium 87 ensemble have been built. Two of them serve as the single photon emitter, which generate the entanglement between ensemble and photon. What’s more, crossed AODs are equipped to multiplex and demultiplex optical circuit so that ensemble is divided into 2 hundred of 2D sub-memory cells. And the third ensemble is used as quantum telecommunication, which converts 780nm photon into telecom-wavelength one. And we have been building double-MOT system, which provides more atoms in ensemble and larger optical density.

Q1.00177 Compact atom interferometer using single laser

SHENG-WEI CHIOW, NAN YU, Jet Propulsion Laboratory — Atom interferometer (AI) based sensors exhibit precision and accuracy unattainable with classical sensors, thanks to the inherent stability of atomic properties. The complexity of required laser system and the size of vacuum chamber driven by optical access requirement limit the applicability of such technology in size, weight, and power (SWAP) challenging environments, such as in space. For instance, a typical physics package of AI includes six viewports for laser cooling and trapping, two for AI beams, and two more for detection and a vacuum pump. Similarly, a typical laser system for an AI includes two lasers for cooling and repumping, and two for Raman transitions as AI beam splitters. In this presentation, we report our efforts in developing a miniaturized atomic accelerometer for planetary exploration. We will describe a physics package configuration having minimum optical access (thus small volume), and a laser and optics system utilizing a single laser for the sensor operation. Preliminary results on acceleration sensitivity will be discussed. We will also illustrate a path for further packaging and integration based on the demonstrated concepts. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
Q1.00178 Extraction of Bose-Hubbard parameters from a 1D microscopic model, TOM KRISTENSEN, ANDREA SIMONI, Université de Rennes 1 — The Bose-Hubbard model is a powerful tool to understand the many-body physics of cold atoms in lattices. The link between its parameters and the underlying microscopic model is therefore of outstanding importance. The standard Bose-Hubbard model assumes that (i) the excited energy bands are neglected, (ii) tunneling is allowed only between nearest neighbors and (iii) the interaction only acts on-site. However it has been shown in Ref. [1] from an exact 2-body 1D calculation that the effective interaction of two cold atoms in a lattice strongly depends on the center-of-mass motion, a behavior not predicted by the standard Bose-Hubbard model. We present here an approach to extract effective Bose-Hubbard parameters from a microscopic two-body model that is based on the solution of the Schrödinger equation in a lattice without approximations. As a crucial intermediate we compute the two-body interacting Green function, expressed in terms of regular and irregular solutions. In order to avoid solution linear-dependence problems, we adapt the algorithm of Ref. [2] to our spectral-element solution approach. [1] H. Terrier et al., Phys. Rev. A 93, 032703 (2016) [2] S. J. Singer et al., J. Chem. Phys. 87, 4762 (1987)

Q1.00179 Photoassociation spectroscopy of a degenerate Fermi gas of 173 Ytterbium atoms, JEONG HO HAN, JIN HYOUN KANG, MOOSONG LEE, YONG-IL SHIN, Department of Physics and Astronomy and Institute of Applied Physics, Seoul National University — We report photoassociation (PA) spectroscopy of ultracold Yb fermions near dissociation limit with dipole-forbidden intercombination transition. The photoassociative spectrum is measured with red-detuned lasers over a scan range up to 1GHz with respect to the F=5/2 → F′=7/2 atomic resonance. Because of the high nuclear spin (I=5/2) nature of the system, we observe a complicated structure appears with several vibrational series each following the LeRoy-Bernstein progression. We compare our results with a numerical calculation based on a single channel Mørre-Pichler model. We also investigate the magnetic field dependence of the photoassociation spectrum.

1 This work was supported by IBS-R009-D1 and the National Research Foundation of Korea (Grant No. 2014-H1A8A1021987)

Q1.00180 Towards a scalable quantum computation platform with solid-state spins in low temperature, WENGANG ZHANG, XIANZHI HUANG, XIAOLONG OUYANG, XIN WANG, PANYU HOU, WENQIAN LIAN, HUILI ZHANG, CHUHENG ZHANG, LI HE, XIUYING CHANG, LUMING DUAN, Center for Quantum Information, IIS, Tsinghua University, CENTER FOR QUANTUM INFORMATION, IIS, TSINGHUA UNIVERSITY TEAM, DEPARTMENT OF PHYSICS, UNIVERSITY OF MICHIGAN, ANN ARBOR TEAM — Nitrogen-vacancy (NV) center can be treated as an “ion” trapped in the diamond lattice. An electron spin triplet ground state (S=1) of NV center can be polarized, coherently manipulated and detected. Together with hyper ne-coupled proximal Carbon-13 and Nitrogen-14 (15) nuclear spins, NV center acts as a promising platform for large scale quantum computation platform at room temperature. By cooling down the diamond to liquid-helium temperature (4K), phonons can be largely suppressed, giving us much longer spin relaxation time (T1) and coherence time (T2) compared with room temperature, and a possibility to readout electron spin state in a single shot. Here we report our progress in building up a prototype for a scalable diamond based quantum computer.

1 This work was supported in part by the National Basic Research Program of China 2011CBA00302, the quantum information project from the Ministry of Education of China, IRPA MUSIQ program, the AFOSR and the ARO MURI program.

Q1.00181 Experimental realization of an entanglement access network and secure multi-party computation, XIUYING CHANG, Center for Quantum Information in Tsinghua University, DONGLIN DENG, Department of Physics, University of Michigan, XINXING YUAN, PANYU HOU, YUANYUAN HUANG, Center for Quantum Information in Tsinghua University, LUMING DUAN, Department of Physics, University of Michigan, DEPARTMENT OF PHYSICS, UNIVERSITY OF MICHIGAN COLLABORATION, CENTER FOR QUANTUM INFORMATION IN TSINGHUA UNIVERSITY TEAM — To construct a quantum network with many end users, it is critical to have a cost-efficient way to distribute entanglement over different network ends. We demonstrate an entanglement access network, where the expensive resource, the entangled photon source at the telecom wavelength and the core communication channel, is shared by many end users. Using this cost-efficient entanglement access network, we report experimental demonstration of a secure multiparty computation protocol, the privacy-preserving secure sum problem, based on the network quantum cryptography.

Q1.00182 Fabrication of Diamond for Low Temperature Experiments, WENQIAN LIAN, LI HE, XIN WANG, XINXING YUAN, HUILI ZHANG, CHUHENG ZHANG, XIUYING CHANG, PANYU HOU, WENGANG ZHANG, XIAOLONG OUYANG, XIANZHI HUANG, LUMING DUAN, Tsinghua Univ — The nitrogen-vacancy (NV) center in diamond is a promising physical implementation of quantum computing. At low temperature (about 4K), NV center shows a lot of advantages comparing with room temperature. The coherence time of electron spin in NV center is about 10 ms. Besides, the electron spin state read out efficiency is increased by single shot read out scheme. Most importantly, the electron spin can be resonantly driven, so remote NV centers can be entangled by the interference of the resonant zero phonon line photons, which is a promising scheme for the realization of quantum computer based on NV center. Here we show the fabrication work on diamond and the basic test at the low temperature toward quantum network based on NV center.

Q1.00183 Tomography of Correlation Functions in Sodium Bose-Einstein Condensates, HAIYU LIANG, TIAN TIAN, HAOXIANG YANG, LIYUAN QIU, ANJUN CHU, YANBIN YANG, Tsinghua Univ, YINGMEI LIU, Department of Physics, Oklahoma State University, Stillwater, OK 74078, USA, LUMING DUAN, Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA — Haiyu Liang 1, Tian Tian 1, Haoxiang Yang 1, Liyuan Qiu 1, Anjun Chu 1, Yanbin Yang 1, Yingmei Liu 2, and Luming Duan 1,3,1. Center for Quantum Information, IIS, Tsinghua University, Beijing 100084, China 2. Department of Physics, Oklahoma State University, Stillwater, OK 74078, USA 3. Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA We present a novel experimental scheme for reconstructing single-particle correlation functions of ultracold atoms from absorption images taken after various time of flights. The efficiency of this scheme is experimentally demonstrated in two different systems, i.e., a sodium Bose-Einstein condensate with an imprinted phase controlled by a digital mirror device, and a quasi-one-dimensional Bose gas of ultracold sodium atoms. This scheme is independent of atomic species, and may thus be applicable to other ultracold atomic systems.

1 We thank the National Basic Research Program of China.
Q1.00184 Fano-Feshbach resonances in ultracold gas of thulium\textsuperscript{1}, ALEXEY AKIMOV, IVAN COJOCARU, Texas A&M University, VLAD TSYGANOK, EMIL DAVLETOV, ILIA LUCHNOKOV, VYACHESLAV BUSHMAKIN, ELENA KALGANOVA, VLADIMIR KHELEBINIKOV, Russian Quantum Center — Fano-Feshbach resonances play important role in controlling interaction between particles in ultracold quantum gases and quantum simulators. These resonances allow one to change in wide range scattering length of two interacting atoms using magnetic field. While in alkaline atoms these resonances could only be observed in relatively high magnetic fields, in rare earth elements because of high orbital moment in the ground state one could expect number of low-field Fano-Feshbach at low (few Gauss) field. Indeed, such low field resonances been already observed in dysprosium and erbium. In this contribution, we report first observation of low—field magnetic field Fano-Feshbach resonances in ultracold thulium. Been on the resonance atoms experience strong modification of the scattering length, which also lead to increased rate of 3-body inelastic collisions and therefore enhanced loss of atoms from the optical dipole trap. In our experiments, atoms were prepared in narrow transition magneto-optical trap and then loaded in optical dipole trap formed by two crossed laser beams at wavelength 532 nm. Then atoms were evaporative cooled and magnetic field depended losses were observed clearly demonstrating number of low field Fano-Feshbach resonances.

\textsuperscript{1}Russian Science Foundation Grant No. 17-12-01419

Q1.00185 Vortex cluster shedding in an oblate Bose-Einstein condensate\textsuperscript{1}, YOUNGHOON LIM, JUNHONG GOO, WOO JIN KWON, JOON HYUN KIM, SANG WON SEO, YONG-IL SHIN, Center for Correlated Electron Systems, Institute for Basic Science (IBS), Seoul 08826, Republic of Korea — We present the observation of vortex cluster shedding from a moving obstacle in an oblate Bose-Einstein condensate (BEC). We investigate the evolution of the vortex shedding pattern as a function of the obstacle velocity, and observe regular shedding of vortex clusters consisting of two like-sign vortices at low obstacle velocity. As \( v \) increases, the vortex shedding pattern becomes irregular with many larger clusters, which shows a transition to turbulence. To quantitatively characterize the vortex shedding pattern, we analyze the cluster charge distribution as a function of the obstacle velocity. The transition from regular to turbulent shedding is manifested with a rapid decrease of fractional population of two like-sign vortex clusters. In particular, we observe a saturating behavior of the Stouhal number with increasing \( v \), which is associated with the shedding frequency. We will discuss possible extension of this work to test the universality of the vortex shedding dynamics.

\textsuperscript{1}This work was supported by IBS-R009-D1

Q1.00186 Experimental study of vortex dynamics in a highly oblate fermionic condensate, BUMSUUK KO, JEE WOO PARK, YONG-IL SHIN, Seoul National University — In a 2D superfluid, quantized vortices are topological point defects whose dynamics reveal the thermodynamic and transport properties of the superfluid. In this presentation, we report on our experimental progress on the study of the vortex dynamics in a fermionic condensate of \( ^6\text{Li} \) atoms with strong interactions. We simultaneously trap \(^{23}\text{Na} \) and \(^{6}\text{Li} \) atoms in an optically plugged quadrupole trap, and perform forced rf-evaporation of \(^{23}\text{Na} \) to sympathetically cool \(^{6}\text{Li} \). A Fermi gas of about 10\(^6 \) lithium atoms is prepared in an oblate optical dipole trap (aspect ratio of 1:100) at a temperature of \( T/T_F = 0.15 \). Strong s-wave interactions are induced in a spin-mixture of the two lowest hyperfine states using a broad Feshbach resonance, and a fermionic condensate is formed by evaporative cooling. Using a moving optical obstacle, we can generate a vortex dipole in the condensate. We will discuss the measurements of the critical velocity for vortex shedding as a function of the interaction strength.

Q1.00187 Observation of the Topological Change Associated with the Dynamical Monodromy, DANIEL SALMON, MATTHEW NEREM, SETH AUBIN, JOHN DELOS, William & Mary Coll — Classical mechanics is an old theory and new phenomena do not often appear. A recently predicted phenomenon is called “Dynamical Monodromy. Monodromy is the study of the behavior of a system as it evolves “once around a closed circuit. Systems that do not return to their original state after forming a closed circuit in some space are said to exhibit “nontrivial monodromy. One such system is a collection of non-interacting particles moving in a “champagne bottle potential. A loop of trajectories of this system exhibits a topological change when each of the particles traverse a monodromy circuit in Energy-Angular Momentum space (any closed path that encloses the singular point at the origin). This system has been realized using a rigid spherical pendulum, with a permanent magnet at its end. Magnetic fields generated by coils are used to create the champagne-bottle potential, as well as drive the pendulum through the monodromy circuit.

Q1.00188 Topological Changes of Wave Functions Associated with Hamiltonian Monodromy\textsuperscript{1}, CHEN CHEN, JOHN DELOS, William and Mary — Almost everything that happens in classical mechanics also shows up in quantum mechanics when we know where to look for it. A recently discovered phenomenon in classical mechanics involves topological changes in the loops that define action and angle variables as a result of a passage around a “monodromy circuit”. This phenomenon is known by the short name “Hamiltonian monodromy” (or, more ponderously, “nontrivial monodromy of action and angle variables in integrable Hamiltonian systems”). In this paper, we show a corresponding change in quantum wave functions: these wave functions change their topological structure in the same way that the action and angle loops change.

\textsuperscript{1}Supported by NSF and William and Mary

Q1.00189 Interaction Corrections to Chern Numbers\textsuperscript{1}, CHENG LI, TIN-LUN HO, Ohio State Univ - Columbus — Chern numbers play a key role in many areas in physics as they describe the topology of a quantum state. Motivated by the recent experiment by Ian Spielmans group at NIST (arXiv:1610.06228) on the second Chern number \( C_2 \) of the Yang monopole, we have studied the effect of particle interaction. We show that interaction will stretch the monopole into an extended manifold of singularity, which will cause a gradual change of the second Chern number as the monopole leaves the 4D surface where \( C_2 \) is calculated. Such gradual change is in fact contained in the data of the NIST experiment.

\textsuperscript{1}This work is supported by the MURI grant FP054294-D, and the NASA grant 1541824 in Fundamental Physics.
Q1.00190 Single-Photon Switching and Entanglement of Solid-State Qubits in an Integrated Nanophotonic System, RUFFIN EVANS, ALP SIPAHIGIL, DENIS SUKACHEV, Harvard University Department of Physics, MICHAEL BUREK, Harvard University Paulson School of Engineering, JOHANNES BORREGAARD, MIHIR BHASKAR, CHRISTIAN NGUYEN, Harvard University Department of Physics, JOSE PACHECO, EDWARD BIELEJEC, Sandia National Laboratories, MARKO LONCAR, Harvard University Paulson School of Engineering, MIKHAIL LUKIN, Harvard University Department of Physics — Efficient interfaces between photons and quantum emitters form the basis for quantum networks and enable optical non-linearities at the single-photon level. We demonstrate a platform for scalable quantum nanophotonics based on silicon-vacancy (SiV) color centers coupled to diamond nanodevices. By placing SiV centers inside diamond photonic crystal cavities, we realize a quantum-optical switch controlled by a single color center. We control the switch using SiV metastable states and observe switching at the single-photon level. Raman transitions are used to realize a single-photon source with a tunable frequency and bandwidth in a diamond waveguide. By measuring intensity correlations of indistinguishable Raman photons emitted into a single waveguide, we observe quantum interference resulting from the superradiant emission of two entangled SiV centers. We also discuss current work to extend the coherence time of the SiV spin degree of freedom, engineer deterministic multi-emitter interactions via the cavity mode, and related work with the Germanium-Vacancy center.

Q1.00191 Progress toward the measurement of nuclear-spin-dependent (NSD) parity non-conserving (PNC) transition in Cesium ground-hyperfine states, JUNGU CHOI, GEORGE TOH, DAN ELLIOTT, Purdue Univ, COHERENT AND QUANTUM OPTICS LAB TEAM — We report our progress on the measurement of weak-force mixing of the ground hyperfine levels in atomic cesium. The effect of this mixing is manifested through weak amplitudes for transitions, which we will observe using an interference between optical and rf transitions. The cesium atomic beam interacts with rf fields confined in an open cavity via Stark-induced and Parity Non-conserving (PNC) transitions, as well as with optical fields via a strong Raman interaction. We have built the rf cavity resonator from copper-clad substrates and highly-reflecting cylindrical mirrors for the cesium ground hyperfine transition at 9.2 GHz. We performed characterization of the cavity mode that shows good field patterns and a reasonable quality factor of the mode for a few percent uncertainty experiment. We have made other preparations, including improving on phase-locked Raman lasers, to observe interference between optical and rf transitions from which the nuclear anapole moment will be derived. We present preliminary measurement results with focus on how to reduce systematic errors and other challenges we are facing.

Thursday, June 8, 2017 4:30PM - 6:00PM — Session R1 Meet the APS Editors East Lobby —
4:30PM R1.00001 Meet the APS Editors —

Thursday, June 8, 2017 7:00PM - 9:00PM — Session S1 DÂMOP Banquet Hyatt Regency Sacramento Regency Ballroom —
7:00PM S1.00001 Awards Presentations —
7:30PM S1.00002 Dinner —
8:30PM S1.00003 After-dinner Talk: Meeting the Global Climate and Energy Challenge, SALLY M. BENSON, Stanford University —.

