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The existing theoretical analysis of the metastable decay relies on the rotating wave approximation (RWA) and gives an exponentially small switching rate [2]. Therefore if corrections to the RWA modify the switching rate, they can become substantial even where they are small. We incorporate them within a semiclassical perturbation theory in the Floquet basis. Our analytical results are corroborated by numerical calculations and suggest a switching mechanism that had been previously overlooked.


Michigan State University — Experiments with Josephson bifurcation amplifiers have reached the regime where the switching between different metastable states is governed by quantum fluctuations [1]. The existing theoretical analysis of the metastable decay relies on the rotating wave approximation (RWA) and gives an exponentially small switching rate [2]. Therefore if corrections to the RWA modify the switching rate, they can become substantial even where they are small. We incorporate them within a semiclassical perturbation theory in the Floquet basis. Our analytical results are corroborated by numerical calculations and suggest a switching mechanism that had been previously overlooked.


Dykman, Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, Michael Marthaler, Institut fuer Theoretische Festkoerperfysik and DFG-Center for Functional Nanostructures (CFN), Karlsruhe Institute of Technology, D-76128 Karlsruhe, Vittorio Peano, Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824 — Relaxation of a quantum system is usually due to emission of excitations of a thermal reservoir. The emission events happen at random. For periodically modulated systems, the corresponding noise leads to a finite-width distribution over the quasi-energy (Floquet) states. It can be characterized by an effective nonzero quantum temperature even where the temperature of the reservoir is zero. We show that, as a result, the spectra of fluctuations and response of a parametrically modulated underdamped nonlinear oscillator can display a fine structure. The form of the spectra sensitively depends on the temperature of the reservoir.

8:12 AM A27.00002 Switching in modulated quantum oscillators beyond the rotating wave approximation. Vittorio Peano, Albert-Ludwigs University Freiburg, Michael Marthaler, Karlsruhe University, Michael Dykman, Michigan State University — Experiments with Josephson bifurcation amplifiers have reached the regime where the switching between different metastable states is governed by quantum fluctuations [1]. The existing theoretical analysis of the metastable decay relies on the rotating wave approximation (RWA) and gives an exponentially small switching rate [2]. Therefore if corrections to the RWA modify the switching rate, they can become substantial even where they are small. We incorporate them within a semiclassical perturbation theory in the Floquet basis. Our analytical results are corroborated by numerical calculations and suggest a switching mechanism that had been previously overlooked.


8:24 AM A27.00003 Many-body effects of quantum impurity models via circuit QED. Prasenjit Dutt, Michel Devoret, Karin Le Hur, Yale University, New Haven, CT. — Circuit QED systems serve as an ideal quantum simulator of condensed matter models due to the great degree of experimental precision and control with which they can be manipulated. Quantum impurity models exhibiting renormalization and confinement ideas reminiscent of QCD, can be realized in circuits comprising superconducting qubits and long transmission lines, which play the role of macroscopic bosonic baths. In particular, it is possible to use such systems to engineer standard low energy many-body Hamiltonians such as the spin-boson or anisotropic Kondo model. We develop a framework combining input-output theory and many-body techniques to study correlated photon transport and specifically the qubit response in such circuits.

36 AM A27.00004 Autoresonant vs. ladder climbing response in a superconducting Josephson phase circuit. Nadvat Katz, Yaara Roef, Yoni Shalibo, Hebrew University, Radoslaw Bialczak, John Martinis, UCSB, Ido BARTH, Lazar Friedland, Hebrew University — Anharmonic oscillators exhibit a unique response to a chirped drive, referred to as either autoresonance or ladder climbing. This typically involves a bifurcation of the oscillation amplitude depending both on the strength of the drive and on the system’s anharmonicity. In this parameter space, the threshold of bifurcation exhibits a transition between sequential state excitation (quantum ladder climbing) and the population of coherent-like states (classical autoresonance). Previous attempts to experimentally map this transition have only been possible in either classical or quantum conditions. Superconducting Josephson phase circuits enable us to map these two regimes, including the intermediate regime, due to their tunable anharmonicity. We measure the bifurcation phenomena in this system over the relevant parameter space where the transition is observed. We compare to numerical simulations and theoretical analysis.

8:48 AM A27.00005 Quantum Transport of Strongly-Correlated Photons in Waveguide QED. Huaixiu Zheng, Daniel J. Gauthier, Harold U. Baranger, Duke University — We present an exact solution of the quantum transport problem of multi-mode photons in a waveguide quantum electrodynamics (QED) system, which may be realized in a variety of circuit-QED, plasmonic, photonic, or cold-atom contexts. The bosonic modes are strongly coupled to a local atomic or qubit system, which can be a two-level, Gamma-type three-level, or N-type four-level system. We show that strong coupling produces dramatic quantum optics effects. In particular, multi-photon bound states emerge in the scattering of two or more photons. Such bound states have a large impact on the transport of coherent-state wave-packets. For a two-level system, the single-photon probability is suppressed while multi-photon probabilities are strongly enhanced, resulting in non-classical statistics. For a three-level system, as one tunes the coupling strength and the control field, the transmitted light can show bunching or antibunching, indicating effective attractive or repulsive interactions. Finally, for a N-type four-level system, we demonstrate that the multi-photon components of a signal can be largely suppressed, leading to a potential single-photon filter.