Friday, June 9, 2017 8:00AM - 9:48AM — Session T2 Focus Session: New Topological Quantum Matter 306-307 - Waseem Bakr, Princeton University
8:00AM T2.00001 Observation of a dynamical topological phase transition in the non-equilibrium dynamics of ultracold quantum gases in driven optical lattices, CHRISTOF WEITENBERG, University of Hamburg — Ultracold atoms are a versatile system to emulate solid-state physics including the fascinating phenomena of gauge fields and topological band structures. By circular driving of a hexagonal optical lattice, we engineer the Berry curvature of the Bloch bands and realize a Haldane-like model. We have developed a full momentum-resolved state tomography of the Bloch states, which allows measuring the distribution of Berry curvature and obtaining the Chern number [1]. Furthermore, we study the time-evolution of the many-body wavefunction after a sudden quench of the lattice parameters and observe the appearance, movement, and annihilation of dynamical vortices in reciprocal space. We identify them as the Fisher zeros in the Loschmidt amplitude and define them as a dynamical equivalent of an order parameter, which suddenly changes its value at critical evolution times [2]. Our measurements constitute the first observation of a so-called dynamical phase transition and address the intriguing question of the relation between this phenomenon and the equilibrium phase transition in the system. [1] Flaschner et al., Science 352, 1091 (2016). [2] Flaschner et al., arXiv:1608.05616 (2016).
8:30AM T2.00002 Crystalline symmetry in topological quantum states of ultracold atoms, QI ZHOU, Department of Physics and Astronomy, Purdue University — Symmetry plays a fundamental role in topological quantum states. In this talk, I will discuss practical schemes for exploring the interplay between crystalline symmetries and topology in ultracold atoms. In optical lattices with nonsymmorphic symmetries, nonsymmorphic Chern insulators arise. A variety of new phenomena, such as band structures resembling Mobius strips, quantum dynamics controlled by non-abelian Berry connections, and nonsymmorphic topological pumping, can be naturally accessed in laboratories.
9:00AM T2.00003 Disordered topological wires in a momentum-space lattice, ERIC MEIER, FANGZHAO AN, BRYCE GADWAY, Univ of Illinois - Urbana — One of the most interesting aspects of topological systems is the presence of boundary modes which remain robust in the presence of weak disorder. We explore this feature in the context of one-dimensional (1D) topological wires where staggered tunneling strengths lead to the creation of a mid-gap state in the lattice band structure. Using Bose-condensed 87Rb atoms in a 1D momentum-space lattice, we probe the robust topological character of this model when subjected to both site energy and tunneling disorder. We observe a transition to a topologically trivial phase when tailored disorder is applied, which we detect through both charge-pumping and Hamiltonian-quenching protocols. In addition, we report on efforts to probe the influence of interactions in topological momentum-space lattices.

9:12AM T2.00004 Chern number measurement in photonic Landau levels, NATHAN SCHINE, MICHELLE CHALUPNIK, JONATHAN SIMON, Univ of Chicago — Nontrivial topology is at the heart of a host of intriguing phenomena in condensed matter physics. Synthetic materials consisting of a quantum gas of photons or ultracold atoms have established themselves as ideal systems to explore these phenomena. As experiments push into the strongly-interacting, strongly-correlated regime, characterizing topological many-body states through measurements of topological quantum numbers becomes critical. We present a real-space Chern number measurement in a photonic integer quantum Hall system, produced in a degenerate manifold of a multimode non-planar ring resonator. Through controlled spatial excitation of the resonator and holographic reconstruction of the resulting modes, we measure arbitrary ‘band projectors’ from which the Chern number is calculated. This system and measurement technique is compatible with strong interactions via cavity Rydberg electromagnetically induced transparency. We will further discuss how spatial curvature in our system allows measurement of two additional topological quantum numbers, enabling detailed characterization of novel manybody quantum states.

9:24AM T2.00005 Topological states of photons in coupled microwave cavities, JOHN OWENS, AMAN LACHAPELLE, RUICHAO MA, BRENDA SAXBERG, JONATHAN SIMON, DAVID SCHUSTER, University of Chicago — We present recent results in using coupled cavity arrays to explore quantum many-body phenomena. We create tight binding lattices with arrays of evanescently coupled three-dimensional coaxial microwave cavities. Topologically non-trivial band structures are engineered by utilizing the chiral coupling of the cavity modes to form rings in a magnetic field. Using screws made of different dielectric material, we can control every lattice site in real-time, to its depth in the lattice. We then map each lattice site and measure the band structure, the edge dispersion, and time-resolved dynamics of pulses we inject at a particular site. These lattices can be cooled to superconducting temperatures to realize disorder, long-coherence, topological tight binding models that are compatible with effective onsite photon-photon interactions by coupling lattice sites to superconducting qubits. This will allow us to explore the interplay between topology and coherent interaction in these artificial strongly-correlated photonic quantum materials.

9:36AM T2.00006 Detection of topological invariants in driven-dissipative and interacting systems, DOMINIK LINZNER, RUI LI, MICHAEL FLEISCHHAUER, Department of Physics and Research Center OPTIMAS, University of Kaiserslautern — We propose a conceptual detection scheme of topological invariants for thermal and driven, dissipative gaussian systems. In closed systems topological order can be measured by means of quantized transport which coincides with a quantized winding of the polarization. This connection breaks down for mixed states, e.g. in the presence of a finite temperature. While in previous work [1] we have identified that the winding of the polarization is still quantized in open systems and can therefore be used to classify topological order, the same no longer holds true for transport properties. We show for the case of one-dimensional systems that an auxiliary system at T ≈ 0 coupled to the finite-temperature or driven system can inherit its topological properties. Thus a non-trivial winding of the polarization in the open system leads to a quantized particle transport in the auxiliary system. We also show for the example of the 1D extended superlattice Bose-Hubbard model that the transfer of topological properties also holds for interacting systems. This allows us to detect topological order in driven-dissipative as well as interacting systems. [1] D. Linzner, L. Wawer, F. Grusdt and M. Fleischhauer, Phys. Rev. B 94, 201105(R) (2016)

Friday, June 9, 2017 8:00AM - 10:00AM Session T3 Cavities and Laser Cooling 308 - Dan Stamper-Kurn, University of California, Berkeley

8:00AM T3.00001 Superradiant Supercooling, GRAHAM GREVE, BAOCHEN WU, JILA/CU-Boulder, JAMES THOMPSON, CU-Boulder — We will describe recent progress learning to exploit collective effects of many laser-cooled atoms in a medium finesse optical cavity. We will first describe experimental work attempting to observe a newly predicted collective cooling mechanism in which rubidium atoms are cooled as they undergo lasing in a deep bad-cavity or superradiant regime. It is predicted that the cooling rate is collectively enhanced by the number of atoms, and the ultimate temperature limits can be well below the limit for standard cavity cooling. We will describe a novel trapping geometry for allowing the atoms to undergo guided falling in the cavity mode, and if time permits, we will discuss the generation of 10 dB of spatially-homogeneous spin-squeezing for future work on entanglement-enhanced atom interferometry.

8:12AM T3.00002 Laser cooled anions as a sympathetic coolant, JULIAN FESEL, CERN, AEGIS COLLABORATION — Several ongoing experiments at CERN aim at testing the CPT theorem and the weak equivalence principle using antimatter, among them the AEGIS experiment. For the latter, antiprotons inside a Penning trap interacting with Rydberg positronium form antihydrogen, which will then be used for precision measurements. The achievable sensitivity of these measurements is determined by the antihydronium temperature which, for this production scheme, is determined by the temperature of the antiprotons. We are investigating the use of laser-cooled anionic molecules to sympathetically cool antiprotons confined in the same trapping potential. A test setup to produce cold ground state C2- molecules is currently being commissioned. This setup will be presented, together with a theoretical study on the feasibility of several laser cooling schemes, including one using the AC-Stark shift. Laser cooling of anions — which has so far never been achieved — would also enable the sympathetic cooling of any other negatively charged species, opening new opportunities in a variety of research areas.

8:24AM T3.00003 Cooperatively coupled motion with superradiant and subradiant atoms, GUIN-DAR LIN, KUAN-TING LIN, ER-SIANG TANG, National Taiwan University — We investigate the coupled motion of cooperative atoms subjected to the Doppler dissipative force. The dipole-dipole interaction introduces mutual decay channel and splits the super-radiant and sub-radiant states. The Doppler force is thus modified due to the collective emission and coupled recoil. Such a cooperative effect is more evident when the inter-atom separation is less than or comparable to a wavelength. In an optical molasses, we find that, along the axis of two atoms, there presents an effective potential with mechanically stable and unstable regions alternatively as their separation increases. Taking the cooperative Lamb shift into account, we map out the stability diagram and investigate the blockade effect.

1We thank the support from MOST of Taiwan under Grant No. 105-2112-M-002-015-MY3 and National Taiwan University under Grant No. NTU-ERP-105R891401.
8:36AM T3.00004 Build-up cavity enhanced photoionization of ultracold atoms as a source for focused ion beams , GUS TEN HAAF, STEINAR H.W. WOUTERS, DANIEL F.J. NIJHOF, PETER H.A. MUTSAERS, EDGAR J.D. VREDENBREKT , Eindhoven University of Technology — Focused ion beams (FIBs) are indispensable tools in the semiconductor industry and materials science as they offer the possibility for in situ sample manipulation at the nanometer length scale. The FIB probe size is limited by aberrations of the electrostatic lens system and the transverse reduced brightness and energy spread of the ion beam. Here we present measurements of these beam parameters for a new FIB source that is based on the photoionization of a magneto-optically cooled $^{87}$Rb atoms. Recent measurements have shown that the transverse reduced brightness of the atomic beam is six times higher than that of the industry standard liquid metal ion source. Furthermore, comparison of current measurements with numerical calculations of the two-step photoionization shows that 75% of the atoms can be ionized when using a build-up cavity to enhance the intensity in the ionization laser beam. The maximum current measured to date is 600 pA. A retarding field analyser is used to measure the energy spread of the beam which is mostly determined by the range over which the atoms are ionized inside an electric field that is needed to prevent disorder-induced heating. The experimental results will be presented together with their implications for the FIB probe size.

8:48AM T3.00005 Emergence of Coherence from Incoherence in Cavity-Coupled Arrays of Three-level Atoms¹ , PEIRU HE, MURRAY HOLLAND, JILA, CU Boulder, ANA MARIA REY, JILA, NIST — We investigate the emergence of many-body synchronization in macroscopic arrays of V-type three-level atoms. The two optical transitions are separately coupled to two cavity modes in the bad cavity regime, meaning that for these modes the cavity decay rate is larger than all other relevant system frequencies. While synchronization and superradiance have been demonstrated in two-level arrays coupled to one bad cavity mode, the three-level case, possessing more degrees of freedom, is anticipated to exhibit richer physics. Using the cumulant expansion approach, we find both transitions can individually synchronize when the ground state is incoherently pumped to the two excited states. Of particular interest is the fact that the two-point correlation function between the excited states becomes nonzero and oscillates in time, indicating an emergent coherence between these two levels even in the absence of any external coherent drive. The oscillations are robust and only decay at the collective decay rate (the smallest frequency scale in the problem). We derive analytical expressions for the oscillation frequency and the associated linewidth. We further examine the phase diagrams to determine the parameter regime where the emergent coherence exists.

¹ NSF, NIST

9:00AM T3.00006 Strong Coupling of Two Light Fields mediated by a Single Atom , CHRISTOPH HAMSEN, TATJANA WILK, KARL NICOLAS TOLAZZI, GERHARD REMPE, Max Planck Institute of Quantum Optics — Light fields consist of photons that carry neither mass nor charge and therefore do not interact in vacuum. Even in nonlinear optical media, typical interaction strengths are negligible at the level of individual quanta. In novel quantum systems, strong interactions between individual photons of a single light field have been demonstrated based on e.g. photon or Rydberg blockade. This led to the realization of single-photon switches, transistors, and phase shifters. Here, we demonstrate how two optical fields coupled to different longitudinal modes of a cavity can be brought to interaction using a single atom. While each field by itself achieves full transmission, already a single photon in one mode suppresses the transmission of the other mode. In analogy to the cavity quantum electrodynamics situation, we refer to this as strongly-coupled light fields. The novel quantum system exhibits single-photon switching and strong correlations between different light fields.

9:12AM T3.00007 Combining sideband cooling schemes for fluorescence imaging of fermions in an optical lattice , RHYS ANDERSON, GRAHAM EDGE, PEIHANG XIU, VIJIN VENU, FUDONG WANG, STEFAN TROTZKY, JOSEPH THYWISSEN, University of Toronto — Quantum gas microscopes offer a unique tool with which to study strongly interacting cold atom systems. We report on the combination of Raman sideband cooling and electromagnetically-induced transparency (EIT) cooling of potassium-40 for this purpose. EIT cooling is performed in the plane perpendicular to the imaging axis via the D$_1$ transition, and provides the fluorescence necessary for imaging. Other laser beams detuned by 25 GHz from the D$_2$ line drive Raman transitions to lower energy, using an additional cavity crossing a 1200 Er lattice, with a bias magnetic field, and beam polarization keeps the atoms confined to stretched states. Collection of scattered photons through a 0.8 NA microscope objective results in detection of 600 photons per atom in a two second exposure, which is sufficient to resolve individual atoms with a PSF of FWHM 600 nm. The combination of these two cooling schemes resulted in a five-fold improvement in photon collection rate relative to either individual scheme for our system, while still allowing for 94 % of the atoms to remain pinned between two successive exposures. Fluorescence imaging of samples will allow for characterization of the dynamics of interacting fermions in periodic potentials.

9:24AM T3.00008 Success probability of atom-molecule sympathetic cooling: A statistical approach , MASATO MORITA, University of Nevada, Reno , ROMAN KREMS, University of British Columbia, TIMUR TSCHERBUL, University of Nevada, Reno — Sympathetic cooling with ultracold atoms is a promising route toward creating colder and denser ensembles of polar molecules at temperatures below 1 mK. Rigorous quantum scattering calculations can be carried out to identify atom-molecule sympathetic cooling can be estimated. Our analysis shows that, for a range of experimentally relevant collision systems, the cumulative probabilities are not sensitive to the number of rotational states in the basis set, potentially leading to a dramatic reduction of the computational cost of simulating cold molecular collisions in external fields.

9:36AM T3.00009 Sympathetic laser cooling of antiprotons with molecular anions. , SEBASTIAN GERBER, JULIAN FÉSÉL, INGMAR TIEJTE, CHRISTIAN ZIMMER, ALEXANDER HINTERBERGER, MICHAEL DOser, CERN, PAULINE YZOMBARD, DANIEL COMPARAT, Laboratoire Aime Cotton, University Paris-Sud, AEGIS COLLABORATION — Antimatter experiments conducted at the Antiproton Decelerator (AD) at CERN address the fundamental questions why primordial antimatter is not observed in the present Universe. The weak equivalence principle (WEP) can be tested measuring the gravitational acceleration of antihydrogen atoms in the Earth’s gravitational field that are horizontally emitted from a Penning trap. The antihydrogen atoms can be produced via resonant charge exchange of Rydberg positronium and antiprotons at temperatures potentially determined by the recoil limit of the constituents To prepare an ensemble of cold antihydrogen with a narrow velocity spread we plan to extend the existing electron cooling mechanism of antiprotons by laser-cooling techniques of negative $C_2$ trapped in a Penning trap in order to sympathetically cool antiprotons to the mK regime. The generation of cold antihydrogen atoms can ultimately also be used for precision spectroscopy experiments of electromagnetic interaction as a test of CPT symmetry. In this presentation the status of the experiment at CERN and a computational study of sympathetic cooling of antiprotons using photodetachment cooling, Doppler and AC Stark Sisyphus cooling of $C_2$ will be presented.
molecular photoionization. The hybrid basis representation limits it to relatively low energies (< 50 eV), requires an approximation to exchange matrix elements involving continuum functions, and hampers its coupling to modern electronic structure codes for the description of correlated target states. We describe a successful implementation of the method using completely adaptive overset grids to describe continuum functions, in which spherical subgrids are placed on every atomic center to complement a spherical master grid that describes the behavior at large distances. An accurate method for applying the free-particle Greens function on the grid eliminates the need to operate explicitly with the kinetic energy, enabling a rapidly convergent Arnoldi algorithm for solving linear equations on the grid, and no approximations to exchange operators are made. Results for electron scattering from several polyatomic molecules will be presented.

This research is supported by the Army Research Office, Research Corporation for Science Advancement, and Denison University.

8:00AM T4.00001 Overset grid implementation of the complex Kohn variational method for electron-polyatomic scattering1. C. WILLIAM MCCURDY, University of California, Davis and Lawrence Berkeley National Lab., ROBERT L. LUCHESE, Texas A & M University, LOREN GREENMAN, University of California, Davis — The complex Kohn variational method, which represents the continuum wave function in each channel using a combination of Gaussians and Bessel or Coulomb basis functions, has been successful in numerous applications to electron-polyatomic molecule scattering and molecular photoionization. The hybrid basis representation limits it to relatively low energies (< 50 eV), requires an approximation to exchange matrix elements involving continuum functions, and hampers its coupling to modern electronic structure codes for the description of correlated target states. We describe a successful implementation of the method using completely adaptive overset grids to describe continuum functions, in which spherical subgrids are placed on every atomic center to complement a spherical master grid that describes the behavior at large distances. An accurate method for applying the free-particle Greens function on the grid eliminates the need to operate explicitly with the kinetic energy, enabling a rapidly convergent Arnoldi algorithm for solving linear equations on the grid, and no approximations to exchange operators are made. Results for electron scattering from several polyatomic molecules will be presented.

1Work supported by the NSF under PHY-1403245 and XSEDE-090031.

8:12AM T4.00002 B-spline R-matrix with pseudostates calculations for electron-impact excitation and ionization of magnesium. OLEG ZATSARINNY, KLAUS BARTSCHAT, Drake University — The B-spline R-matrix with Pseudo-States method [1,2] employed to treat electron collisions with magnesium atoms. Predictions for elastic scattering, excitation, ionization, and ionization-excitation were obtained for all transitions between the lowest 25 states of Mg in the energy range from threshold to 100 eV. The accuracy of the results was checked by comparing with available experimental data and with results obtained in different approximations with increasing number of coupled states. The largest scattering model included 716 coupled states, most of which were pseudo-states that simulate the effect of the high-lying Rydberg continuum and, most importantly, the ionization continuum on the results for transitions between the discrete states of interest. Similar to our work on e-Be collisions [3], this effect is particularly strong at “intermediate” incident energies of a few times the ionization threshold. The dataset generated from the largest model is estimated to be accurate to within a few percent for the cross sections of relevance for plasma modelling. [1] O. Zatsarinny, Comp. Phys. Commun. 174 (2006) 273. [2] O. Zatsarinny and K. Bartschat, J. Phys. B 46 (2013) 112001. [3] D. V. Fursa and I. Bray, J. Phys. B 49 (2016) 235701.