9:00 AM A27.00006 Superradiance and Phase Multistability in Circuit Quantum Electrodynamics. Michael Delanty, Stojan Rebić, Jason Twamley, Centre for Engineered Quantum Systems, Macquarie University, Sydney, NSW 2109, Australia — By modelling the coupling of multiple superconducting qubits to a single cavity in the circuit-quantum electrodynamics (QED) framework we find that it should be possible to observe superradiance and phase multistability using currently available technology (M. Delanty, S. Rebić and J. Twamley, arxiv:1007.2231). Due to the exceptionally large couplings present in circuit-QED we predict that superradiant microwave pulses should be observable with only a very small number of qubits (just three or four), in the presence of energy relaxation and small differences in the qubit-field coupling strengths. This paves the way for circuit-QED implementations of superradiant state readout and decoherence free subspace state encoding in subradiant states. The system considered here also exhibits phase multistability when driven with large field amplitudes, and this effect may have applications for collective qubit readout and for quantum feedback protocols. Furthermore, we extend our analysis to superradiance and collective effects in multi-resonator circuit-QED systems.

9:12 AM A27.00007 Design and Calibration of an Improved Josephson Parametric Amplifier. William F. Kindel, Hsiang-Sheng Kù, University of Colorado, Francois Mallet, Jila, Leila R. Vale, Gene C. Hilton, Kent D. Irwin, National Institute of Standards and Technology, Konrad W. Lehner, JILA — Phase sensitive amplifiers are of interested because in principal they can amplify one quadrature of a tone without any added noise, unlike phase insensitive amplifiers which amplify both quadratures but must add half a quanta of noise. In situations where a signal of interest is encoded in the modulation of only one quadrature of a tone, phase sensitive detection is clearly advantageous. With the goal of creating a microwave-frequency phase-sensitive amplifier that adds no noise, we will present the design and performance of a recently tested Josephson Parametric Amplifier (JPA). Initial measurements indicate that the JPAs added noise is no greater than 0.1 quanta. This is a substantial improvement over a previous design for which the added noise was 0.3 quanta [1]. I will discuss changes made to the design and possible reason for the improvement.

9:24AM A27.00008 Parametric processes in a cavity resonator terminated with a DC-SQUID
FRANCOIS NGUYEN, EVA ZAKKA BAJJANI, NIST Boulder, MINHYEAA LEE, University of Colorado, LAFEE SPIETZ, LEILA VALE, RAYMOND SIMMONDS, JOSE AUMENTADO, NIST Boulder — The coplanar waveguide resonators with SQUIDS have become common to several recent superconducting quantum information experiments. In this talk, we will present some recent results which demonstrate the manipulation of the internal harmonic modes of a microwave cavity resonator using a flux-driven SQUID as a parametric mode mixing resource.

9:36AM A27.00009 Quantum non-demolition measurement of microwave photons in superconducting circuits using engineered quadratic interactions CHUNQING DENG, University of Waterloo, JAY GAMBETTA, ADRIAN LUPASCU — We present a quantum electrical circuit with Josephson junctions formed by two anharmonic oscillators coupled with an interaction of the form $g^{1/2}$, where $\gamma_1$ and $\gamma_2$ are position-like coordinates. This type of coupling allows the quantum non-demolition measurement of the energy of one oscillator by monitoring the frequency of the second oscillator. We find that the optimized coupling strength $g$ scales as $\sqrt{\omega_1 \omega_2} / \sqrt{\gamma_1 \gamma_2}$, with $\omega_1, \omega_2$ the frequency, and $\gamma_1, \gamma_2$ the maximum photon storage capacity of each resonator. With an optimized coupling, it is possible to achieve high fidelity detection of up to 10 photons over a time of the order of microseconds. We discuss the possibility of observing quantum jumps in the number of photons and related applications. We also present our experimental work on the implementation of this detection scheme. C. Deng, J. M. Gambetta, and A. Lupascu, arXiv:1008.3363 (2010).

9:48AM A27.00010 Lossless on-chip microwave circulator using Josephson parametric converters1, BALEEGH ABDU, ARCHANA KAMAL, MICHAEL HATRIDGE, FLAVIUS SCHACKERT, KURTIS GEERLINGS, MICHEL DEVORET, Applied Physics Department, Yale University — Motivated by our recent theoretical work on non-reciprocal parametric devices [1], we propose a novel scheme for realizing a four-port, lossless, on-chip microwave circulator using a compact design of Josephson parametric converters (JPC’s) and hybrids. The JPC, which is normally used as a phase-preserving quantum-limited amplifier, is operated here in a pure conversion mode with unity photon gain. The non-reciprocity of the device is induced by a phase shift between the two pump signals feeding two JPC’s sharing a common idler port. The non-reciprocity direction can thus be reversed much more rapidly than by changing a magnetic field. Furthermore, since the device consists only of purely dispersive components, the proposed circulator should not add any noise to signals it processes.

1Work supported by IARPA, ARO and NSF.

10:00AM A27.00011 Dynamic range and noise of the Josephson parametric converter1,2, FLAVIUS SCHACKERT, BALEEGH ABDU, MICHAEL HATRIDGE, LUIGI FRUNZIO, ROBERT J. SCHELOKOPF, MICHEL H. DEVORET, Yale University — We present recent progress in characterizing key properties of the Josephson parametric converter (JPC): its dynamic range and noise performance. The JPC is a phase-preserving parametric amplifier operating in the microwave regime. It is based on a ring of four Josephson junctions, which provides the non-linearity, coupled to two microwave resonators, which increase the effective interaction between the incoming signal and this non-linearity. The JPC operates with a minimal number of modes, which simplifies its analysis, and is close to the ideal non-degenerate parametric amplifier operating at the quantum limit of noise. Besides having sufficient gain and bandwidth, a practical amplifier useful for e.g. the readout of superconducting qubits will need to exhibit a sufficiently low noise temperature and dynamic range. While dynamic range ensures that an incoming signal does not saturate the amplifier, a low noise temperature is necessary to minimally degrade signal-to-noise ratio.