1Work supported by the NSF under PHY-1403245 and XSEDE-090031.

8:24AM T4.00003 B-spline R-matrix calculations for electron-impact excitation of N\(^{3+}\). LUIS FERNANDEZ-MENCHERO, OLEG ZATSARINNY, KLAUS BARTSCHAT, Drake University — There are major discrepancies between recent ICFT (Intermediate Coupling Frame Transformation) [1] and DARC (Dirac Atomic R-matrix Code) calculations [2] regarding electron-impact-excitation rates for transitions in several Be-like ions. To identify possible reasons for these discrepancies and to estimate the accuracy of the various results, we carried out independent B-Spline R-Matrix (BSR) calculations for electron-impact excitation of N\(^{3+}\). Our close-coupling expansions contain the same 238 target states as the previous ICFT and DARC calculations, but with an improved representation of the target structure. We find close agreement among all calculations for the strong transitions between low-lying states, whereas serious discrepancies remain for the weak transitions and those involving high-lying excited states. The variations in the final results for the collision strengths are mainly due to differences in the structure description, specifically the inclusion of correlation effects, rather than the treatment of relativistic effects or problems with the validity of the three methods to describe the collision. [1] L. Fernández-Menchero et al., Astron. Astroph. 566 (2014) A104. [2] K. M. Aggarwal et al., Mon. Not. R. Astr. Soc. 461 3997.

1Work supported by the NSF under PHY-1403245, PHY-1520970, and XSEDE-090031.

8:36AM T4.00004 Electron excitation of Cesium and its application to plasma modeling. RAJESH SRIVASTAVA, PRITI PRITI, Indian Institute of Technology (IIT) Roorkee, Roorkee 247667, India, DIPTI DIPTI, NIST, 100 Bureau Drive, Gaithersburg, MD 20899, USA, REETESH GANGWAR, Weizmann Institute of Science, Rehovot 7610001, Israel — Electron impact excitation cross-sections and rate coefficients have been calculated using fully relativistic distorted wave theory for several fine-structure transitions from the ground as well as excited states of cesium. As an application, the calculated detailed cross-sections are used to construct a reliable collisional radiative (CR) model [1] to characterize the hydrogen-cesium plasma. These processes play dominant role in low pressure hydrogen-cesium plasma, which is relevant to the negative ion based neutral beam injectors for the ITER project. The calculated cross-sections and the extracted plasma parameters from the present model are compared with the available experimental and theoretical results [2]. [1] R. K. Gangwar, Dipi, R. Srivastava and L. Stafford, Plasma Sources Sci. Technol. 25, 035025 (2016). [2] Priti, Dipi, R K Gangwar and R Srivastava, J. Quant. Spectrosc. Radiat. Transf. 187, 426 (2017).

1Work is supported by SERB-DST, New Delhi and CSIR, New Delhi.

¹This work is financially supported by University Grants Commission (UGC), Government of India under Raman Post Doctoral Fellowship.
²Faculty at Department of Physics, Keshav Mahavidyalaya, University of Delhi, Delhi-110034, India.

9:00AM T4.00006 Dissociative recombination of HCl+: direct an indirect mechanisms, ASA LARSON, Stockholm University, SAMANTHA FONSECA, NICOLAS DOUGUET, Drake Univ, ANN OREL, UCDavis — We present the study of the Dissociative Recombination (DR) of HCl+ treating both the direct and indirect dissociation mechanisms. The relevant electronic states are calculated from ab initio principles by combining electron scattering calculations to obtain resonance positions and autoionization widths with multi-reference configuration interaction calculations of the ion and Rydberg states. Direct and indirect DR cross sections were calculated independently and added incoherently. The former was obtained by solving the time-dependent Schrodinger equation and propagating the wave packets along the resonant states, while the latter was computed using a theoretical model. In this model, an upper bound for the indirect process is obtained using a vibrational frame transformation of the elements of the scattering matrix at energies just above the ionization threshold. Vibrational excitations of the ionic core from the ground vibrational state to the first three excited states are considered and autoionization is neglected. The calculated cross section is compared to measurements.

9:12AM T4.00007 The conversion of resonances to bound states in the presence of a Coulomb potential and the computation of autoionization lifetimes from quantum defects². ROBERT LUCHESE, Texas A&M University, C. W. MCCURDY, University of California, Davis, T. N. RESCIGNO, Lawrence Berkeley National Laboratory — The conversion of resonant metastable states to bound states with changing potential strength in the presence of a Coulomb potential proceeds by a mechanism fundamentally different from the same process in the case of short-range potentials. This phenomenon, which can accompany changes in molecular geometry, is central to the physics of the process of dissociative recombination of electrons with molecular cations. We verify computationally that there is no direct connection between a resonance pole of the S-matrix and the bound state poles for several model problems. We present a detailed analysis of the analytic structure of the scattering matrix in which the resonance pole remains distinct in the complex plane while a new state appears in the bound state spectrum. Nonetheless, as might be expected from quantum-defect theory, there is a close analytic relation between the resonant behavior of scattering at positive energies and the energies of the bound states. This connection allows the width of a resonance at low energies to be calculated directly from the behavior of the quantum defects with changing potential strength or molecular geometry.

²US-DOE, OBES, Chemical Sciences, Geosciences, and Biosciences Division

9:24AM T4.00008 Intramolecular electron transfer in transient ammonia anion resonances. DANIEL SLAUGHTER, HIDEHITO ADANIYA, ALI BELKACEM, TOM RESCIGNO, Lawrence Berkeley National Laboratory — We report a combined experimental and theoretical study of dissociative electron attachment (DEA) dynamics of ammonia. Fragment momentum imaging experiments performed at MPIK Heidelberg and LBNL Berkeley found that DEA involving two electronic Feshbach resonances produce both H- and NH2- from ammonia. Two-body dissociation producing H- occurs via direct dissociation on either of two resonant anion states, with the lower and higher energy resonances leading to ground state and electronically excited NH2*, respectively. Using ab initio electronic structure theory we found that dissociation to H and NH2- involves a virtual anion state that asymptotically approaches the lower of these two dissociation limits, with nonadiabatic coupling due to electron transfer at considerable N-H distances. Through complex Kohn electron scattering calculations we examine the electron attachment probabilities in the molecular frame and compare these with measured fragment angular distributions to analyze and draw conclusions on the transient anion dynamics for each dissociation channel.

¹work support by U.S. D.O.E. Office of Science, Basic Energy Sciences, Chemical Sciences, Geosciences and Biosciences Division

9:36AM T4.00009 Spin entanglement in elastic electron scattering from lithium atoms. KLAUS BARTSCHAT, SAMANTHA FONSECA DOS SANTOS, Drake University — In two recent papers [1,2], the possibility of continuously varying the degree of entanglement between an elastically scattered electron and the valence electron of an alkali target was discussed. In order to estimate how well such a scheme may work in practice, we present results for elastic electron scattering from lithium in the energy regime of 1–5 eV and the full range of scattering angles 0°–180°. The most promising regime for Bell-correlations in this particular collision system are energies between about 1.5 eV and 3.0 eV, in an angular range around 110° ± 10°. In addition to the relative exchange asymmetry parameter, we present the differential cross section that is important when estimating the count rate and hence the feasibility of experiments using this system. [1] K. Blum and B. Lohmann, Phys. Rev. Lett. 116 (2016) 033201. [2] B. Lohmann, K. Blum, and B. Langer, Phys. Rev. A 94 (2016) 032331.

¹Work supported by the NSF under PHY-1403245.
9:48AM T4.00010 Positron Annihilation in the Undergraduate Laboratory

ENGRECHT, St. Olaf College — While there are a variety of undergraduate laboratory experiments in the literature, they tend to focus on specific positron experiments and use specialized equipment that limit their flexibility. Here we present a positron spectroscopy experimental apparatus designed for the undergraduate lab. Rather than specialized pulse processing the apparatus utilizes a PC oscilloscope as its primary data acquisition utility with pulse processing happening in software instead of hardware. This allows the apparatus to explore a variety of physical phenomena with the positron annihilation including material science, 2 and gamma annihilation properties, polarimetry via Compton scattering, QED tests, and local hidden variable theories. The supporting software is flexible and allows students to pursue these experiments through exploration rather than simply supporting data acquisition.

1St. Olaf College

Friday, June 9, 2017 8:00AM - 10:00AM —
Session T5 Focus Session: Molecular Imaging and Control 310 - Anthony Starace, University of Nebraska–Lincoln

8:00AM T5.00001 Ultrafast Imaging of Isolated Molecules with Electron Diffraction

CENTURION, University of Nebraska - Lincoln — Capturing molecular dynamics as they take place is essential for understanding and eventually controlling the outcome of chemical reactions. Ultrafast electron diffraction can be used to image the structure of isolated molecules with atomic resolution, however, until recently it was not possible to reach the femtosecond resolution needed to observe the nuclear motion. We have recently imaged a vibrational wavepacket in iodine with a resolution of 0.1 Å in space and 230 fs in time with electron diffraction, using the MeV electron source at SLAC National Laboratory. This result opens the door to imaging structural dynamics in more complex reactions. Work is currently ongoing in diffraction experiments to capture conformational changes in molecules and also towards improving the temporal and spatial resolution.

1This work was supported by the AMOS program in the Chemical Sciences, Geosciences, and Biosciences Division, Basic Energy Sciences, Office of Science, U.S. Department of Energy under Award Number: DE-SC0014170.

8:30AM T5.00002 Laser-induced electron diffraction for dynamic imaging of molecules

LIN, Kansas State University — Electron diffraction is the well-established tool for probing the structure of gas-phase molecules near the equilibrium geometry. To study chemical dynamics ultra-short electron pulses below a few tens of femtoseconds are needed. Laser-induced electron diffraction (LIED) is a method where molecules can be probed with femtosecond temporal resolution and sub-angstrom spatial resolution. In LIED, molecules are exposed to an intense femtosecond laser pulse. The electrons that have been previously removed by the laser field can be driven back later to rescatter with the parent molecular ion. Using diffusion images from large-angle backscattered events, sub-angstrom spatial resolution can be achieved with tens to hundreds eV electrons. Recent LIED experimental results showing bond breaking in molecules will be illustrated. Practical issues related to the retrieval of diffusion images from LIED on aligned molecules and possibilities of real-time imaging of dissociating molecules using LIED will be presented.

US Department of Energy

9:00AM T5.00003 Simultaneous x-ray imaging of A and B state dynamics in iodine at the LCLS

WARE, ADI NATAN, JAMES CRYAN, PHIL BUCKSBAUM, Stanford University, SLAC, and PULSE Institute, JAMES GLOWNIA, SLAC and LCLS — We will discuss our most recent analysis of the nuclear dynamics of photoexcited iodine from the LCLS. At the LCLS, we pumped a gas cell of iodine with a weak 520nm, 50 fs pulse from the X state into the dissociating A and bound B electronic states, and the nuclear dynamics are then probed with 9 keV, 40 fs x-rays with variable time delay. The A and B electronic states are perpendicular and parallel electronic transitions respectively, so their time-dependent x-ray diffraction signals can be isolated from each other. This work highlights the difficulty of using x-ray diffraction to film the excited state dynamics in molecules: the diffraction signal is an incoherent sum of all populated electronic states and, when the x-ray coherence time is shorter than the electronic coherence time, the signal can potentially include coherent interference between electronic states. Thus, even for simple systems like iodine, distinguishing the nuclear dynamics on different electronic surface s becomes a difficult task. For iodine, the analysis required knowledge of the dipole selection rules between the X and the A and B electronic states as well as the bound and dissociating character of the A and B states in order to separate the total diffraction signal into its A and B state contributions.

Research supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Atomic, Molecular, and Optical Science Program. Use of LCLS supported under DOE Contract No. DE-AC02-76SF00515

9:12AM T5.00004 Detection of Core Hole Localization in X-ray Photoionization

TREVISAN, California State University Maritime Academy, CLYDE MCCURDY, University of California, Davis and Lawrence Berkeley National Laboratory, THOMAS RESIGNO, Lawrence Berkeley National Laboratory — In the quest to find further evidence of the core hole localization phenomenon we recently found in CF4, we present ab initio calculations of molecular frame photoelectron angular distributions of electrons ejected from the core orbitals of the fluorne K-edge of various isomers of difluoroethylene (C2H2F2). In the case of CF4, the probability of removing a core electron from any of the four F atoms is nearly the same for all directions of photoejection of the electron. However, we found that for a particular decay channel, detecting an F+ ion makes the probability of having this ion be the atom that was core ionized nearly unity, because of a chemical effect related to the electronegativity of fluorine. C2H2F2 has two symmetry-equivalent fluorine atoms. Our work explores the extent to which the localization of core holes also takes place on one of two of the fluorine equivalent atoms following X-ray photoionization and is clearly visible in an experiment that averages around the axis of recoil of ion fragments after Auger decay.

U.S. DOE, Office of Science, WDTS

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spectrum of Rydberg states in coexistence with a cold plasma. We also find that the dependence of initial Rydberg atom binding energy and density. The effective electron temperature is determined when the avalanche ends, i.e., when the dipole collisions, or hot-cold Rydberg collisions results in a high enough ion density to trap electrons. Thereafter, during the avalanche regime, the asymptotic expansion velocities and effective plasma electron temperatures of ultra-cold plasmas (UNPs) which evolve from cold, dense, laser-cooling.

Γ is limited to \( 10^9 \) atoms with a width of 4 mm). This greatly reduces the plasma expansion rate, giving more time for laser cooling. We have also installed lasers for optically pumping atoms out of dark states that are populated during laser cooling. We will discuss these new systems, along with the results of our first attempts at laser-cooling.

\( l_0 \) is a photodetachment length of 2 mm). The optical centrifuge is formed by combining oppositely-chirped pulses of 800 nm light, and overlapping them spatially and temporally. Polarization-sensitive Doppler-broadened line profiles characterize the anisotropic kinetic energy release of the super rotor molecules, showing that they behave like molecular gyroscopes. Studies are reported for collisions of \( \text{CO}_2 \) super rotors with \( \text{CO}_2, \) He and Ar. These studies reveal how mass, velocity and rotational adiabaticity impact the angular momentum relaxation and reorientation. Quantum scattering calculations provide insight into the J-specific collision cross sections that control the relaxation.

9:36AM T5.00006 Laser-induced echoes: from molecular alignment to harmonics generation in free electron lasers, ILYA SH. AVERBUKH, E. GERSHNAEBEL, Y. PRIOR, Weizmann Institute of Science, Rehovot, G. KARRAS, E. HERTZ, F. BILLARD, B. LAVOREL, O. FAUCHER, Laboratoire Interdisciplinaire CARNOT de Bourgogne, UMR 6303 CNRS-Unisvrsite de Bourgogne, Dijon, J.-M. HARTMANN, G. SIGOUR, LISA, CNRS (UMR 7583), Unisvrsite Paris Est Creteil, K. LIN, P. LU, J. MA, X. GONG, Q. SONG, Q. JI, W. ZHANG, H.P. ZENG, J. WU, State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai — Recently we predicted a novel phenomenon of molecular alignment echoes, and demonstrated it by measuring laser-induced birefringence in a thermal \( \text{CO}_2 \) gas excited by a pair of femtosecond laser pulses [PRL 114, 153601 (2015)]. Here we report a new effect of fractional echoes observed in the same system via the third harmonic generation from a probe pulse [PRA 94, 033404 (2016)]. Moreover, using the technique of coincidence Coulomb explosion imaging (COLTRIMS) for the direct spatiotemporal analysis of molecular angular distribution, we observed a gamut of novel types of echoes, including fractional echoes of high order, spatially rotated echoes, and the counter-intuitive imaginary echoes at negative times [PRX 6, 041056 (2016)]. Remarkably, a phenomenon similar to fractional echoes of high order lies behind the recent demonstration of the efficient generation of high harmonics in free-electron lasers [Nat. Photonics 10, 512 (2016)].
Electron strong coupling in low-density ultracold plasmas \(^1\). WEI-TING CHEN, CRAIG WITTE, JACOB ROBERTS, Colorado State University — Three-body recombination is one of the main heating mechanisms that prevents electrons in ultracold plasmas (UCPs) from reaching higher degrees of strong coupling. Such heating has been predicted to limit the degree of electron strong coupling in a UCP to strong coupling parameter \(\Gamma \sim 0.2\) [F. Robicheaux and James D. Hanson, Phys. Rev. Lett. 88, 055002 (2003)]. The recombination rate scales as \(\Gamma^2\) and linearly with plasma frequency. On the other hand, the UCP formation time does not scale linearly with plasma frequency. These two different behaviors with respect to the plasma frequency suggest that by operating at low density, there is a period of time right after formation that the three-body recombination effect is insignificant such that \(\Gamma\) can exceed the 0.2 limit temporally. To experimentally verify this, we measured the temperature and density of low-density UCPs so as to extract \(\Gamma\). This was accomplished by measuring an electron oscillation frequency and damping rate. For low-temperature conditions in our system, \(\Gamma \sim 0.35\) was measured.

\(^1\)Supported by the AFOSR

Temperature measurements in a Yb/Ca dual-species ultracold neutral plasma \(^1\). TUCKER SPRENKLE, ADAM DODSON, SCOTT BERGESON, Brigham Young University — We report temperature measurement in an expanding dual-species Ca/Yb ultracold neutral plasma. This plasma is formed by sequentially ionizing Ca atoms and Yb atoms in a dual-species magneto-optical trap. We present measurements of the plasma temperature for a range of relative Ca\(^+\)/Yb\(^+\) densities and mixtures, and discuss our results in terms of dynamic shielding in this strongly-coupled Coulomb system.