1Work supported by IARPA, ARO and NSF.

10:12AM A27.00012 Microwave Photon Counter Based on Josephson Junctions, Y.-F. CHEN, D. HOVER, S. SENDELBACH, L. MAURER, R. MCDERMOTT, University of Wisconsin, S.T. MERKEL, E.J. PRITCHETT, F.K. WILHELM, Institute for Quantum Computing, University of Waterloo — We describe a microwave photon counter based on current-biased Josephson junctions. The absorption of a single microwave photon causes a junction to switch to the voltage state, producing a large and easily measured classical signal. With a two-junction circuit, we have performed a microwave version of the Hanbury Brown and Twiss experiment at 4 GHz, and demonstrated a clear signature of photon bunching for a thermal source. The design is readily scalable to tens of parallelized junctions, a configuration that would allow number-resolved counting of microwave photons. We discuss possible applications to cavity state readout and to measurement of the counting statistics of microwave photons emitted by mesoscopic conductors.

10:24AM A27.00013 Quantum Limited Amplification and Detection with a Non-Linear Cavity Detector, CATHERINE LAFLAMME, AASHISH CLERK, Department of Physics, McGill University — A variety of recent experiments demonstrate the power of using driven microwave resonators for quantum measurement and amplification. Here, we consider theoretically the use of a driven cavity with a Kerr-type non-linearity to amplify a dispersively coupled signal. We consider the regime where there is no multi-stability in the cavity dynamics; this is similar to recent experiments [1] where the amplifier quantum-limit in this case involves the physics of backaction, unlike the more studied ‘scattering’ mode of operation. We calculate the added noise of this non-linear cavity amplifier, and show that it exhibits universal scaling in the vicinity of the bifurcation point. We also show that for low frequencies the nonlinear cavity amplifier reaches the fundamental quantum limit on its noise temperature, but has large backaction - imprecision noise correlations. This implies that the non-linear cavity cannot be simply used for QND qubit measurement, but could have interesting applications to non-resonant force sensing. Our results have applications to quantum information processing, electromechanics and optomechanics.

1M. Hatridge et al., arXiv:1003.2466v1
2F.R. Ong et al., arXiv:1010.6284v1

10:36AM A27.00014 A flux-driven Josephson parametric amplifier for experiments with propagating quantum microwaves, E.P. MENZEL, A. BAUST, F. DEPPE, T. NIEMCZYK, E. HOFFMANN, M. HAEBERLEIN, A. MARX, R. GROSS, Walther-Meissner-Institut and TU Muenchen, Garching, Germany, E. SOLANO, Universidad del Pais Vasco and IKERBASQUE Foundation, Bilbao, Spain, K. INOMATA, RIKEN, Wako-shi, Japan, T. YAMAMOTO, Y. NAKAMURA, NEC, Tsukuba and RIKEN, Wako-shi, Japan — For the detection of propagating quantum microwaves in circuit QED linear amplifiers are key ingredients. Phase sensitive amplifiers [e.g., Josephson parametric amplifiers (JPA)] in principle allow for the amplification of one signal quadrature without adding noise. In practice, however, internal losses often introduce a finite amount of noise. We have recently shown that, despite such a residual noise, signals on the quantum level can be fully characterized using two amplification chains and suitable correlations [E.P. Menzel et al., PRL 105, 100401 (2010)]. In this work, we characterize a flux-driven JPA. At 5.64 GHz the maximum degenerate gain is 25.5 dB and the signal bandwidth is 1.8 MHz. Phase-insensitive measurements yield a noise temperature of $100 \pm 50$ mK, which is below the standard quantum limit of 135 mK.

1This work is supported by SFB 631, NIM, Basque Government IT4729-10, Spanish MICINN FIS2009-12773-C02-01, and EU project SOLID.
Monday, March 21, 2011 8:00AM - 11:00AM – Session A29 GQI: Quantum Communication, Theoretical Entanglement, and Cryptography

8:00AM A29.00001 Intrinsic Quantum Correlations of Weak Coherent States for Quantum Communication, YONG MENG SIA, ERIN SCANLON, TRAVIS BEAULIEU, VIKTOR BOLLEN, KIM FOOK LEE, Michigan Technological University — Intrinsic quantum correlations of weak coherent states are observed between two parties, which can be used as a supplement to the existence of decoy-state BB84 and differential-phase-shift quantum key distribution protocols. In a proof-of-principle experiment, we generate bi-partite correlations of weak coherent states using weak local oscillator fields in two spatially separated balanced homodyne detections. We employ non-linearity of post-measurement method to obtain the bi-partite correlations from two single-field interferences at individual homodyne measurement. This scheme is then used to demonstrate bits correlations in a transmission fiber over a distance of 10 km. We believe that the scheme can add another physical layer of security to these protocols for quantum key distribution and implement linear optics quantum computing with weak coherent states.