\(^1\)Funded in part by National Science Foundation grant PHY-1500376

Ultracold Molecular Assembly. NICHOLAS HUTZLER, LEE LIU, YICHAO YU, JESSIE ZHANG, JONATHAN HOOD, KANG-KUEN NI, Harvard University — Studies of quantum many-body physics and information rely on the ability to coherently control strongly-interacting quantum objects. Ultracold polar molecules in optical traps are very promising candidates due to their many long-lived internal states and strong, long-range, anisotropic, and highly tunable interactions. A powerful and successful method is to start with ultracold atoms and coherently associate them into ultracold molecules. We take the approach of forming these molecules one-by-one via combining pairs of ultracold atoms in optical tweezers with complete and dynamic control over geometry. The flexibility of this approach allows us to work with NaCs, which has a very large dipole moment of 4.6 D. In this talk, we discuss progress trapping and cooling single atoms, and schemes for molecule formation [arxiv:1701.03121].

Quantum Reactive Scattering of Ultracold K+KRb Reaction: Universality and Chaotic Dynamics \(^1\). J. F. E. CROFT, University of Nevada, Las Vegas, NV 89154, C. MAKRIDES, JQI and NIST, Gaithersburg, MD, M. LI, A. PETROV, Temple University, Philadelphia, PA 19122, B. K. KENDRICK, Los Alamos National Laboratory, Los Alamos, NM 87545, N. BALAKRISHNAN, University of Nevada, Las Vegas, NV 89154, S. KOTOCHIGOVA, Temple University, Philadelphia, PA 19122 — A fundamental question in the study of chemical reactions is how reactions proceed at a collision energy close to absolute zero. This question is no longer hypothetical: quantum degenerate gases of atoms and molecules can now be created at temperatures lower than a few tens of nanoKelin. In this talk, we discuss the benchmark ultracold reaction between, the most-celebrated ultracold molecule, KRb and K. We report numerically exact quantum-mechanical calculations of the K+KRb reaction on an accurate ab initio ground state potential energy surface of the K\(_2\)Rb system and compare our results with available experimental data and predictions of universal models. The role of non-additive three-body contributions to the interaction potential is examined and is found to be small for the total reaction rates. However, the rotationally resolved rate coefficients are shown to be sensitive to the short-range interaction potential and follow a Poissonian distribution.

\(^1\)This work was supported in part by NSF grants PHY-1505557 (N.B.), PHY-1619788 (S.K.), ARO MURI grant No. W911NF-12-1-0476 (N.B. & S.K.), and DOE LDRD grant No. 20170221ER (B.K.).
8:24AM T7.00003 Reaching the Quantum Cramér-Rao Bound for Transmission Measurements\footnote{Work supported by the W.M. Keck Foundation}

TIMOTHY WOODWORTH, KAM WAI CLIFFORD CHAN, ALBERTO MARINO, University of Oklahoma — The quantum Cramér-Rao bound (QCRB) is commonly used to quantify the lower bound for the uncertainty in the estimation of a given parameter. Here, we calculate the QCRB for transmission measurements of an optical system probed by a beam of light. Estimating the transmission of an optical element is important as it is required for the calibration of optimal states for interferometers, characterization of high efficiency photodetectors, or as part of other measurements, such as those in plasmonic sensors or in ellipsometry. We use a beam splitter model for the losses introduced by the optical system to calculate the QCRB for different input states. We compare the bound for a coherent state, a two-mode squeezed-state (TMSS), a single-mode squeezed-state (SMSS), and a Fock state and show that it is possible to obtain an ultimate lower bound, regardless of the state used to probe the system. We prove that the Fock state gives the lowest possible uncertainty in estimating the transmission for any state and demonstrate that the TMSS and SMSS approach this ultimate bound for large levels of squeezing. Finally, we show that a simple measurement strategy for the TMSS, namely an intensity difference measurement, is able to saturate the QCRB.

\[ \sqrt{\gamma^2 + \Delta^2} \leq 2 \gamma \]  

8:36AM T7.00004 A sensitive electrometer based on a Rydberg atom in a Schrödinger-cat state\footnote{Supported by NSF} \footnote{present address: Georgia Tech Research Institute} \footnote{present address: US Army Research Lab}

SEBASTIEN GLEYZES, ADRIEN FACON, EVA-KATHARINA DIETSCH, ARTHUR LARROUY, DORIAN GROSSO, SERGE HAROCHE, JEAN-MICHEL RAIMOND, MICHEL BRUNE, Laboratoire Kastler Brossel, Collège de France, CNRS, ENSTA-PSL Research University, UPMC-Sorbonne Universities, 11, place Marcelin Berthelot, Paris, FR — Metrology experiments based on the measurement of small rotation of a large angular momentum are limited by the projection noise. When the measurement is performed using classical states, the precision cannot exceed the standard quantum limit (SQL), that scales like \[ 1/\sqrt{n}. \] To beat the SQL, one needs to make use of non-classical states. Our system is a Rydberg atom with a large angular principal number \[ n \sim 50. \] In the presence of a small electric field, the degeneracy between levels with the same \[ n \] is lifted. Then, using a radio frequency field with a well-defined polarization, it is possible to restrict the evolution of the atom to a subspace of the Rydberg manifold where the system behaves like a large spin \[ J = (n - 1)/2, \] whose frequency is proportional to the local amplitude of the electric field. We have used this effective spin to perform a quantum-enabled measurement of the static electric field [1]. We prepare a Schrödinger cat state of the Rydberg atom, and observe how the quantum phase of the cat provides a very sensitive signal to measure the variation of the static electric field allowing us to go beyond the SQL.

\[ J^z \approx \frac{\alpha J^z}{\sqrt{2}} \]


8:48AM T7.00005 Spin-motion coupling for sensitive amplitude detection with large ion crystals \footnote{Ministry of Education in Singapore; National Research Foundation}

JUSTIN G. BOHNET, National Institute of Standards and Technology, KEVIN A. GILMORE\footnote{present address: Georgia Tech Research Institute}, Dept. Physics, U. Colorado, BRIAN C. SAWYER\footnote{present address: US Army Research Lab}, JOSEPH W. BRITTON\footnote{present address: Georgia Tech Research Institute}, JOHN J. BOLLINGER, National Institute of Standards and Technology — During the past decade, optomechanical systems have shown increasingly sensitive techniques for measuring a mechanical oscillator’s amplitude, using the coupling of the oscillator to an optical field. Here we present experimental measurements of the amplitude of a center-of-mass (COM) drumhead motion of a 2D ion crystal composed of 100 ions in a Penning trap using a spin-dependent, optical-dipole force to couple the oscillator to the electron spin of the trapped ions. For motion off-resonant with the trap axial frequency we demonstrate measurements of amplitudes as small as 50 pm, 40 times below the ground state zero-point fluctuations. We show the sensitivity of our technique is limited by the quantum projection noise of the trapped ions. In the future, we expect to achieve a sensitivity of \(20 \text{ pm}/\sqrt{\text{Hz}}\), which can be useful for detecting extremely weak forces \(< 1 \text{ nN}\) and electric fields, as well as exploring protocols for sensing beyond the standard quantum limit for force detection.

9:00AM T7.00006 The role of thermal motion in free-space light-atom interaction\footnote{Work supported by the W.M. Keck Foundation}

YUE SUM CHIN, Centre for Quantum Technologies, National University of Singapore, MATTHIAS STEINER, CHRISTIAN KURTSIEFER, Centre for Quantum Technologies, National University of Singapore; Department of Physics, National University of Singapore — The prospects of distributed quantum networks have triggered much interest in developing light-matter interfaces. While this is usually realized by optical resonators, tightly focused free-space interfaces offer a complementary alternative. Our version of free-space light-matter interface is formed by a pair of high numerical aperture (NA=0.75) lenses and a single atom held in an optical tweezer. Operating near the diffraction limit, we show that a simple measurement strategy for the TMSS, namely an intensity difference measurement, is able to saturate the QCRB.

\[ \sqrt{\frac{\Delta^2}{\gamma^2 + \Delta^2}} \leq \frac{2}{\gamma} \]

9:12AM T7.00007 Quantum Sensing Beyond the Shot-Noise Limit with Plasmonic Sensors\footnote{Work supported by the W.M. Keck Foundation}

MOHAMMADJAVAD DOWRAN, ASHOK KUMAR, University of Oklahoma, BENJAMIN LAWRIE, RAPHAEL POOSER, Oak Ridge National Laboratory, ALBERTO MARINO, University of Oklahoma — The use of quantum resources offers the possibility of enhancing the sensitivity of a device beyond the shot noise limit and promises to revolutionize the field of metrology through the development of quantum enhanced sensors. In particular, plasmonic sensors, which are widely used in bio-chemical sensing applications, provide a unique opportunity to bring such an enhancement to real-life devices. Resonance plasmonic sensors respond to changes in refractive index through a shift of their characteristic transmission spectrum. We show that the use of quantum squeezed states to probe plasmonic sensors can enhance their sensitivity by lowering the noise floor and allowing the detection of smaller changes in refractive index. In our experiment, we use one of the beams of a two-mode squeezed state generated via four-wave-mixing in a Rb atoms to probe the sensor. A squeezing level of 4 dB is obtained after transmission through the plasmonic sensor, which consists of a triangular nano-hole array in a thin silver film and exhibits a sensitivity of the order of \(10^{-10} \text{ RIU}/\sqrt{\text{Hz}}\). The use of quantum states leads to 40% enhancement in the sensitivity of the plasmonic sensor with respect to the shot noise limit.
9:24AM T7.00008 Generation of atomic spin squeezed states in nanophotonic waveguides using QND measurement. XIANGONG QI, University of New Mexico, JONGMIN LEE, YUAN-YU JAU, Sandia National Labs, IVAN DEUTSCH, University of New Mexico — Nanophotonic waveguides strongly enhance the entangling strength of the atom-light interface. We study their application to the generation of spin squeezed states of trapped ultracold cesium atoms in two geometries — cylindrical optical nanofibers and square waveguides. We consider two different protocols — squeezing the clock transition by the birefringence coupling and squeezing a spin coherent state via the Faraday interaction. We unify our analysis based on a universal parameter — the optical depth per atom. In calculating the spin squeezing parameter, we have established a set of stochastic master equations to describe the individual and collective spin dynamics. Our simulation shows that ~10 dB of spin squeezing may be achievable with a few thousands of atoms on these nanophotonic waveguides. Our result can be generalized to other nanophotonic platforms, for implementing non-Gaussian states, and to improve quantum sensing precision using spin squeezing techniques.

1Center for Quantum Information and Control

9:36AM T7.00009 Measuring signatures of quantum chaos in strongly-interacting systems1, GREGORY BENSTE, Stanford University, BRIAN SWINGLE, University of Maryland, MONIKA SCHLEIER-SMITH, PATRICK HAYDEN, Stanford University — Strongly-coupled many-body quantum systems generically exhibit signatures of quantum chaos. Recent theoretical work on black holes has focused on probing these signatures using so-called “out-of-time-order” (OTO) correlation functions, which measure a quantum-mechanical version of the classical butterfly effect. We propose a general echo-type protocol to experimentally measure these correlators in arbitrary many-body systems that involves reversing the sign of the Hamiltonian [1]. We detail a realistic implementation in a single-body system employing cold atoms and cavity quantum electrodynamics to verify feasibility with current technology. Applying this protocol to diverse experimental systems could place bounds on quantum information processing, uncover new bounds on transport coefficients, offer insight into closed-system thermalization, and perhaps even enable experimental tests of the holographic principle.

1 NSF, AFOSR, Alfred P. Sloan Foundation, Simons Foundation, CIFAR

9:48AM T7.00010 Distinguishing time-reversible from time-irreversible processes with Interference patterns.1, ZILIN CHEN, PETER BEIERLE, HERMAN BATELAAN, University of Nebraska - Lincoln — In interference experiments, coherence is often incomplete. Coherence can be lost by dephasing or decoherence processes. The former is associated with time-reversible processes, while the latter is associated with time-irreversible processes. Even though there is a significant difference, the interference patterns appear similar; the pattern are more or less washed out. Entropy is a convenient measure of time reversibility. However, to determine the entropy, the coherence terms, i.e., the off-diagonal elements of the density matrix, need to be known. At first glance, it seems not possible to determine the reversibility from an interference pattern that provides only knowledge of the diagonal elements of the density matrix. Inspired by the lens-less imaging experiments by Gao et al.[1], we show by theoretical analysis that the spatial correlation function of repeated measurements of the interference pattern allows one to assess the reversibility. The second-order correlation function is proportional to the Fourier transformation of the spatial pattern of the double slits, but only if a dephasing process disturbs the wave. For a decoherence process the interference pattern is not recovered. This provides a method to establish time-reversibility, or the absence thereof, in matter-wave experiments. [1] Rui-Feng L, Xin-Xing Y, Yi-Zhen F, et al. Subwavelength Fourier-transform imaging without a lens or a beamsplitter[J]. Chinese Physics B, 2014, 23(5): 054202.

1We acknowledge support by NSF under the award number 1602755

Friday, June 9, 2017 8:00AM - 9:30AM — Session T8 Focus Session: Quantum Simulation — 314 - Andrew Wilson, NIST

8:00AM T8.00001 Using time reversal to detect entanglement and spreading of quantum information1. MARTIN GAERTTNER, Univ Heidelberg — Characterizing and understanding the states of interacting quantum systems and their non-equilibrium dynamics is the goal of quantum simulation. For this it is crucial to find experimentally feasible means for quantifying how entanglement and correlation build up and spread. The ability of analog quantum simulators to reverse the unitary dynamics of quantum many-body systems provides new tools in this quest. One such tool is the multiple-quantum coherence (MQC) spectrum previously used in NMR spectroscopy which can now be studied in so far inaccessible parameter regimes near zero temperature in highly controllable environments. I present recent progress in relating the MQC spectrum to established entanglement witnesses such as quantum Fisher information. Recognizing the MQC as out-of-time-order correlation functions, which quantify the spreading, or scrambling, of quantum information, allows us to establish a connection between these quantities and multi-party entanglement. I will show recent experimental results obtained with a trapped ion quantum simulator and a spinor BEC illustrating the power of time reversal protocols.

1Supported by: JILA-NSF-PFC-1125844, NSF-PHY-1521080, ARO, AFOSR, AFOSR-MURI, DARPA, NIST.

8:42AM T8.00003 Towards a photonic Mott insulator in superconducting circuits. RUICHAO MA, CLAI OWENS, BRENDAN SAXBERG, AMAN LACHAPELLE, DAVID SCHUSTER, JONATHAN SIMON, University of Chicago — Recent developments in circuit QED provide superconducting circuits as a unique platform for exploring quantum many-body phenomena with light. The absence of particle number-conservation, however, makes creating and understanding of many-body photonic states challenging. Here we make a one-dimensional lattice of coupled superconducting qubits with an additional pumping site and a lossy site incorporated at the end of the chain, which serves as an effective chemical potential for photons. When driven on the pumping site, the photons can spontaneously thermalize into the ground state of the lattice while the excess energy is dissipated via the lossy site. In the presence of strong photon-photon interaction via the qubit non-linearity, we expect the creation of a Mott insulator state of light, which we can probe with temporal- and spatially-resolved measurements. The performance of such an autonomous stabilizer can be compared to both analytical and numerical results from a simple model. These experiments will give insights to the microscopic investigation of non-equilibrium thermodynamics in strongly-interacting quantum system, including the interplay between external driving and dissipation. The work also provides a new approach to preparation of more exotic quantum photonic states.
8:54AM T8.00004 Analog Quantum Simulation of Complex Dynamics. NATHAN LYSNE, KEVIN KUPER, POUL JESSEN. The University of Arizona — Recent advances in quantum control have made analog quantum simulation (AQS) a promising tool for the study of complex many-body physics. However, as experimental AQS grows in sophistication, questions arise about how much and in which ways we can trust the outcome of a given simulation. Notably, the absence of error correction makes it critical to understand the role of imperfections when the simulated dynamics are chaotic and therefore hypersensitive to errors. The quantum kicked top (QKT) is an ideal model for such studies. We discuss results from recent work using the $d = 16$ electronic ground state manifold of an individual Cs atom for AQS of a QKT with spin $J = 15/2$. As a baseline, we see close agreement between simulated and predicted dynamics in a mixed phase space over hundreds of kicks. Earlier studies have hinted at features in the QKT dynamics that reflect classical phase space structures even when the fidelity of microscopic behavior (quantum state) is poor, suggesting the existence of global properties that can be reliably simulated in the presence of errors. We present data from experiments and numerical simulations in the presence of deliberately applied errors, showing that the frequency content of the perturbation plays a central role in the robustness of AQS.

9:06AM T8.00005 Cryogenic Ion Chains for Large scale Quantum Simulations. GUIDO PAGANO, HARVEY KAPLAN, WEN-LIN TAN, PAUL HESS, JIEHANG ZHANG, ERIC BIRCKELBAW, MICAH HERNANDEZ, CHRISTOPHER MONROE. Joint Quantum Institute, University of Maryland-College Park — Ions confined in RF Paul traps are a useful tool for quantum simulation of long-range spin-spin interaction models. As the system size increases, classical simulation methods become incapable of modeling the exponentially growing Hilbert space, necessitating quantum simulation for precise predictions. Current experiments are limited to less than 30 qubits due to collisions with background gas that regularly destroys the ion crystal. We report results achieved in our cryogenic ion-trap quantum simulator, where we can routinely trap up to 100 ions in a linear chain and hold them for hours, thanks to differential cryo-pumping that reduces residual background pressure. Such a long chain provides a platform to investigate simultaneous cooling of many vibrational modes which will enable quantum simulations that outperform their classical counterpart. Our apparatus serves as a versatile test-bed to investigate a variety of Hamiltonians, including spin 1 and spin 1/2 systems with Ising or XY interactions. This work is supported by the ARO Atomic Physics Program, the AFOSR MURI on Quantum Measurement and Verification, the IC Postdoc Fellowship Program and the NSF Physics Frontier Center at JQI.