8:12AM A29.00002 Achieving the physical limits of the bounded-storage model, PRABHA MANDAYAM, Caltech, STEPHANIE WEHNER, Centre for Quantum Technologies — The security of most cryptographic systems in use today is based on the premise that certain computational problems are hard to solve for the adversary. However, recent cryptographic models such as the bounded-storage model and the noisy-storage model, are based on more physical assumptions regarding the two parties’ resources and allow us to obtain security without relying on any additional hardness results. In the bounded-storage model, where the adversary’s quantum storage is limited, it is known that security can be achieved if the adversary can store strictly less than half of the qubits transmitted during the protocol. It has been an open question whether security can still be achieved if the adversary’s storage were any larger. Here, we answer this question positively and demonstrate a two-party protocol which is secure as long as the adversary cannot store even a small fraction of the transmitted pulses. This not only settles the question, but also highlights the sharp contrast to classical bounded storage, where it is known that security can only be obtained if the adversary’s classical storage is at most quadratic in the storage required by the honest players. In the more general setting of the noisy-storage model, where the adversary’s memory is simply assumed to be imperfect, we show that our protocol extends security to a larger class of noisy quantum memories. (Reference: arXiv - quant-ph 1009.1596)

8:24AM A29.00003 High-speed single-photon signaling for daytime QKD, JOSHUA BIENFANG, ALESSANDRO RESTELLI, CHARLES CLARK, NIST/JQI — The distribution of quantum-generated cryptographic key at high throughputs can be critically limited by the performance of the systems’ single-photon detectors. While noise and afterpulsing are considerations for all single-photon QKD systems, high-transmission rate systems also have critical detector timing-resolution and recovery time requirements. We present experimental results exploiting the high timing resolution and count-rate stability of modified single-photon avalanche diodes (SPADs) in our GHz QKD system operating over a 1.5 km free-space link that demonstrate the ability to apply extremely short temporal gates, enabling daytime free-space QKD with a 4% QBER. We also discuss recent advances in gating techniques for InGaAs SPADs that are suitable for high-speed fiber-based QKD. We present afterpulse-probability measurements that demonstrate the ability to support single-photon count rates above 100 MHz with low afterpulse probability. These results will benefit the design and characterization of free-space and fiber QKD systems.

8:36AM A29.00004 Security Proof for QKD Using Qudits and Finite Key Length Analysis of Protocols, LANA SHERIDAN, THINH LE, Centre for Quantum Technologies, National University of Singapore, VALERIO SCARANI, Department of Physics and Centre for Quantum Technologies, National University of Singapore — It is advantageous to use \( d \)-dimensional quantum systems for QKD because each signal carries \( \log d \) > 1 bits, allowing a larger amount of information to be sent per transmission through the channel, and moreover, studies have indicated that the resistance to noise of the protocols increases when the dimension is increased. We provide a security bound against coherent attacks that takes into account finite-key effects for two families of protocols: two-basis protocols, the natural generalization of the Bennett-Brassard 1984 protocol for qubits, and \( (d+1) \)-basis protocols, the generalization of the six-state protocol for qubits. In the asymptotic limit, our bound vindicates the previous partial results concerning the higher resistance to noise. We also show that for finite key lengths the key rate corrections vary little with \( d \) for \( 2 \leq d \leq 10 \) indicating the protocol can be effective in realistic conditions. Finally, we consider some other finite key techniques for more general protocols.

8:48AM A29.00005 Quantum Spread Spectrum Communication, TRAVIS HUMBLE, Oak Ridge National Laboratory — Spread spectrum techniques are widely used in classical contexts, including sensing and communication, for establishing low probability of intercept, resistance to narrowband jamming, and multiuser access protocols. In SS, the spectrum of the signal is spread much larger than the minimal information bandwidth to yield a boost in channel capacity. In this contribution, we apply SS modulation to the transmission and detection of the single-photon spectral probability amplitude (as opposed to SS of the field). We draw upon previous methods for coherently dilating single-photon spectral states to motivate our ideas. Techniques for direct modulation of the spectral amplitude, modulation via pumped single-photon up-conversion, and modulation via spread spectral teleportation are developed as particular modulation schemes for quantum spread spectrum communication. We quantify QSSC performance using the channel capacity and process gain expressed in terms of the spread bandwidth, and we investigate its behavior for a frequency-selective fading model. We conclude by discussing the potential for QSSC to underlie a QKD multiuser access control (MAC) protocol.
9:00AM A29.00006 Remote Semi-State Preparation as SuperDense Quantum Teleportation¹ , HERBERT J. BERNSTEIN, ISIS Institute & School NS, Hampshire College — Recent advances in experimental technique make SuperDense Teleportation (SDT) possible. The effect uses remote state preparation to send more state-specifying parameters per bit than ordinary quantum teleportation (QT) can transmit. SDT uses a maximal entanglement to teleport the relative phases of an n-dimensional equimodular state. This means that one can send only n-1 of the total (2n-2) parameters — comprising the relative phases and amplitudes — of a general state. Nevertheless, for n≥ 3, SDT sends more of these state-specifying parameters than QT for a given number of classical bits. In the limit of large n the ratio is 2 to 1, hence the nomenclature Bennett suggested, SDT, by analogy with Super Dense Coding. Alice’s measurements and Bob’s transformations are simpler than in QT. The roles of Charles the state chooser, and Diana who deploys it, are different than in QT. I briefly review possible experimental realizations, including two that are under consideration at the present time by an experimental group leading in higher-dimension entanglement work.

¹Supported in part by NSF grants PHY97-22614 & 07-58149 & KITP, UCSB, including an ITP Scholar-ship.

9:12AM A29.00007 Entangled assisted zero-error codes , WILLIAM MATTHEWS, LAURA MANCINSKA, DEBBIE LEUNG, MARIS OZOLS, AIDAN ROY, University of Waterloo — Zero-error information theory studies the transmission of data over noisy communication channels with strictly zero error probability. For classical channels and data, much of the theory can be studied in terms of combinatorial graph properties and is a source of hard open problems in that domain. In recent work, we investigated how entanglement between sender and receiver can be used in this task. We found that entanglement-assisted zero-error codes (which are still naturally studied in terms of graphs) sometimes offer an increased bit rate of zero-error communication even in the large block length limit. The assisted codes that we have constructed are closely related to Kochen-Specker proofs of non-contextuality as studied in the context of foundational physics, and our results on asymptotic rates of assisted zero-error communication yield non-contextuality proofs which are particularly ‘strong’ in a certain quantitative sense. I will also describe formal connections to the multi-prover games known as pseudo-telep-ath games.

9:24AM A29.00008 Extreme Spin Squeezing Beyond Spin-1/2 Ensembles , COLLIN TRAIL, LEIGH NORRIS, IVAN DEUTSCH, University of New Mexico — We consider a protocol for squeezing the collective spin of a cold atomic ensemble through coherent control of the spin and light-polarization interactions. By retroreflecting a short pulse of light through the ensemble followed by a quantum eraser and phase matching, we achieve exponential scaling of the squeezing with optical density. We show how these results can be extended using state preparation and mapping techniques for s≥1/2 systems, and extend our model of photon-atom scattering to account for decoherence in the higher dimensional case.

9:36AM A29.00009 Engineered optical nonlinearity for a quantum light source , AGATA BRANCZYK, ALESSANDRO FEDRIZZI, TIM STACE, TIM RALPH, ANDREW WHITE, The University of Queensland — Many applications in optical quantum information processing benefit from careful spectral shaping of single-photon wavepackets. By engineering the nonlinearity profile of a poled crystal, we were able to tailor the joint spectral wave-function of photons created in parametric down-conversion. We designed a crystal with an approximately Gaussian nonlinearity profile and confirmed successful wave-packet shaping by two-photon interference experiments. To further explore the underlying spectral correlations in the spectral amplitude, we also measured spatial quantum beating patterns. We numerically show how our method can be applied for attaining one of the currently most important goals of single-photon quantum optics, the creation of pure single photons without spectral correlations.

9:48AM A29.00010 Disappearance of entanglement: a topological point of view¹ , DONG ZHOU, ROBERT JOYNT, GIA-WEI CHERN, JIANJIA FEI, University of Wisconsin-Madison — We give a topological classification of the evolution of entanglement, particularly the different ways the entanglement can disappear. Four categories exhaust all possibilities given the initial quantum state is entangled and the final one is not. Exponential decay of entanglement, entanglement sudden death and sudden birth can all be understood and visualized in the associated geometrical picture - the polarization vector representation. The entanglement evolution categories of any model are determined by the topology of the state space, the limiting state and the memory effect of the environment. Transitions between these types of behaviors as a function of physical parameters are also possible. These transitions are thus intrinsic to the quantum nature. We illustrate the general concepts with a visualizable model.

¹NSF-DMR-0805045, the DARPA QuEST program, and by ARO and LPS W911NF-08-1-0482

10:00AM A29.00011 Optimal Entanglement Transformations Among N-qubit W-Class States¹ , WEI CUI, ERIC CHITAMBAR, HOI-KWONG LO, University of Toronto — We investigate the physically allowed probabilities for transforming one N-partite W-class state to another by means of local operations assisted with classical communication (LOCC). Recently, Kintas and Turgut have obtained an upper bound for the maximum probability of transforming two such states [1]. Here, we provide a simple sufficient and necessary condition for when this upper bound can be satisfied and thus when optimality of state transformation can be achieved. Our discussion involves obtaining lower bounds for the transformation of arbitrary W-class states and showing precisely when this bound saturates the bound of [1]. Finally, we consider the question of transforming symmetric W-class states and find that in general, the optimal one-shot procedure for converting two symmetric states requires a non-symmetric filter by all the parties.

¹We thank Benjamin Fortescue for helpful discussions in the development of this work as well as support from the funding agencies CIFAR, CRC, NSERC, and QuantumWorks.

10:12AM A29.00012 Negativity Fonts in Four qubit Maximally Entangled States¹ , SANTOSH SHEELY SHARMA, Depto. de Física, Universidade Estadual de Londrina, Londrina 86051-990, PR Brazil, NARESH KUMĀR SHARMA, Depto. de Matemática, Universidade Estadual de Londrina, Londrina 86051-990 PR, Brazil — Recently, we introduced negativity fonts as the basic units of multipartite entanglement in pure states. We show that the relation between global negativity of partial transpose of N-qubit state and linear entropy of reduced single qubit state yields an expression for global negativity in terms of determinants of negativity fonts. Transformation equations for determinants of negativity fonts under local unitaries (LU’s) are used to construct N-qubit LU invariant and N-tangle (an entanglement monotone). The difference of squared negativity and N-tangle is an N qubit invariant which contains information on entanglement of the state caused by quantum coherences that are not annihilated by removing a single qubit. Entanglement monotones that detect the entanglement of specific parts of a four qubit state are also constructed. It is shown that these entanglement monotones bring out distinct features of several states which have been proposed to be the maximally entangled four qubit states.