9:18AM T8.00006 Bang-bang shortcut to adiabaticity in trapped ion quantum simulators. JAMES FREERICKS. Georgetown University, SHANKAR BALASUBRAMANIAN, Massachusetts Institute of Technology, SHUYANG HAN, BRYCE YOSHIMURA. Georgetown University — We model the bang-bang optimization protocol as a shortcut to adiabaticity in the ground-state preparation of an ion-trap-based quantum simulator. The bang-bang protocol is a double quench of the field with a hold time in between. We compare the ground-state population after the “adiabatic” preparation protocol for a locally adiabatic ramp of the field, an exponential ramp of the field, and the bang-bang shortcut. We find that for long-range spin-spin couplings, the bang-bang protocol is superior, being overtaken by the locally adiabatic one as the range of the interaction shrinks. It is always better than an exponential ramp. But, unlike the locally adiabatic ramp, which requires detailed knowledge of the energy spectra for all field values, the bang-bang approach can be optimized knowing nothing about the underlying Hamiltonian. Hence, this method may be advantageous in examining properties of complex systems, especially those for which we do not know the low-lying energy spectra a priori. Examples of the bang-bang approach and an explanation for why it works will be given in the presentation as well.

Friday, June 9, 2017 8:00AM - 10:00AM – Session T9 Precision Electric and Magnetic Field Measurements 315 - Cristopher Holloway, NIST

8:00AM T9.00001 Simultaneous Vector Magnetometry. JENNIFER SCHLOSS. Massachusetts Institute of Technology. JOHN BARRY, MIT Lincoln Labs, MATTHEW TURNER, RONALD WALSTROM, Harvard University — We present a method for simultaneous broadband measurement of all components of a time-varying magnetic field, demonstrated on an ensemble of nitrogen-vacancy (NV) centers in diamond. Using a multichannel lock-in technique, a single photodetector records the field’s projections onto the four NV crystallographic axes. By removing dead time associated with addressing NV resonances sequentially, we demonstrate a dramatic speedup in vector field sensing compared to conventional vector magnetometry on NV ensembles. Applications of this technique include fast rotation sensing, e.g. for navigation, and magnetic imaging of dynamics in neuronal networks.

8:12AM T9.00002 SQCRAMscope imaging of transport in an iron-pnictide superconductor. FAN YANG, ALICIA KOLLAR, STEPHEN TAYLOR, JOHANNA PALMSTROM, Stanford University, JIUN-HAW CHU, Stanford University and University of Washington, IAN FISHER, BENJAMIN LEV, Stanford University — Microscopic imaging of local magnetic fields provides a window into the organizing principles of complex and technologically relevant condensed matter materials. However, a wide variety of intriguing strongly correlated and topologically nontrivial materials exhibit poorly understood phenomena outside the detection capability of state-of-the-art high-sensitivity, high-resolution scanning probe magnetometers. We have recently introduced a quantum-noise-limited scanning probe magnetometer that can operate from room-to-cryogenic temperatures with unprecedented DC-field sensitivity and micron-scale resolution. The Scanning Quantum Cryogenic Atom Microscope (SQCRAMscope) employs a magnetically levitated atomic Bose-Einstein condensate (BEC), thereby providing immunity to conducative and blackbody radiative heating. We will report on the first use of the SQCRAMscope for imaging a strongly correlated material. Specifically, we will present measurements of electron transport in iron-pnictide superconductors across the electron nematic phase transition at $T = 135$ K.

8:24AM T9.00003 High-Spectral-Resolution NMR Using NV Centers in Diamond. DOMINIK BUCHER, DAVID GLENN, RONALD WALSTROM, Harvard University — Nitrogen-vacancy centers grown or implanted at the electron nematic phase transition at $T = 135$ K. Specifically, we will present measurements of electron transport in iron-pnictide superconductors across the electron nematic phase transition at $T = 135$ K.

8:00AM T9.00001 Simultaneous Vector Magnetometry. JENNIFER SCHLOSS, Massachusetts Institute of Technology, JOHN BARRY, MIT Lincoln Labs, MATTHEW TURNER, RONALD WALSTROM, Harvard University — We present a method for simultaneous broadband measurement of all components of a time-varying magnetic field, demonstrated on an ensemble of nitrogen-vacancy (NV) centers in diamond. Using a multichannel lock-in technique, a single photodetector records the field’s projections onto the four NV crystallographic axes. By removing dead time associated with addressing NV resonances sequentially, we demonstrate a dramatic speedup in vector field sensing compared to conventional vector magnetometry on NV ensembles. Applications of this technique include fast rotation sensing, e.g. for navigation, and magnetic imaging of dynamics in neuronal networks.

8:12AM T9.00002 SQCRAMscope imaging of transport in an iron-pnictide superconductor. FAN YANG, ALICIA KOLLAR, STEPHEN TAYLOR, JOHANNA PALMSTROM, Stanford University, JIUN-HAW CHU, Stanford University and University of Washington, IAN FISHER, BENJAMIN LEV, Stanford University — Microscopic imaging of local magnetic fields provides a window into the organizing principles of complex and technologically relevant condensed matter materials. However, a wide variety of intriguing strongly correlated and topologically nontrivial materials exhibit poorly understood phenomena outside the detection capability of state-of-the-art high-sensitivity, high-resolution scanning probe magnetometers. We have recently introduced a quantum-noise-limited scanning probe magnetometer that can operate from room-to-cryogenic temperatures with unprecedented DC-field sensitivity and micron-scale resolution. The Scanning Quantum Cryogenic Atom Microscope (SQCRAMscope) employs a magnetically levitated atomic Bose-Einstein condensate (BEC), thereby providing immunity to conducative and blackbody radiative heating. We will report on the first use of the SQCRAMscope for imaging a strongly correlated material. Specifically, we will present measurements of electron transport in iron-pnictide superconductors across the electron nematic phase transition at $T = 135$ K.
8:36AM T9.00004 Fiber-coupled Vapor Cell for Rydberg Electromagnetically-induced Transparency, MATTHEW SIMONS, JOSHUA GORDON, CHRISTOPHER HOLLOWAY, National Institute of Standards and Technology — Rydberg atom-based RF electric field (E-field) measurements have the potential to become a reference for RF calibrations. Rydberg states of alkali atoms (Cs, Rb) are coupled through electromagnetically-induced transparency (EIT), where an RF field can interact, causing Autler-Townes splitting. The split is proportional to the strength of the RF E-field, providing an SI-traceable, self-calibrated method for RF E-field metrology. A necessary step towards developing this technique as a new standard is the ability to directly compare the atom-based probe to existing E-field probes. Previously, this technique has been confined to the optical table, making measurements in typical RF calibration environments impossible. We demonstrate a fiber-coupled Cs vapor cell, with counter-propagating fields coupled through the cell via GRIN lenses, supporting Rydberg EIT. This probe can be scanned over printed circuit boards and co-planar waveguides, and placed in environments such as TEM cells and anechoic chambers.

8:48AM T9.00005 Picoliter NMR spectroscopy using nitrogen-vacancy centers in nanofabricated diamond, PAUL KEHAYIAS, Harvard-Smithsonian CFA, ANDREY JARMOLA, ODMR Technologies Inc., NAZANIN MOSAVIAN, ILJA FESCENKO, FRANCISCO BENITO, ABDELGHANI LARAOUI, JANIS SMITS, UNM Center for High Technology Materials, LYKOURGOS BOUGAS, Johannes Gutenberg Universitat Mainz, DMITRY BUDKER, Helmholtz Institut Mainz, ALEX NEUMANN, STEVEN BRUECK, VICTOR ACOSTA, UNM Center for High Technology Materials — Nuclear magnetic resonance (NMR) spectroscopy is a powerful tool for analytical chemistry, though one drawback is that its utility can be limited by poor sensitivity. This makes NMR characterization challenging for samples with few nuclear spins. Building on the recent advances of using nitrogen-vacancy (NV) color centers in diamond for NMR spectroscopy, we present a detailed experimental analysis of the frequency range of 1–500 GHz. Using Rydberg states, it is possible to sensitively probe the electric field in this frequency range using the combination of two quantum interference phenomena: electromagnetically induced transparency and the Autler-Townes effect. The new standard for RF E-field measurements can be modeled by the classical description of a harmonically bound electron. The classical damped, driven, coupled-oscillators model yields significant insights into the deep connections between classical and quantum physics. We will present a detailed experimental analysis of the noise processes in making such measurements in the laboratory and discuss the prospects for building a practical atomic microwave receiver.

9:00AM T9.00006 Rydberg Dipole Antennas, DANIEL STACK, BRADON RODENBURG, STEPHEN PAPAS, WANGSHEN SU, MARC ST. JOHN, MITRE Corp, PAUL KUNZ, US Army Research Laboratory, MATT SIMON, JOSHUA GORDON, CHRISTOPHER HOLLOWAY, National Institute of Standards and Technology — Measurements of microwave frequency electric fields by traditional methods (i.e. engineered antennas) have limited sensitivity and can be difficult to calibrate properly. A useful tool to address this problem are highly-excited (Rydberg) neutral atoms which have very large electric-dipole moments and many dipole-allowed transitions in the range of 1–500 GHz. Using Rydberg states, it is possible to sensitively probe the electric field in this frequency range using the combination of two quantum interference phenomena: electromagnetically induced transparency and the Autler-Townes effect. The new standard for RF E-field measurements can be modeled by the classical description of a harmonically bound electron. The classical damped, driven, coupled-oscillators model yields significant insights into the deep connections between classical and quantum physics. We will present a detailed experimental analysis of the noise processes in making such measurements in the laboratory and discuss the prospects for building a practical atomic microwave receiver.

9:12AM T9.00007 Photon Shot Noise Limited Radio Frequency Electric Field Sensing Using Rydberg Atoms in Vapor Cells, SANTOSH KUMAR, AKBAR J. JAHANGIRI, HAOQUAN FAN, Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, 440 W. Brooks St. Norman, OK 73019, USA, HARALD KUEBLER, 5. Physikalisches Institut, Universität Stuttgart, Germany, JAMES P. SHAFFER, Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, 440 W. Brooks St. Norman, OK 73019, USA — We report Rydberg atom-based radio frequency (RF) electrometry measurements at a sensitivity limited by probe laser photon shot noise. By utilizing the phenomena of electromagnetically induced transparency (EIT) in room temperature atomic vapor cells, Rydberg atoms can be used for absolute electric field measurements that significantly surpass conventional methods in utility, sensitivity and accuracy. We show that by using a Mach-Zehnder interferometer with homodyne detection or using frequency modulation spectroscopy with active control of residual amplitude modulation we can achieve a RF electric field detection sensitivity of 3 μV/√Hz. The sensitivity is limited by photon shot noise on the detector used to readout the probe laser intensity. We suggest a new multi-photon scheme that can mitigate the effect of photon shot noise. The multi-photon approach allows an increase in probe laser power without decreasing atomic coherence times that result from collisions caused by an increase in Rydberg atom excitation. The multi-photon scheme also reduces Residual Doppler broadening enabling more accurate measurements to be carried out.

1This work is supported by DARPA, and NRO.

9:24AM T9.00008 Sensing electric and magnetic components of microwave fields using Rydberg and ground-state atoms, TOBIAS THIELE, JILLA, Univ of Colorado - Boulder and ETH Zurich, JOANNIS KOEPESSL, ETH Zurich, YIHENG LIN, JILA, Univ of Colorado - Boulder, JOHANNES DEIGLMAYR, ETH Zurich, MARK O. BROWN, CINDY REGAL, JILA, Univ of Colorado - Boulder, ANDREAS WALLRAFF, FREDERIC MERKT, ETH Zurich — Precise sensing of electromagnetic fields has many applications ranging from definition of RF standards to magnetic field sensing in magnetic resonance imaging. Atoms as sensors are particularly attractive due to the quantum nature of their interaction with electromagnetic fields. We present two different experiments that exploit sensitive Rabi-rate measurements in atoms to determine the magnetic or electric components of microwave fields. First, we show measurements of two-dimensional spatial distributions of an electric field amplitude and its direction with respect to a bias field using a supersonic beam of Rydberg atoms in a cryogenic environment. Rydberg atoms are ideally suited to measure small variations in electric fields because of their large magnetic moment. We present here how we use a combination of the polarization of the magnetic component of a microwave field to sense small changes in the polarization axis of single ground-state atoms in optical tweezers. This platform has recently attracted much attention because of the possibility to control the position and state of the atom. A combination of both techniques opens perspectives to precisely and non-invasively detect very small changes in electromagnetic fields in free space or close to surfaces.

9:36AM T9.00009 Rydberg-atom-based electric field sensing: continuous-frequency measurements of high-intensity microwave electric fields, DAVID ANDERSON, Rydberg Technologies LLC, GEORG RAITHEL, University of Michigan, Rydberg Technologies LLC, ERIC PARADIS, Eastern Michigan University, Rydberg Technologies LLC, MATTHEW SIMONS, CHRISTOPHER HOLLOWAY, National Institute of Standards and Technology — In this talk I will describe recent work employing Rydberg electromagnetically induced transparency in atomic vapors for atom-based electric field measurements and sensing. This will focus on the demonstration of high-intensity microwave electric-field measurements exceeding 1 kV/m and strong-field measurement capability over a continuous microwave frequency range in the K_{a}-band, up to ±1 GHz detuned from the next relevant atomic transition (15% band coverage). Time permitting, developments towards improved measurement sensitivity of weak fields, polarization-selectivity, as well as DC-field measurement applications will also be discussed.

1Part of the presented material is based upon work supported by the Defense Advanced Research Projects Agency (DARPA) and the Army Contracting Command - Aberdeen Proving Ground (ACC-APG) under Contract number W911NF-15-P-0032.
doped with rubidium atoms at densities on the order of $10^{17}$ cm$^{-3}$. We prepare the atomic spin state of the implanted rubidium atoms with optical pumping, and measure the spin state with optical spectroscopy. The combination of high atomic densities and optical addressability make this a promising experimental platform for applications such as magnetometry. We measure $T_1^*$ and $T_2$ times for this system using free-induction decay and spin-echo techniques, and observe a strong dependence of $T_2^*$ on the density of orthohydrogen impurities in the para-hydrogen matrix.

This material is based upon work supported by The National Science Foundation under Grant # PHY 1607072

Friday, June 9, 2017 10:30AM - 12:30PM
Session U2 Hot Topics 306-307 - Bob Jones, University of Virginia

10:30AM U2.00001 Quantum acoustics with superconducting qubits. YIWEN CHU, Yale University — The ability to engineer and manipulate different types of quantum mechanical objects allows us to take advantage of their unique properties and create useful hybrid technologies. Thus far, complex quantum states and exotic quantum control have been demonstrated in systems ranging from trapped ions to superconducting resonators. Recently, there have been many efforts to extend these demonstrations to the motion of complex, macroscopic objects. These mechanical objects have important applications as quantum memories or transducers for measuring and connecting different types of quantum systems. In particular, there have been a few experiments that couple motion to nonlinear quantum objects such as superconducting qubits. This opens up the possibility of creating, storing, and manipulating non-Gaussian quantum states in mechanical degrees of freedom. However, before sophisticated quantum control of mechanical motion can be achieved, we must realize systems with long coherence times while maintaining a sufficient interaction strength. These systems should be implemented in a simple and robust manner that allows for increasing complexity and scalability in the future. In this talk, I will describe our recent experiments demonstrating a high frequency bulk acoustic wave resonator that is strongly coupled to a superconducting qubit using piezoelectric transduction. In contrast to previous experiments with qubit-mechanical systems, our device requires only simple fabrication methods, extends coherence times to many microseconds, and provides controllable access to a multitude of phonon modes. We use this system to demonstrate basic quantum operations on the coupled qubit-phonon system. Straightforward improvements to the current device will allow for advanced protocols analogous to what has been shown in optical and microwave resonators, resulting in a novel resource for implementing hybrid quantum technologies.

11:00AM U2.00002 Laser cooling of SrOH and magneto-optical trapping of CaF. JOHN DOYLE, Harvard University — Several promising goals of modern quantum science will be aided by the extension of precision control beyond atoms and bi-alkali molecules to a diverse set of molecular species with varying complex internal structures. Direct laser cooling and trapping of molecules is one promising route. For example, diatomic molecules with one or more unpaired electron spins and polyatomic molecules with multiple spin-active degrees of freedom have been coldly prepared in trapped ion and laser-cooled optical lattice experiments, respectively. For these optical species we use a variety of methods that allow us to masterfully control and manipulate the molecules. For example, we have demonstrated optical pumping, and measure the spin state with optical spectroscopy. The combination of high atomic densities and optical addressability make this a promising experimental platform for applications such as magnetometry. We measure $T_1^*$ and $T_2$ times for this system using free-induction decay and spin-echo techniques, and observe a strong dependence of $T_2^*$ on the density of orthohydrogen impurities in the para-hydrogen matrix.

This material is based upon work supported by The National Science Foundation under Grant # PHY 1607072

11:30AM U2.00003 Experimental Constraint on Dark Matter-Standard Model Coupling with Atomic Clocks. MICHAL ZAWADA, Nicolaus Copernicus University — All the evidence for existence of the dark matter (DM) comes from astrophysical observations at the galaxy scale. The nature of the DM composition, however, will be known only after the positive detection of the DM candidates. The nonbaryonic DM is most probably described by fields not yet included in the standard model. The viable cold DM particles candidates, axions, WIMPs, super-WIMPs, require existence of fields which can be coupled to the standard model fields. Therefore, existing experiments focus on searches for such couplings. Unfortunately, no experimental data proved any positive detection. E.g., the LUX experiment, which studied potential coupling between WIMPs and nucleons, reported recently constraints on the scattering cross section per nucleon below 1045 cm2. Lack of any detected DM in the form of particles yielded alternative theories, such as oscillating massive scalar fields or topological defects in the scalar fields. Recently, we have shown that a single optical atomic clock can be used as a detector for the DM in the form of stable topological defects. We exploited differences in the susceptibilities to the fine structure constant of essential parts of an optical atomic clock, i.e. the atoms and the cavity. With a system of two strontium optical lattice clocks we performed an experiment which constrained the strength of atomic coupling to hypothetical DM cosmic objects. Under the conditions of our experiment, the degree of constraint was found to exceed the previously reported limits by more than three orders of magnitude.