¹Financial Support from Fundacao araucaria and CNPQ Brazil is acknowledged.

10:24AM A29.00013 ABSTRACT WITHDRAWN –
The Kitaev model on the honeycomb lattice can be solved exactly through mapping into free majorana fermions with a $Z_2$ gauge field. As a benchmark for DMRG on this two dimensional system, we have simulated this model with a cylindrical geometry with varying widths. The ground state energy and degeneracy match well with theoretical predictions. The different degenerate ground states exhibit the same short range spin-spin correlation patterns. The von Neumann entanglement entropy and its spectrum are evaluated. We show that the entropy of the Kitaev model satisfies the area law, with the entropy being more specifically proportional to the number of bonds cut at the boundary of two different regions. The degeneracy of entanglement spectrum can also be determined by the number of dangling majorana fermions at the cut. The above results hold for both the gapped and gapless phase. The non-Abelian phase obtained by applying a magnetic field, which is not exactly solvable, will also be discussed.

10:48AM A29.00015 Towards entanglement of very high orbital angular momentum$^1$, ROBERT FICKLER, RADEK LAPKIEWICZ, CHRISTOPH SCHAEFF, PEIZHE LI, SVEN RAMELOW, MARCIN WIESNIAK, ANTON ZEILINGER, University of Vienna, Faculty of Physics, IQOQI Vienna, University of Sciences, Austria — Orbital angular momentum (OAM) of single photons has become an often used tool to realize entanglement in higher dimensions$^{[1,2]}$. Laguerre-Gaussian modes of light with their helical phase structure carry photonic OAM and thus can be used to disentangle quantum entangled states. The total angular momentum of light can be quantized in units of the Planck constant divided by 2$\pi$. Here we report on a practical demonstration of a combined JPC and fluxonium system with a high Q resonator$^1$. We will discuss experimental requirements of the combined JPC and fluxonium system and anticipated improvements in measurement fidelity.

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1Supported by ERC (Advanced Grant QIT4QAD) and the Austrian Science Fund (grant F4007).


11:15AM B27.00001 Quantum Noise in a Chirped Superconducting Nonlinear Resonator, KATER MURCH, R. VIJAY, QNL, UC Berkeley, IDO BARTH, LAZAR FRIELAND, Racah Institute of Physics, Hebrew University, IRFAN SIDDIQI, QNL, UC Berkeley

— A nonlinear Josephson junction oscillator driven near resonance can exhibit bistability, forming the basis for sensitive, digital quantum state readout. We consider the case of a high-$Q$ resonator embedded with a Josephson junction excited with a chirped frequency signal. For sufficient drive amplitude, the resonator phase locks with the drive signal and enters the high amplitude oscillation state, a phenomenon known as autoresonance. The probability of capture in a given chirped pulse depends on the initial phase difference between the drive signal and of the fluctuation induced oscillations of the resonator. We find that the width of this threshold is in agreement with recent theoretical predictions and is set by zero-point fluctuations of the resonator. Autoresonant capture forms the basis for fast readout of a superconducting qubit coupled to a high-$Q$ resonator.

11:27AM B27.00002 Measurement backaction and the quantum Zeno effect in a superconducting qubit, DANIEL H. SLICHTER, R. VIJAY, IRFAN SIDDIQI, Quantum Nanoelectronics Laboratory, Dep. of Physics, UC Berkeley — Strong measurement of a quantum system can inhibit quantum state evolution, a phenomenon known as the quantum Zeno effect. If the measurement is not perfectly non-demolition, it can also cause spurious transitions between states. We study these effects in a transmon qubit dispersive coupled to a superconducting microwave readout cavity. We use a fast, ultralow-noise parametric amplifier to amplify the microwave photons used to probe the qubit state, enabling continuous high-fidelity monitoring of the qubit. This arrangement allows us to observe quantum jumps between the qubit states in real time. We examine the dependence of the jump times on measurement strength and the qubit excitation protocol.

11:39AM B27.00003 Investigation of the measurement dynamics of a flux qubit inductively coupled to a readout dc-SQUID, PETER GROSZKOWSKI, JAY GAMBERTA, FRANK WILHELM, IQC, University of Waterloo — In this paper we investigate the measurement dynamics of a flux qubit inductively coupled to a capacitively shunted, readout dc-SQUID. We study how the measurement induced dephasing and relaxation rates scale as a function of the qubit operation point and measurement strength. We find analytical solutions when the measurement is quantum-non-demolition (QND) and provide a numerical investigation for non-QND operation. This is of importance as the measurement of the flux qubit when operated at its sweet spot is inherently non-QND. We conclude this with a discussion of the measurement efficiency and signal-to-noise ratio.

11:51AM B27.00004 Optimization of SQUID-based microwave parametric amplifiers for qubit readout, CHRIS MACKLIN, R. VIJAY, E. LEVENSON-FALK, D. SLICHTER, Z. MINEV, I. SIDDIQI, QNL, UC Berkeley — We present recent experimental and theoretical results on the optimization of SQUID-based microwave parametric amplifiers for ultra low noise readout of superconducting and spin-based qubits. The devices consist of an unshunted two-junction SQUID in parallel with an on-chip capacitor, forming a non-linear microwave resonator. The SQUID is operated in a non-linear regime below the critical current, thus producing no local dissipation. These amplifiers have gain exceeding 20 dB, 10 MHz of tunable bandwidth, and quantum-limited noise performance. We present measurements on amplifiers with tunnel type and weak link Josephson junctions. We discuss the use of array structures to optimize dynamic range as well as a resonant flux-coupled input capable of operation in a transmission configuration and potentially suitable for on-chip integration.