12:00PM U2.00004 Microscopy of atomic Fermi-Hubbard systems in new regimes. WAHEEM A. BAKR, Princeton University — The ability to probe and manipulate ultracold fermions in optical lattices at the atomic level using quantum gas microscopes has enabled quantitative studies of Fermi-Hubbard models in a temperature regime that is challenging for state-of-the-art numerical simulations. Experiments have focused on spin-balanced gases of repulsively interacting atoms with the hope of elucidating phenomena in the high-temperature superconductors. In this talk, I will present experiments that explore the Hubbard model in two new regimes: repulsive gases with spin-imbalance and attractive spin-balanced gases. In the first regime, we observe canted antiferromagnetism at half-filling, and stronger correlations in the direction orthogonal to the magnetization. Away from half-filling, the polarization of the gas exhibits non-monotonic behavior with doping, resembling the behavior of the magnetic susceptibility of the cuprates. The attractive Hubbard model studied in the second set of experiments is the simplest theoretical model for studying pairing and superconductivity of fermions in a lattice. Our measurements on the normal state reveal checkerboard charge-density wave correlations close to half-filling. Compared to the paired atom fraction, we find the charge-density-wave correlations to be a much more sensitive thermometer in the low temperature regime relevant for future studies of inhomogeneous superfluid phases in spin-imbalanced attractive gases.
10:30AM U3.00001 Observation of a triplet structure in d-wave Feshbach resonances

YUE CUI, MIN DENG, CHUYANG SHEN, SHEN DONG, CHENG CHEN, State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, BO GAO, Department of Physics and Astronomy, University of Toledo, MENG KHOON TETY, LI YOU, State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University; Collaborative Innovation Center of Quantum Matter — A d-wave Feshbach resonance between the $^{85}\text{Rb}(2, -2) + ^{87}\text{Rb}(1, -1)$ scattering channel is observed in a mixture of ultracold $^{85}\text{Rb}$ and $^{87}\text{Rb}$ atoms. Analogous to the well-known doublet splitting of the p-wave resonance in $^{40}\text{K}$ [1], we find a triplet structure originating from the magnetic dipole-dipole interaction between the valence electron spins of the two heteronuclear atoms. The three components of the resonance are respectively associated with the partial wave projections onto the direction of the magnetic field being $m_l = 0$, $|m_l| = 1$ and $|m_l| = 2$. Such an interpretation and our observations are well characterized using the semi-analytic multichannel quantum-defect theory [2]. This work opens up new possibilities of studying the anisotropy in d-wave interaction dominated physics.


10:42AM U3.00002 ABSTRACT WITHDRAWN

10:54AM U3.00003 Final state distribution in three-body recombination of three ultracold $^{87}\text{Rb}$ atoms

B. RUZIC, Joint Quantum Institute, Y. WANG, APS, J. D’INCAO, JILA, P. JULIENNE, Joint Quantum Institute, J. WOLF, A. KRUKOW, M. DEISS, University of Ulm, E. TIEMANN, University of Hannover, J. HECKER DENSCHLAG, University of Ulm — We use numerical calculations of coupled 3-body equations to obtain predictions of the distribution of Rb$_3$ dimer vibrational-rotational states when three ultracold Rb atoms undergo 3-body recombination. We assume the three body potentials at long range are given by pairwise addition of the known two-body potentials having the known van der Waals coefficient and the scattering length for two Rb atoms and having a number N of s-wave bound states. We solve the 3-body equations in the adiabatic hyperspherical representation to obtain the product distributions as N increases from unity and compare them to recently measured product distributions at the University of Ulm. We find points of agreement as well as difference with the observations, and use these to get insights into the nature of threshold three-body recombination of ultracold Rb atoms.

11:06AM U3.00004 Three-body scattering dynamics of ultracold magnetic lanthanides

Svetlana Kotochigova, Ming Li, Temple University, Constantinos Makrides, JQI and NIST, Alexander Petrov, Temple University, Eite Tiesinga, JQI and NIST — We theoretically investigate the origin of an extremely strong temperature dependence of the Feshbach-Fano (FF) resonance profiles observed experimentally [1,2] in atom-loss spectra of magnetic lanthanides, Dy and Er. This temperature dependence leads to a rapid increase of resonance density in these recombination spectra. We show with a resonant scattering model that the Wigner-threshold power law of the three-body recombination rate as a function of collision energy is very different for s- and d-wave entrance channels. Our resonance profiles for the Er loss features are in good agreement with experimental measurements [2] for temperatures from 230 nK to 2 µK indicating that the entrance channel has long-range repulsive three-body potentials, governed by the asymptotic behavior of the grand-angular-momentum operator and the total orbital angular momentum of the three atoms.


11:18AM U3.00005 Analytical coupled-channels treatment of two-body scattering in the presence of three-dimensional isotropic spin-orbit coupling

Qingze Guan, Doerte Blume, Washington State Univ — It is shown that the single-particle spin-orbit coupling terms, which—in the cold atom context—are associated with synthetic gauge fields, can significantly and non-trivially modify the phase accumulation at small interparticle distances even if the length scale ($k_{so}$)$^{-1}$ associated with the spin-orbit coupling term is significantly larger than the van der Waals length $r_{vdW}$ that characterizes the two-body interaction potential. A theoretical framework, which utilizes a generalized local frame transformation and accounts for the phase accumulation analytically, is developed. Comparison with numerical coupled-channels calculations demonstrates that the phase accumulation can, to a very good approximation, be described over a wide range of energies by the free-space scattering phase shifts—an evaluated at a scattering energy that depends on $k_{so}$, and the spin-orbit coupling strength $k_{so}$.

1Support by the NSF is gratefully acknowledged.

11:30AM U3.00006 Energetics and control of ultracold isotope-exchange reactions between heteronuclear dimers in external fields

Michal Tomza, Univ of Warsaw — We show that isotope-exchange reactions between ground-state alkali-metal, alkaline-earth-metal, and lanthanide heteronuclear dimers consisting of two isotopes of the same atom are exothermic with an energy change in the range of 1-8000 MHz, thus resulting in cold or ultracold products. For these chemical reactions, there are only one rovibrational and at most several hyperfine possible product states. The number and energetics of open and closed reactive channels can be controlled by the laser and magnetic fields. We suggest a laser-induced isotope- and state-selective Stark shift control to tune the exothermic isotope-exchange reactions to become endothermic, thus providing the ground for testing models of the chemical reactivity. The present proposal opens the way for studying the state-to-state dynamics of ultracold chemical reactions beyond the universal limit with a meaningful control over the quantum states of both reactants and products. [1] M. Tomza, Phys. Rev. Lett. 115, 063201 (2015).
Interesting behavior due to rotational excitation of the HD and H−. The interference is governed by a newly discovered mechanism which leads to an effective quantization of the ultracold scattering phase shifts. Upon whether the interference between the reaction pathways encircling the conical intersection is constructive or destructive, the nature of phase leads to a significant (up to three orders of magnitude) enhancement or suppression of the ultracold reaction rate coefficients depending and the associated with the D− complex was observed with depletion spectroscopy, depleting to vibrational levels ν = 1, 2, 3, and 45 of the C1Σ+ state. We augment the REMPI data with a form of depletion spectra in regions of dense spectral lines. The A1Σ+ − b3Π+ complex was observed with depletion spectroscopy, depleting to vibrational levels ν = 0 → 29 of the A1Σ+ state and ν = 8 → 18 of the b3Π+ state. For all three series, we determine the term energy and vibrational constants. Finally, we outline several possible future projects in ultracold molecules based on the data presented here.

This work was supported by the NSF (grant No. PHY-1607610).

The C1Σ+, A1Σ+, and b3Π+ states of LiRb. — Quantum reactive scattering calculations for the H/D + HD(v = 4, j = 1, 2) → H/D + HD(v′, j′) and H + H2(v = 4, j = 1, 2) → H + H2(v′, j′) exchange reactions are presented for the ground electronic state of H2. A numerically exact three-dimensional time-independent scattering method based on hyperspherical coordinates is used to compute rotationally resolved reaction cross sections and non-thermal rate coefficients for collision energies between 1 μK and 100 K. The geometric (Berry) phase associated with the D2h conical intersection in H2 is included using a U(1) vector (gauge) potential approach. It is shown that the geometric phase leads to a significant (up to three orders of magnitude) enhancement or suppression of the ultracold reaction rate coefficients depending upon whether the interference between the reaction pathways encircling the conical intersection is constructive or destructive. The nature of the interference is governed by a newly discovered mechanism which leads to an effective quantization of the ultracold scattering phase shifts. Interesting behavior due to rotational excitation of the HD and H2 is observed which might be exploited by experimentalists to control the reaction outcome.

This work was supported in part by NSF grant PHY-1505557 (N.B.) and ARO MURI grant No. W911NF-12-1-0476 (N.B.), and DOE LDRD grant No. 20170221ER (B.K.).

Friday, June 9, 2017 10:30AM - 12:30PM –
Session U5 Ionization and Dissociation in Strong-Fields 310 - George Gibson, University of Connecticut

Frequency Modulated Excitation of Rydberg Floquet States in Li+. — The Floquet structure of atomic states perturbed by oscillating electric fields is well understood from high resolution spectroscopy. The effect of the oscillating fields is to frequency modulate the atomic states. Here we use a frequency modulated (FM) diode laser to excite the Floquet structure of Li Rydberg states perturbed by synchronous microwave (MW) fields. The probability of excitation depends on the phase shift between the laser and state modulation. We observe the phase dependence of the excitation probability, and compare our results to the Floquet description to produce an absolute measure of the phase shift between the frequency modulation of the laser and the MW field at the atoms. This can be used as a reference to determine the absolute phase shift of previous phase dependent ionization experiments, which tests the predictions of the classical electron motion model.
10:42AM U5.00002 Strong-field electron tunnelling dynamics in atomic hydrogen
ROBERT SANG, U.SATYA SAINDH, HAN XU, ATIA-TUL NOOR, WILLIAM WALLACE, Australian Attosecond Science facility, Centre for Quantum Dynamics, Griffith University, Nathan, QLD 4111, Australia, XIAOSHAN WANG, School of Nuclear Science & Technology, Lanzhou University, Lanzhou, 730000, China, ĀNATOLI KHEIFITS, Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT 0200, Australia, IGOR IVANOV, Centre for Relativistic Laser Science, Institute for Basic Science, Gwangju 500-712 Republic of Korea, KLAUS BARTSCHAT, NICOLAS DOUGUET, Department of Physics and Astronomy, Drake University, Des Moines, Iowa, 50311, USA, IGOR LITVINYUK, Australian Attosecond Science facility, Centre for Quantum Dynamics, Griffith University, Nathan, QLD 4111, Australia. 

An atom in the presence of an ultra-short pulse of light can significantly distort the binding potential and it is possible for an electron to tunnel through the atomic binding potential. Previous attoclock experiments hinted at zero-tunnelling delays, however, exact theoretical solutions were not available to study the ionization dynamics in detail. Atomic Hydrogen (H) is the simplest atomic system and can be solved exactly using 3D-TDSE. We use the attoclock technique to investigate tunnelling dynamics with H using COLTRIMS and 770nm, 6fs pulses at intensities from 0.165-0.39 PW/cm². We compare these results with the full solution of 3D-TDSE.

10:54AM U5.00003 Correlated two-electron quantum dynamics in intense laser fields
DIETER BAUER, MARTINS BRICS, JULIUS RAPP, ADRIAN HANUSCH, University of Rostock — Two electrons interacting with each other, a binding potential, and a laser field turn out to be a real buzzkill for time-dependent many-body approaches. In particular, TDDFT with known and practicable exchange-correlation potentials fails in reproducing typical strong-field laser-atom phenomena of current interest such as photoelectron or transient absorption spectra. Even high-harmonics spectra, commonly believed to be an "easy" observable for TDDFT, can be qualitatively wrong. Failures of that kind will be illustrated in the talk. The challenge is to overcome these troubles with TDDFT. Working methods like MCTDHF or TDCI are quite expensive. As TDDFT is based on the single-particle density and MCTDHF/TDCI on the wavefunction, the obvious idea is to go just one “small” step beyond TDDFT and consider the one-body reduced density matrix (1-RDM) as the basic variable. Deriving equations of motion for the eigenfunctions and eigenvalues of the 1-RDM leads to time-dependent natural orbital theory (TDNOT). It will be shown in the talk that TDNOT indeed overcomes all the problems TDDFT has with two electrons in intense laser fields.

11:06AM U5.00004 Cation dynamics of molecular Hydrogen in the presence of a strong laser field, preliminary results
A. GATTON, E. CHAMPENOISE, K. LARSEN, N. SHIVARAM, S. BAKHTI, W. ISKANDER, LBNL, T. SIEVERT, KSU, D. REEDEY, UN-Reno, M. WELLER, U-Frankfurt, J.B. WILLIAMS, UN-Reno, A. LANDERS, Aubern, TH. WEBER, LBNL — We present preliminary results from a new 2-color laser-synchrotron Cold Target Recoil Ion Momentum Spectrometer (COLTRIMS) experiment in which we overlap a pulsed laser (I0=100ps, 5x10^{11} W/cm²) with light from beamline 10.0.1 (18.56eV, 80ps, 50meV resolution) at the Advanced Light Source at Lawrence Berkeley National Lab. The data (absent the laser) shows asymmetric proton emission in the fragmenting hydrogen cation due to the retro-action of the photoelectron Coulomb potential, as reported recently by Waitz et al. (PRL 116, 043001 (2016)). Preliminary analysis hints that this effect exists and may even be enhanced in the laser dressed states of the dissociating cation. Of even more interest, preliminary analysis hints at the signature of light induced conical intersections in the dissociation of the laser dressed hydrogen cations, as recently reported by Natan et al. (PRL 116, 143004 (2016)).

11:18AM U5.00005 Angular-momentum-assisted dissociation of CO in strong optical fields
AMY MULLIN, HANNAH OGDEN, MATTHEW MURRAY, QINGNAN LIU, CARLOS TORO, University of Maryland — Filaments of gas jets by intense, chirped pulses is observed as a result of chemical reactions of highly excited CO. At laser intensities greater than 10^{14} W cm^{-2}, the C2 emission shows a strong dependence on laser polarization. Oppositely chirped pulses of light with ω₀ = 800 nm are recombed spatially and temporarily to generate angularly accelerating electric fields (up to 30 THz) that either have an instantaneous linear polarization or act as a dynamic polarization grating that oscillates among linear and circular polarizations. The angularly accelerating linear polarization corresponds to an optical centrifuge that concurrently drives molecules into high rotational states (with J=50) and induces strong-field dissociation. Higher order excitation is observed for the time-varying laser polarization configuration that does not induce rotational excitation. The results indicate that the presence of rotational angular momentum lowers the threshold for CO dissociation in strong optical fields by coupling nuclear and electronic degrees of freedom.

11:30AM U5.00006 Angle-dependence of strong-field ionization of singly- and doubly-charged carbonyl sulfide
PETER SANSOR, ROBERT R. JONES, Department of Physics, University of Virginia, ADONAY SISAYA, Department of Chemistry, Louisiana State University, PAUL ABANADOR, FRANCOIS MAUGER, METTE GAARDE, KENNETH J. SCHAFER, Department of Physics and Astronomy, Louisiana State University, KENNETH LOPATA, Center for Computation and Technology / Department of Chemistry, Louisiana State University — We have studied the ionization probability of OCS molecules exposed to intense 780 nm laser pulses as a function of the angle between the molecular axis and the linear laser polarization. The molecules are exposed to two laser pulses. The first induces no ionization but, instead, creates a rotational wave packet within each molecule that exhibits preferential alignment in the laboratory frame at specific time delays. We measure the variation in the single and double ionization yield as a function of the delay between the two pulses. We obtain the angular dependent ionization probability by fitting the observed delay-dependent yields to moments of the angular distribution of the rotational wavepacket which can be accurately calculated. The experimentally determined angular distributions are compared to results of new time-dependent density functional theory predictions as well as previous measurements and calculations performed at somewhat lower laser intensities [1]. Accurate molecular ionization rate anisotropies are an important pre-requisite to utilizing strong-field techniques, such as high-harmonic spectroscopy, to probe of intramolecular electron dynamics. [1] J.L. Hansen et al., J. Phys. B 45, 015101 (2012); R. Johansen et al., J. Phys. B 49, 205601 (2016).
Physics, PULSE Institute — Strong field ionization of molecules is more complex than its atomic counterpart due to nuclear motion. This is

infrared fields

involved in strong-field ionization. We measure the photoelectron spectrum as a function of pulse shape and use a recently developed

shaped few-cycle laser pulses.

1 This work was supported by the National Science Foundation under Grant No. PHY-0649578

11:42AM U5.00007 Strong Field Probes of Ultrafast Molecular Dynamics: Dissociation of NO$_2$. RUARUDIR FORBES, University College London; University of Ottawa, ANDREY E. BOGULASVSKIY, Department of Physics, University of Ottawa, IAIN WILKINSON, Institute Methods for Material Development, Helmholtz Centre Berlin and National Research Council of Canada, JONATHAN G. UNDERWOOD, Department of Physics and Astronomy, University College London, ALBERT STOLOW, Department of Physics and Chemistry, University of Ottawa and National Research Council of Canada — Strong laser-field based methods such as high-harmonic generation and strong field ionization (SFI) are considered novel probes of ultrafast excited state molecular dynamics. We present an experimental femtosecond time-resolved SFI study of the excited state dynamics of NO$_2$ using channel-resolved above-threshold ionization (ATI) as the probe technique (DRAI) make use of Photoelectron Coincidence (PEPICO) spectroscopy to study correlations in fragmentation dynamics in molecular systems. The use of PEPICO and covariance methods allows us to correlate ATI photoelectrons associated with a particular ionic fragment and, hence, SFI electron orbital ionization channel. In all ionization channels considered, we observed variations in the ion and photoelectron yields as a function of pump-probe delay as well as the observation of persistent ATI combs at long time delays. In disentangling the excited state dynamics of NO$_2$, we examine the complex roles of one-photon excitation, multiphoton excitation to higher lying excited neutral states, non-adiabatic excited state dynamics and several neutral and ionic dissociation channels.