12:03PM B27.00005 Fluxonium qubit readout with the Josephson parametric converter$^1$, M. HATRIDGE, B. ABDO, A. KAMAL, N. MASLUK, F. SCHÄCKERT, M.H. DEVORET, Applied Physics Dep., Yale University — Rapid, single shot quantum-non-demolition readout is a prerequisite for proposed active quantum feedback and error correction experiments in superconducting qubit systems. The fluxonium qubit, an artificial atom comprised of a Josephson junction array inductively shunting a Cooper-pair box, is a non-Purcell limited system with excellent coherence times, making it a natural candidate for such experiments. The largest obstacle towards achieving single shot fluxonium readout is the severe signal-to-noise ratio degradation of the qubit readout by the microwave frequency amplification chain. This degradation can be minimized through the addition of a quantum-limited pre-amplifier to the chain. We have designed and constructed such an amplifier, the Josephson Parametric Converter (JPC), which achieves nearly quantum limited amplification with a bandwidth and dynamic range suitable for readout of our current fluxonium design, and are currently integrating the JPC and fluxonium. We will discuss experimental requirements of the combined JPC and fluxonium system and anticipated improvements in measurement fidelity and speed.

$^1$Work supported by IARPA, ARO and NSF.
The dephasing rate is found to be close to the quantum limit for most pump parameters. This is correlated with the gain of the nonlinear resonator operated as a small-signal amplifier. The corresponding phase with Wigner tomography. In the quasi-adiabatic process of tuning the qubit frequency, the dynamic phase measurement can be pushed to the case of zero interaction. When the qubit is detuned far away from the resonator in frequency, linear dispersive interaction has been used for the readout of qubit states by employing these devices, including a new readout scheme for superconducting flux qubits and for the detection of microwave cavity photons.

This work was supported by DARPA QuEST.

Multiplexing Readout of a Qubit Array via a Single Transmission Line. MARKUS JERGER, STEFANO POLETTO, ALEXANDER LUKASHENKO, ALEXEY V. USTINOV, Physikalisches Institut, Karlruhe Institute of Technology and DFG-Center for Functional Nanostructures (CFN), D-76128 Karlsruhe, Germany, PASCAL MACHA, UWE HÜBNER, EVGENI IL’ICHEN, Institute of Photonic Technology, PO Box 100239, D-07702 Jena, Germany — A resonant circuit coupled to a qubit displays a shift of its resonance frequency depending on the quantum state of the qubit. The qubit state can be thus measured by probing the resonator near its resonance frequency. By coupling every qubit to its individual resonator of distinct frequency, one can read out the state of an array of many qubits through a single microwave line coupled to all resonators. Moreover, this readout can be performed simultaneously by using a multi-tone microwave pulse with frequency-division multiplexing. We will present measurements on an ensemble of 7 superconducting flux qubits located on one chip and each coupled to an individual transmission-line resonator. We performed spectroscopy of all qubits and determined their parameters in a single measurement run. Our latest experiments on simultaneous preparation and readout of the 7-qubit array will be presented.

Multiplexed dispersive readout of superconducting phase qubits1. YU CHEN, RAMI BAREND, RADOSLAW BIALCZAK, JULIAN KELLY, MICHEAL LENANDER, ERIK LUCERO, MATTEO MARIANTONI, MATTHEW NEELEY, AARON O’CONNELL, PETER O’MAELEY, Department of Physics, University of California-Santa Barbara, HAOHUA WANG, MARTIN WEIDES, JAMES WENNER, THEODORE WHITE, YI YIN, JIAN ZHAO, ANDREW CLELAND, JOHN MARTINIS, Department of Physics, University of California-Santa Barbara — A dispersive readout scheme is being developed for superconducting phase qubits. By inductively coupling to a LC resonator, the measured state of the qubit (left or right side of the potential well) can be read out as a shift of the resonance frequency. Compared to our current SQUID readout, this method eliminates the generation of quasiparticles, increases the reliability by reducing the junction count per qubit from 4 to 1, and reduces the chip wire count since the readout can be frequency multiplexed.

Non-linear interference in superconducting circuit QED. YI YIN, HAOHUA WANG, MATTEO MARIANTONI, RADOSLAW C. BIALCZAK, MIKE LENANDER, ERIC LUCERO, MATTHEW NEELEY, AARON O’CONNELL, DANIEL SANK, JIM WENNER, Physics Department, University of California, Santa Barbara, TSUYOSHI YAMAMOTO, NanoElectronics Research Laboratories, NEC Corporation, Japan, ANDREW CLELAND, JOHN MARTINIS, Physics Department, University of California, Santa Barbara — In circuit quantum electrodynamics, the strong coupling between superconducting qubits and a coplanar waveguide resonator (CPW) has been utilized to study the light-atom interaction. When the qubit is detuning far away from the resonator in frequency, linear dispersive interaction has been used for the readout of qubit states by measuring the pulling frequency of the resonator. Alternatively, we investigate dispersive interaction in a broader regime by measuring the accumulated dynamic phase with Wigner tomography. In the quasi-adiabatic process of tuning the qubit frequency, the dynamic phase measurement can be pushed to the case of zero detuning with up to the five-photon Fock state in the CPW resonator. The exotic non-linear behaviors of the qubit on resonator cat state and coherent state have been revealed, strongly depending on the strength of dispersive interaction. Our experimental data are consistent with the numerical calculation using the Jaynes-Cumming model.