11:54AM U5.00008 Double Ionization of Water in Strong NIR Fields. GREG MCCRACKEN, Stanford University, Department of Applied Physics, PULSE Institute, CHELSEA LIEKHS-SCHMALTZ, ANDREAS KALDUN, Stanford University, Department of Physics, PULSE Institute, PHILIP BUCKSBAUM, Stanford University, Department of Physics, Department of Applied Physics, PULSE Institute, THOMAS WEINACHT, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794 — We study double ionization of H$_2$O in 40 fs, 800 nm pulses at intensities ranging from $10^{14}$ W/cm$^2$ to $10^{15}$ W/cm$^2$. Single OH$^+$ and H$^+$ dissociations are fully reconstructed using a time and position sensitive ion detector in ultra-high vacuum. We build a 2D map of the kinetic energy release and angular distribution of the dissociation. The map reveals a wealth of different ionization pathways including tunnel ionization from multiple orbitals, bond softening, and enhanced ionization. The fast unbinding of the water molecule caused by some pathways is also apparent in rovibrational structure of the OH$^+$ fragments seen in the 2D map.

12:06PM U5.00009 Ionization and fragmentation of methane with intense mid-infrared fields. YU HANG LAI, JUNLIANG XU, KAIKAI ZHANG, XIAOWEI GONG, KENT TALBERT, PIERRE AGOSTINI, COSMIN BLACA, LOUIS DIAUMO, The Ohio State University, THE OHIO STATE UNIVERSITY TEAM — We investigated the ionization and fragmentation rate of methane (CH$_4$) at several wavelengths between 3 and 4 µm. We found that the amount of fragmenting ions relative to the intact molecular ions exhibit a pronounced wavelength dependence and is peaked at around 3.3 to 3.6 µm. In contrast, the feature is absent in the same measurements with deuterated methane (CD$_4$). The results suggested that the resonance of C-H bond stretching mode is playing a significant role in the dissociation processes. Moreover, by comparing the total ion yields of CH$_4$ with that of CD$_4$, we found that the overall ionization rate of CH$_4$ is also enhanced at around 3.3 to 3.6 µm. This result has important implications in understanding tunnel ionization in the presence of vibrational resonance.

12:18PM U5.00010 Internal conversion and strong-field molecular ionization with shaped few-cycle laser pulses. VINCENT TAGLIAMONTI, ARTHUR ZHAO, BRIAN KAUFMAN, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794, TAMAS ROZCONYI, Institute of Materials and Environmental Chemistry, Research Centre for Natural Sciences, Budapest 1117 Magyar, Hungary, PHILIPP MARQUETAND, LEA IBELE, University of Vienna, Institute of Theoretical Chemistry, Wien, Austria, THOMAS WEINACHT, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794 — We study strong-field molecular ionization and internal conversion dynamics using few-cycle laser pulses tailored with an ADI based pulse shaper. The pulse shapes we used were chosen to illuminate internal conversion dynamics taking place during resonance enhanced strong-field molecular ionization. We measure the photoelectron spectrum as a function of pulse shape and use a recently developed model to interpret the pulse shape dependent molecular dynamics. Our results highlight the subtle interplay of electronic and nuclear dynamics involved in strong-field ionization.

Friday, June 9, 2017 10:30AM - 12:30PM — Session U6 Quantum/Coherent Control II 311-312 - True Merrill, Georgia Institute of Technology

10:30AM U6.00001 Electric-field noise from carbon-adatom diusion on a Au(110) surface: first-principles calculations and experiments. HOSEIN SADEGHPOUR, ITAMP, Harvard-Smithsonian CFA, EUNJA KIM, UNLV, ARGHAVAN SAFAVI-NAINI, Univ of Colorado - Boulder, PHILIPPE WECK, Sandia National Labs, DUSTIN HITE, KYLE MCKAY, DAVID PAPPAS, NIST-Boulder — The decoherence of trapped-ion quantum gates due to heating of their motional modes is a fundamental science and engineering challenge. Mitigating this noise, is fundamental to efficient and scalable operations in ion microtraps. To understand the possible source of noise by focusing on the diffusion of carbon adatoms, we fabricate a Cu adatom onto the Au(110) surface. Using density functional theory and detailed scanning probe microscopy, we show that the diffusive motion of carbon adatom on gold surface significantly affect the energy landscape and adatom dipole moment variation. A model for the diffusion noise, which varies quadratically with the variation of the dipole moment, qualitatively reproduces the measured noise spectrum, and the estimate of the noise spectral density is in accord with measured values.

10:42AM U6.00002 Demonstration of two-qubit entanglement with ultrafast laser pulses. DAVID WONG-CAMPOS, STEVEN MOSES, KALE JOHNSON, JONATHAN MIZRAHI, CHRISTOPHER MONROE, Joint Quantum Institute and University of Maryland Department of Physics, College Park, Maryland 20742 — One of the major problems in building a quantum computer is the development of scalable and robust methods to entangle many qubits. In trapped ions, the use of electromagnetic fields for quantum computation and entanglement, on the surface of a small system, has been widely studied. However, trap oscillations relative to the trap oscillation period make the operation sensitive to a noisy background environment. In contrast, ultrafast pulses should enable interaction times much faster than external noise sources. Here we demonstrate a fully entangling phase gate between two trapped 171Yb$^+$ ions using a sequence of spin-dependent ultrafast momentum kicks. Due to its fast nature, the demonstrated entangling gate is temperature independent and does not require ground state cooling. We verify entanglement by applying the entangling pulse sequence within a Ramsey interferometer and measuring the resulting parity oscillation. The best achieved fidelity is 60% in about 20 µs, which is limited by the spin-dependent kick fidelity. Future work includes systematically studying the limitations of the spin-dependent kick fidelity and speeding up the gate sequences to less than a harmonic trap evolution period.

1 This work is supported by the ARO and the NSF Physics Frontier Center at JQI.
qubit gates, despite the short T1 time of the excited state. This work is supported by the US Army Research Office.

valence electron of this single trapped atomic ion orbiting its nucleus. We discuss how this process can be used to execute high-speed single

allowed transition via picosecond pulses from a frequency-doubled mode-locked laser. The first pulse localizes the valence electron to one side

information and precision spectroscopy. Using a single trapped atomic ion, we demonstrate Ramsey spectroscopy of a short-lived, electric dipole

TEAM — Ramsey spectroscopy is a powerful technique that continues to evolve and prove useful for a wide variety of applications in quantum

hyperfine qubit gates only with electronic transitions. Here we show an experimental implementation of ultrafast X-rotation of atomic hyperfine

Hilbert space should be accessible only with local operations and classical communications (LOCC) [1]. Therefore, it may be possible to achieve

state intact. However, because atomic clock states are maximally entangled states of the electronic and nuclear degrees of freedom, their entire

Rubidium clock states

potential of the trap. Once an ion moves beyond \(R_{\text{cut}}\), the regular periodic motion of the ion becomes chaotic and it is no longer trapped. Further, using experiment, simulation, and analytical theory, we show that \(R_{\text{cut}}\) can be used to predict the saturated ion number in the trap at low loading rates achievable in many atom-ion hybrid trap systems, which can be used to measure cold ion-atom collision rates.

\[1\] W.W.S. would like to acknowledge NSF support (in part) from grant 1307874.

10:06AM U6.00004 Complete 3-Qubit Grover Search with Trapped Ions\(^1\) , CAROLINE FIGGATT, Joint Quantum Institute and University of Maryland Department of Physics, DMITRI MASLOV, National Science Foundation, NORBERT LINKE, KEVIN LANDSMAN, SHANTANU DEBNATH, CHRISTOPHER MONROE, Joint Quantum Institute and University of Maryland Department of Physics — We present experimental results on a complete 3-qubit Grovers search. The algorithm is performed for all 8 possible single-result oracles and all 28 possible two-result oracles. Two methods of state marking, with and without an ancilla, are used for the oracles. All quantum solutions are shown to outperform their classical counterparts. The algorithms constituent gates include Toffoli-3 and Toffoli-4 gates, with process fidelities 89.6\% and 70.5\%, respectively. The experiments are performed on a programmable quantum computer consisting of a linear chain of five trapped \(^{171}\)Yb\(^{+}\) ions. We execute modular one- and two-qubit gates through Raman transitions driven by a beat note between counter-propagating beams from a pulsed laser [1]. The systems individual addressing capability [2] provides arbitrary single-qubit rotations as well as any two-qubit XX-entangling gate, which are implemented using a pulse-segmentation scheme [3]. [1] PRL 104, 140501 (2010), [2] Nature 536, 63 (2016), [3] PRL 112, 19502 (2014).

\(^1\)This work is supported by the ARO with funding from the IARPA LogiQ program and the AFOSR MURI on Quantum Measurement and Verification.

11:18AM U6.00005 The use and development of ion dispensers for laser-cooled atomic ion experiments , DAVID HUCUL, JUSTIN E. CHRISTENSEN, ERIC R. HUDSON, WESLEY C. CAMPBELL, Univ of California - Los Angeles — Fast, reliable, efficient loading of ions in ion traps is important for laser cooled ion trapping experiments. We utilize a simple surface ionization technique where ions are directly emitted from a platinum surface upon sublimation. This technique of direct ion production has wide applicability to ion trapping experiments and should apply to the direct production of positively charged atomic and molecular species as well as molecular anions. We experimentally demonstrate the ease and flexibility of this technique by directly producing calcium, strontium, cesium, barium, and potassium ions from a heated platinum surface. In addition, this technique is useful for loading rare isotopes into an ion trap. We experimentally demonstrate this by loading large numbers barium ions into an ion trap and distilling rare, isotopically pure ions chains through voltage control and laser heating and cooling. These techniques are directly applicable to the loading of \(^{133}\)Ba\(^{+}\) ions, a candidate qubit that combines the favorable atomic structure of \(^{171}\)Yb\(^{+}\), long-lived metastable states to ensure high fidelity detection, and visible optical transitions to leverage existing optical technologies.

11:30AM U6.00006 Ultrafast time scale X-rotation of cold atom storage qubit using Rubidium clock states \(^1\) , YUNHEUNG SONG, HAN-GYEOL LEE, HYOSUB KIM, HANLAE JO, JAEWOOK AHN, Department of Physics, KAIST — Ultrafast-time-scale optical interaction is a local operation on the electronic subspace of an atom, thus leaving its nuclear state intact. However, because atomic clock states are maximally entangled states of the electronic and nuclear degrees of freedom, their entire Hilbert space should be accessible only with local operations and classical communications (LOCC) [1]. Therefore, it may be possible to achieve hyperfine qubit gates only with electronic transitions. Here we show an experimental implementation of ultrafast X-rotation of atomic hyperfine qubits, in which an optical Rabi oscillation induces a geometric phase [2] between the constituent fine-structure states, thus bringing about the X-rotation between the two ground hyperfine levels. In experiments, cold atoms in a magneto-optical trap were controlled with a femtosecond laser pulse from a Ti:sapphire laser amplifier [3]. Absorption imaging of the as-controlled atoms initially in the ground hyperfine state manifested a beat note between counter-propagating beams from a pulsed laser [1]. The systems individual addressing capability [2] provides arbitrary single-qubit rotations as well as any two-qubit XX-entangling gate, which are implemented using a pulse-segmentation scheme [3]. [1] Quantum Inf. Comput. 7, 1 (2006). [2] Phys. Rev. B 74, 205415 (2006). [3] Phys. Rev. A 91, 053421 (2015).

\(^1\)Samsung Science and Technology Foundation [SSTF-BA1301-12]

11:42AM U6.00007 Picosecond Ramsey spectroscopy of a short-lifetime dipole transition\(^1\) , MICHAEL IP, ANTHONY RANSFORD, CONRAD ROMAN, WESLEY CAMPBELL, ucla, UCLA AMO DEPARTMENT TEAM — Ramsey spectroscopy is a powerful technique that continues to evolve and prove useful for a wide variety of applications in quantum information and precision spectroscopy. Using a single trapped atomic ion, we demonstrate Ramsey spectroscopy of a short-lived, electric dipole allowed transition via picosecond pulses from a frequency-doubled mode-locked laser. The first pulse localizes the valence electron to one side of the nucleus and the arrival of the second pulse either adds constructively to this polarization or depolarizes the atom, depending upon its arrival time relative to the electron’s motion. By scanning the time delay, we measure Ramsey fringes with a period of about 1 fs that show the valence electron of this single trapped atomic ion orbiting its nucleus. We discuss how this process can be used to execute high-speed single qubit gates, despite the short T1 time of the excited state. This work is supported by the US Army Research Office.

\(^1\)US Army Research Office.
11:54AM U6.00008 Investigation of Ion Motional Heating in the Presence of Technical Noise. JONATHON SEDLACEK, MIT Lincoln Laboratory, JULES STUART, Massachusetts Institute of Technology, COLIN BRUZEWICZ, ROBERT MCCONNELL, JEREMY SAGE, JOHN CHIaverini, MIT Lincoln Laboratory — Surface-electrode ion traps show tremendous promise for large-scale quantum information processing. However, motional heating of ions has a detrimental effect on the fidelity of quantum logic operations. Despite the extensive study of motional heating in recent years, the underlying mechanisms are not completely understood. In these experiments however, contributions due to technical noise present on the DC and RF electrodes are often overlooked. We present a method for determining if the motional heating is dominated by residual voltage noise on the DC or RF electrodes. Also, we have found that stray DC electric fields can shift the ion position such that technical noise on the RF electrodes can significantly contribute to the motional heating rate. After minimizing the pseudopotential gradient by using parametric excitation, the motional heating due to RF technical noise can be significantly reduced.

12:06PM U6.00009 Shaping single photons and biphotons by inherent losses and grating defects. CHUNG-YAO YANG, CHIH-SUNG CHIU, WEI-MING SU, RAVIKUMAR CHINNARASU, CHANG-HAU KUO, National Tsing Hua University — Inherent loss is always to be avoided in generating single photons or biphotons, but interestingly it provides opportunities for manipulating the photon wave packet. In this talk we show how inherent loss in parametric down-conversion can be employed to tailor the wave packets of single photons and biphotons. As an example, we propose a scheme to realize a single photon in a single cycle using inherent loss. Our work has potential applications in quantum communication, quantum computation, and quantum interface.

12:18PM U6.00010 Directed Field Ionization. VINCENT C. GREGORIC, Bryn Mawr College, XINYUE KANG, Ursinus College, ZHIMIN CHERYL LIU, Bryn Mawr College, ZOE A. ROWLEY, THOMAS J. CARROLL, Ursinus College, MICHAEL W. NOEL, Bryn Mawr College — Selective field ionization is an important experimental technique used to study the state distribution of Rydberg atoms. This is achieved by applying a steadily increasing electric field, which successively ionizes more tightly bound states. An atom prepared in an energy eigenstate encounters many avoided Stark level crossings on the way to ionization. As it traverses these avoided crossings, its amplitude is split among multiple different states, spreading out the time resolved electron ionization signal. By perturbing the electric field ramp, we can change how the atoms traverse the avoided crossings, and thus alter the shape of the ionization signal. We have used a genetic algorithm to evolve these perturbations in real time in order to arrive at a target ionization shape. This process is robust to large fluctuations in experimental conditions.

This work was supported by the National Science Foundation under Grants No. 1607335 and No. 1607377 and used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number OCI-1053575.

Friday, June 9, 2017 10:30AM - 12:30PM – Session U7 Quantum Degenerate Gases 313 - Ken O’Hara, Pennsylvania State University

10:30AM U7.00001 The contact of a homogeneous unitary Fermi gas. BISWAROOP MUKHERJEE, PARTH PATEL, ZHENJIE YAN, RICHARD FLETCHER, JULIAN STRUCK, MARTIN ZWIERLEIN, Massachusetts Inst of Tech-MIT — The contact is a fundamental quantity that measures the strength of short-range correlations in quantum gases. As one of its most important implications, it provides a link between the microscopic two-particle correlation function at small distance and the macroscopic thermodynamic properties of the gas. In particular, pairing and superfluidity in a unitary Fermi gas can be expected to leave its mark in behavior of the contact. Here we present measurements on the temperature dependence of the contact of a unitary Fermi gas across the superfluid transition. By understanding the whole phase diagram of the repulsive Fermi gas and for realizing repulsive many-body states. We employ radio-frequency spectroscopy to investigate spin-mixtures of ultracold Li-6 atoms in a potential that is homogeneous in two directions and harmonic in the third. We obtain radiofrequency spectra of the homogeneous gas at a high signal-to-noise ratio. We compare our data to existing, but often mutually excluding theoretical calculations for the strongly interacting Fermi gas.


10:42AM U7.00002 Collective modes of fermionic alkaline earth atoms with SU(N) spin symmetry. SAYAN CHOUDHURY, ERICH MUELLER, Cornell Univ, THOMAS KILLIAN, KADEN HAZZARD, Rice University — Alkaline earth atoms have a large spin degeneracy (controllable from \( N = 1, \ldots, 10 \)) and an enhanced interaction symmetry that can enhance quantum fluctuations. Collective modes, excited by quickly changing the trap frequencies in a trapped gas, can be used to investigate properties of the excitations that emerge from these interactions. In particular, the collective mode frequency and damping time reflect properties of the gas’s quasiparticles like their lifetime and typical interaction energy. We calculate the frequencies and damping rate of the breathing and quadrupole modes for fermionic alkaline earth atoms confined by a quasi-2D harmonic trap. We find a significant interaction dependent shift in the collective mode frequencies. For an isotropic trap, the breathing mode does not exhibit damping. However, the quadrupole mode, a crossover occurs from the collisionless to the hydrodynamic regime as the interaction strength increases. For the experimentally relevant case of an anisotropic trap, the breathing and quadrupole modes couple and both of these modes exhibits damping. The most important physical consequence of the large \( N \) in this system is to give the ability to parametrically tune the ratio of the typical interaction strength to collisional damping.

10:54AM U7.00003 Repulsive Fermi polarons in the universal mass-balanced broad-resonance case. FRANCESCO SACIZZA, GIACOMO VALTOLINA, MATTEO ZACCANTI, GIACOMO ROATI, ANDREA AMICO, ALESSIA BURCHIANTI, CHIARA FORT, MASSIMO INGUSCIO, INO-CNR and LENS, University of Florence, PIETRO MASSIGNAN, ICFO-Institut de Ciencies Fonaments, Barcelona, ALESSIO RECANTI, INO-CNR BEC Center and Dipartimento di Fisica, University of Trento — The Fermi polaron represents a fundamental problem in many-body physics. In particular, repulsive Fermi polarons are centrally important for understanding the whole phase diagram of the repulsive Fermi gas and for realizing repulsive many-body states. We employ radio-frequency spectroscopy to investigate spin-mixtures of ultracold Li-6 atoms with tunable polarization in the vicinity of a broad Feshbach resonance. We report on the observation of well-defined coherent quasiparticles up to unitarity-limited interactions. We characterize the many-body system by extracting the key properties of repulsive Fermi polarons: the energy \( E_+ \), the effective mass \( m^* \), the residue \( Z \) and the decay rate \( \Gamma \). Above a critical interaction, we find \( E_+ \) to exceed the Fermi energy of the bath while \( m^* \) diverges and even turns negative, revealing an instability of the repulsive Fermi liquid.
11:06AM U7.00004 Quantum Turbulence in Fermionic Superfluids\textsuperscript{1}, MICHAEL FORBES, Washington State Univ, AUREL BULGAC, University of Washington, GABRIEL WLAZLOWSKI, Warsaw University of Technology — Fermionic superfluids provide a new realization of quantum turbulence, accessible to both experiment and theory, yet relevant to phenomena from both cold atoms to nuclear astrophysics. In this talk I will underscore several unique properties such as the high vortex line density of the unitary Fermi gas, which allows for quantum turbulence in small systems that can be studied experimentally and with a time-dependent density functional theory (TDDFT) that quantitatively captures their behaviour. Applications range from explaining cold atom experiments to resolving the 40-year old mystery of pulsar glitches in neutron stars.

\textsuperscript{1}Funded in part by the Polish National Science Center (NCN), the DOE Office of Science, and a WSU New Faculty Seed Grant

11:18AM U7.00005 Equation of State of Fermi Polarons, ZHENJIE YAN, BISWAROOP MUKHERJEE, PARTH PATEL, RICHARD FLETCHER, JULIAN STRUCK, MARTIN ZWIERLEIN, Massachusetts Institute of Technology — Fermi polarons are spin impurities dressed by interactions with a fermionic bath: an extension of the classic polaron problem where an electron is coupled to a sea of phonons. Here we present thermodynamic measurements of strongly interacting Fermi gases in the polaronic regime. We trap spin-imbalanced \textsuperscript{6}Li gases in a hybrid potential that is harmonic in one dimension and uniform in the other two, allowing us to extract local thermodynamic quantities with high signal to noise. The density and compressibility of the majority spin component are observed to deviate from the ideal Fermi gas. In addition, we report progress towards the gradual undressing of the Fermi polarons as the temperature is increased.

11:42AM U7.00007 Two-dimensional Fermi gases at a p-wave resonance. SHAOQIAN JIANG, FEI ZHOU, Univ of British Columbia — We study the possibility of p-wave superfluid of two-dimensional Fermi gases at a p-wave resonance using a two-channel model. Supplemented by an ε-expansion near two dimensions, a systematic analysis is carried out at the broad-resonance limit when the interchannel coupling is strong. We show that a homogeneous p-wave pairing expected at the mean-field level is actually unstable due to fluctuation effects, in contrast to the previously predicted p + p\textsuperscript{+} superfluid at the narrow-resonance limit. This implies an onset of instability when the interchannel coupling is increased.

11:54AM U7.00008 Time-dependent restricted-active-space self-consistent-field theory for bosonic many-body systems\textsuperscript{1}, CAMILLE LEVEQUE, LARS BOJER MADSEN, Aarhus University — We have developed an \textit{ab-initio} time-dependent wavefunction based theory for the description of many-body systems of bosons. The theory is based on a configuration-interaction interaction Ansatz for the many-body wavefunction with time-dependent consistent-field orbitals. The active space of the orbital excitations is subject to restrictions to be specified based on the physical situation at hand. The restrictions on the active space allow the theory to be evaluated under conditions where other wavefunction based methods, due to exponential scaling in the numerical efforts, cannot. The restrictions also allow us to clearly identify the excitations that are important for an accurate description, significantly beyond the mean-field approach. We first apply this theory to compute the ground-state energy of tens of trapped bosons, and second to simulate the dynamics following an instantaneous quenching of a non-contact interaction. The method provides accurate results and its computational cost is largely reduced compared with other wavefunction based many-body methods thanks to the restriction of the active orbital space. The important excitations are clearly identified and the method provides a new way to gain insight in correlation effects.

\textsuperscript{1}This work was supported by the ERC-StG (Project No. 277767-TDMET) and the VKR center of excellence, QUASCOPE

12:06PM U7.00009 Direct visualization of strong atom–atom interactions with colliding BECs, RACHEL WOOTEN, MACKILLO KIRA, University of Michigan — Macroscopic quantum properties of matter can hardly become more tangible than in the 1997 experiment\textsuperscript{1}, where an interference pattern was literally seen by imaging the collision of two BECs comprised of weakly interacting atoms. Extending such a study to strong interactions is more challenging, but feasible, following an experimental success\textsuperscript{2} in rapidly quenching a BEC from weak to strong atom–atom interactions. A recently developed cluster-expansion approach\textsuperscript{3} yields a nonperturbative description of strongly interacting BECs, and it has been demonstrated to quantitatively explain\textsuperscript{4} experiments. Here, we generalize this method to describe collision of two BECs and a simultaneous quench of atom–atom interactions. We will present how the resulting quantum many-body interactions enhances spatial bunching of the atoms which can be literally seen as dramatic, macroscopically-visible changes in the interference pattern. Consequently, future experiments should easily access many-body correlations via such an imaging.

\textsuperscript{1}M. R. Andrews, \textit{et al.}, Science 275, 637 (1997).
\textsuperscript{4}M. Kira, Nat. Commun. 6 6624 (2015).

12:18PM U7.00010 Probing density and spin correlations in two-dimensional Hubbard model with ultracold fermions, CHUN FAI CHAN, JAN HENNING DREWES, MARCELL GAL, NICOLA WURZ, Physikalisches Institut, Universit\ddot{a}t Bonn, EUGENIO COCCHI, LUKE MILLER, Physikalisches Institut, Universit\ddot{a}t Bonn; Cavendish Laboratory, University of Cambridge, DANIEL PERTOT, FERDINAND BRENECKE, MICHAEL KOEHL, Physikalisches Institut, Universit\ddot{a}t Bonn — Quantum gases of interacting fermionic atoms in optical lattices is a promising candidate to study strongly correlated quantum phases of the Hubbard model such as the Mott-insulator, spin-ordered phases, or in particular d-wave superconductivity. We experimentally realise the two-dimensional Hubbard model by loading a quantum degenerate Fermi gas of \textsuperscript{40}K atoms into a three-dimensional optical lattice geometry. High-resolution absorption imaging in combination with radiofrequency spectroscopy is applied to spatially resolve the atomic distribution in a single 2D layer. We investigate in local measurements of spatial correlations in both the density and spin sector as a function of filling, temperature and interaction strength. In the density sector, we compare the local density fluctuations and the global thermodynamic quantities, and in the spin sector, we observe the onset of non-local spin correlation, signalling the emergence of the anti-ferromagnetic phase. We would report our recent experimental endeavours to investigate further down in temperature in the spin sector.
10:30AM U9.00001 Trapped Circular Rydberg Atoms for Quantum Simulation
TIGRANE CANTAT-MOLTRECHT, THANH LONG NGUYEN, RODRIGO CORTINAS, CLÉMENT SAYRIN, SERGE HAROCHE, MICHEL BRUNE, JEAN-MICHEL RAIMOND, Laboratoire Kastler-Brossel, College de France, CNRS, ENS, PSL Research University, UPNC, Sorbonne Universités — Condensed-matter systems are interesting and important to understand but they are difficult to study, even numerically, given the significant sizes of their Hilbert space. Quantum simulation proposes to mimic those out-of-reach quantum systems with more controllable and accessible ones. The high polarizability of Rydberg atoms allows for strong and tunable short-range interactions, making them nice candidates for a quantum simulation platform. However, low angular momentum Rydberg atoms cannot be efficiently laser-trapped and their lifetimes would limit the scope of such a quantum simulator. We propose instead to use circular Rydberg atoms (of maximum angular momentum) which can be laser-trapped and whose lifetimes can be extended to the one minute range by placing them in a spontaneous emission-inhibiting cavity. We aim at the deterministic preparation of a 1D-chain of 40 atoms, trapped in a Laguerre-Gauss hollow laser beam, with a collective lifetime of 2 seconds. With exchange rates in the $10^{10} - 10^{11}\text{Hz}$ range, this would provide a platform able to simulate quantum many-body physics for more than $10^4$ exchange times. In this talk I will present this novel quantum simulation platform and our latest experimental results in the laser-trapping of circular Rydberg atoms.

10:42AM U9.00002 Control of Rydberg atom blockade by dc electric field orientation in a quasi-one-dimensional sample
LUÍS FELIPE GONCALVES, LUIS GUSTAVO MARCASSA, University of Sao Paulo — Rydberg atoms posses a strong atom-atom interaction, which limits its density in an atomic sample. Such effect is known as Rydberg atom blockade. Here, we present a novel way to control such effect by direct orienting the induced atomic dipole moment using a dc external electrical field. To demonstrate it, we excite the 50S$_{1/2}$ Rb atomic state in a quasi-one-dimensional sample held in a quasi-electrostatic trap. A pure $nS$ state holds only van der Waals interaction at long range, but in the presence of an external electric field the state mixing leads to strong dipole-dipole interactions. We have measured the Rydberg atom population as a function of ground state atoms density for several angles between the electric field and the main axis of the unidimensional sample. The results indicate that the limit on the final Rydberg density can be controlled by electric field orientation. Besides, we have characterized the sample by using direct spatial ion imaging, demonstrating that it does behave as an unidimensional sample.

1This work was supported by Sao Paulo Research Foundation (FAPESP) Grants No. 2011/22309-8 and No. 2013/02816-8, the U.S. Army Research Office Grant No. W911NF-15-1-0638 and CNPq.

10:54AM U9.00003 Excitation dynamics in a lattice of Rydberg superatoms and steady-state bistability
FABIAN LETSCHER, MICHAEL FLEISCHHAUER, Department of Physics and research center OPTIMAS, University of Kaiserslautern, Germany — Due to the strong and long-range interactions between Rydberg atoms, a mesoscopic atomic ensemble within a certain blockade volume suppresses more than one optical excitation. This so called superatom was realized in recent experiments. In the limit of strong dephasing during laser excitation, the superatom excitation probability reaches unity allowing for a much stronger driving strength beyond a two-level system. We study the many-body excitation dynamics of superatom lattices and observe interesting phases and phase transitions of open many body systems. In particular, we investigate the possibility of bistability in the steady state of the open many body system and explore signatures thereof. We clarify the role of long range correlations and a thermodynamic limit on the phase transition to a bistable regime. In a 2D lattice with nearest neighbor blockade, we observe an antiferromagnetically ordered phase with broken sublattice symmetry.

1DFG/SFB TTR 185

11:06AM U9.00004 Time-domain Ramsey interferometry with interacting Rydberg atoms
CHRISTIAN SOMMER, Max Planck Institute for the Science of Light — Many-body effects govern a variety of important quantum phenomena such as the emergence of superconductivity and magnetism in condensed matter physics. Here, we present a theoretical investigation of a many-body system formed by interacting Rydberg atoms. We follow the evolution of the electronic coherence of the atoms in Rydberg states within a time-domain Ramsey-interferometry protocol [1]. An Ising-type Hamiltonian with long range interactions is employed to describe the many-body dynamics. We show that fully analytic expressions for the coherence and the Ramsey-interferometry signal can be obtained in an ultracold gas under a continuous limit assumption and that this treatment can be further extended to correlation functions of the system. From the Ramsey signal a characteristic contrast degradation and phase accumulation signal is obtained which is showing corresponding scaling laws for different ensemble sizes and dimensionalities. Good agreement is found between the theoretical analysis and recent experimental results [2]. References [1] C. Sommer et al. Phys. Rev. A. 94, 053607 (2016) [2] N. Takei et al. Nat. Commun. 7, 13449 (2016)

11:18AM U9.00005 Many-body dynamics of driven-dissipative Rydberg cavity polaritons
TIM PISTORIUS, Institut für theoretische Physik, Leibniz Universität Hannover, JINGTAO FAN, Institute of Laser Spectroscopy, Shanxi University, HENDRIK WEIMER, Institut für theoretische Physik, Leibniz Universität Hannover — The usage of photons as long-range information carriers has greatly increased the interest in systems with nonlinear optical properties in recent years. The nonlinearity is easily achievable in Rydberg mediums through the strong van der Waals interaction which makes them one of the best candidates for such a system. Here, we propose a way to analyze the steady state solutions of a Rydberg medium in a cavity through the combination of the variational principle for open quantum systems and the P-distribution of the density matrix. To get a better understanding of the many-body-dynamics a transformation into the polariton picture is performed and investigated.

1Volkswagen Foundation, Deutsche Forschungsgemeinschaft

11:42AM U9.00007 Lifetimes of Ultralong-range Strontium Rydberg Molecules in a Dense BEC
J. D. WHALEN, F. CAMARGO, R. DING, T. C. KILLIAN, F. B. DUNNING, Rice University, J. PEREZ-RIOS, Purdue University, S. YOSHIDA, J. BURGDORFER, Vienna University of Technology — Ultralong-range Rydberg molecules created in a dense BEC can be used to explore collective many-body phenomena such as the creation of polarons. The atom densities in a BEC, however, are such that even for moderate values of $n, n > 50$, the electron orbit can enclose tens to hundreds of ground-state atoms. Collisional destruction therefore becomes important and can limit the molecular lifetimes. Measurements of the loss of Rydberg molecules with $n = 49, 60$, and $72$ excited in a BEC of $^{88}\text{Sr}$ with a peak density of $4 \times 10^{14} \text{cm}^{-3}$ reveal large loss rates of $1 - 3 \times 10^7 \text{s}^{-1}$. This loss is attributed to two mechanisms: the formation of $\text{Sr}^{2+}$ molecules through associative ionization, and $f$-changing reactions involving the Rydberg electron, with associative ionization being dominant. Collisional losses limit the time available to explore collective effects and possible techniques to increase this time are being examined.

1Research supported by the AFOSR, NSF, Robert A Welch Foundation, and The Rice Dean’s Fund
11:54AM U9.00008 Two-Photon Excitation of Launched Cold Atoms in Flight\textsuperscript{1}, ANNE GOODSELL, RENE GONZALEZ, EDUARDO ALEJANDRO, EMMA ERWIN, Middlebury College — We demonstrate two-photon bi-chromatic excitation of cold rubidium atoms in flight, using the pathway $\text{S}_{1/2} \rightarrow \text{P}_{3/2} \rightarrow \text{D}_{5/2}$ with two resonant photons. In our experiment, atoms are laser-cooled in a magneto-optical trap and launched upward in discrete clouds with a controllable vertical speed of $7.1 \pm 0.6 \text{ m/s}$ and a velocity spread that is less than 10\% of the launch speed. Outside the cooling beams, as high as 14 mm above the original center of the trap, the launched cold atoms are illuminated simultaneously by spatially-localized horizontal excitation beams at 780 nm ($\text{S}_{1/2} \rightarrow \text{P}_{3/2}$) and 776 nm ($\text{P}_{3/2} \rightarrow \text{D}_{5/2}$). We monitor transmission of the 780-nm beam over a range of intensities of 780-nm and 776-nm light. As the center of the moving cloud passes the excitation beams, we observe as much as $97.9 \pm 1.2\%$ transmission when the rate of two-photon absorption is high and the $\text{S}_{1/2}$ and $\text{P}_{3/2}$ states are depopulated, compared to $87.6 \pm 0.9\%$ transmission if only the 780-nm beam is present. This demonstrates two-photon excitation of a launched cold-atom source with controllable launch velocity and narrow velocity spread, as a foundation for three-photon excitation to Rydberg states.

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12:06PM U9.00009 Nondestructive Detection of Polar Molecules via Rydberg Atoms, MARTIN ZEPPENFELD, FERDINAND JARISCH, MPI of Quantum Optics — Research on cold and ultracold molecules is impeded by the difficulty in many cases to efficiently detect molecules, with the choice of molecule species often influenced by the need for a suitable detection scheme. We demonstrate the possibility to efficiently and nondestructively detect basically any polar molecule species using Rydberg atoms \cite{1}. A Rydberg atom senses the presence of a molecule based on Förster resonance energy transfer. We show that huge interaction cross sections of more than $10^{-6} \text{ cm}^2$ exist for low collision energies, allowing for efficient detection \cite{1}. First experimental results on detection of room temperature ammonia molecules with Rubidium Rydberg atoms will be presented. \cite{1} M. Zeppenfeld, arXiv:1611.08893 [physics.atom-ph] (2016).

12:18PM U9.00010 $n\ell \rightarrow n'\ell'$ transition rates in electron and proton - Rydberg atom collision\textsuperscript{1}, DANIEL VRINCEANU, Texas Southern University — Electrons and protons drive the recombination dynamics of highly excited Rydberg atoms in cold rarefied plasmas found in astrophysical conditions such as primordial recombination or star formation in H-II clouds. It has been recognized that collisions induce both energy and angular momentum transitions in Rydberg atoms, although in different proportions, depending on the initial state, temperature and the given species considered in the collision (electron or proton). Most studies focused on one collision type at a time, under the assumption that collision types are independent or their effects are not competing. The classical Monte-Carlo trajectory simulations presented in this work calculate the rates for both energy and angular momentum transfers and show their interdependence. For example, energy transfer with small angular momentum change are more efficient for target states with initial large angular momentum.

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