Circuit QED with a Nonlinear Resonator: ac-Stark Shift and Dephasing. FLORIAN R. ONG, CEA-Saclay and University of Waterloo, M. BOISSONNEAULT, F. MALLEL, A. PALACIOS-LALOY, A. DEWES, A.C. DOHÉRY, A. BLAIS, P. BERTET, D. VION, D. ESTEVE, CEA-SAACLAY TEAM, U. DE SHERBROOKE TEAM, U. OF QUEENSLAND TEAM — Coupling a superconducting qubit to a superconducting resonator enables to investigate the interaction between light and matter with a unique flexibility of design, and allows to reach coupling regimes hardly accessible otherwise [Wallraff Nature 2004]. In this talk, we discuss the ac-Stark shift and the measurement induced dephasing of a qubit embedded in a nonlinear resonator, an architecture that has demonstrated high fidelity single-shot qubit state readout [Mallet Nat. Phys. 2009]. In our experiment, a transmon qubit [Koch PRA 2007] is capacitively coupled to a coplanar waveguide resonator incorporating a Josephson junction that provides a Kerr nonlinearity. We have measured the qubit spectrum while pumping the nonlinear resonator with a microwave tone. Measurements of the qubit frequency shift provide a sensitive probe of the intracavity field, yielding a precise characterization of the resonator nonlinearity. The qubit linewidth has a complex dependence on the pump frequency and amplitude, which is correlated with the gain of the nonlinear resonator operated as a small-signal amplifier. The corresponding dephasing rate is found to be close to the quantum limit for most pump parameters.
1:27PM B27.00012 Improved Superconducting Qubit Readout by Qubit-Induced Nonlinearities in the Straddling Regime, MAXIME BOISSONNEAULT, Universite de Sherbrooke, J.M. GAMBIETTA, IQC and University of Waterloo, J. BOURASSA, A. BLAIS, Universite de Sherbrooke — In dispersive readout schemes, qubit-induced nonlinearities have typically limited the measurement fidelity by reducing the signal-to-noise ratio (SNR) when the measurement power is increased [1]. However, it has been recently shown that these nonlinearities, together with the many-level system (MLS) nature of superconducting qubits, can be used to improve qubit readout in some regimes [2]. Moreover, for the transmon qubit [3], it has been shown that when the resonator’s frequency sits between two of the MLS’ transition frequencies — the so-called straddling regime — contributions of higher levels add constructively to improve the SNR [4]. In this talk, we explore the advantages of using both the qubit-induced nonlinearities and the straddling regime for qubit readout.


1:39PM B27.00013 Purcell Protection and Cycling Transition Measurement with a Superconducting V-system, ANTHONY HOFFMAN, SRIKANTH SRINIVASAN, Princeton University, JAY GAMBIETTA, Institute for Quantum Computing, ANDREW HOUCK, Princeton University — We perform time-domain experiments on a superconducting qubit with a V-level energy structure coupled to a superconducting, coplanar waveguide resonator. Quantum interference and the V-level energy scheme allow independent control of the qubit energy and dipole via two on-chip fast flux bias lines [1]. The tunable dipole is predicted to protect the qubit from cavity-induced spontaneous emission. We probe this “Purcell protection” by measuring the qubit lifetime at constant cavity-qubit detuning for a range of coupling strengths. We also show how the coupled cavity-qubit energy spectrum allows for a cycling-type measurement that is predicted to improve the signal to noise ratio of qubit state readout by as much as an order of magnitude.


1:51PM B27.00014 Quantum State Tomography of a Cooper-pair Box, SERGEY NOVIKOV, V. ZARETSKEY, B. SURI, Z. KIM, Dept. of Physics, Univ. of Maryland, B.S. PALMER, Lab. for Physical Sciences, F.C. WELLSTOOD, JQI, CNAM, Dept. of Physics, Univ. of Maryland — A 4.8 GHz microwave pulse shaping system with 3 ns Gaussian pulse rise time, arbitrary pulse envelope and phase control has been implemented. The system utilizes a two-channel 1 GSa/s DAC board to supply control voltages to an IQ mixer. The signals to the mixer have been optimized to obtain an on-off ratio of >85 dB and phase deviations <5%. The setup has been used to manipulate an Al/AlOx/Al Cooper-pair box (CPB) qubit coupled to a lumped-element microwave resonator (f₀ = 5.446 GHz). The CPB has a charging energy E_C/h = 6.25 GHz and a maximum E_J/h = 19 GHz which was decreased to an effective E_J/h = 0.5 GHz by a global magnetic field. By measuring the microwave transmission at f₀ in a pulsed-probe scheme, we perform a dispersive readout of the qubit. We present tomography data on the (|g⟩, |e⟩, (|g⟩+|e⟩)/√2 and (|g⟩+|e⟩)/√2 states. We find good agreement with theory, confirming that we have achieved the desired microwave pulse control.

2:03PM B27.00015 A phase qubit coupled to an RF-SQUID resonator, JED WHITTAKER, SHANE ALLMAN, University of Colorado at Boulder, KATARINA CICAK, FRANCOIS NGUYEN, NIST, ADAM SIROIS, University of Colorado at Boulder, JOHN TEUFEL, EVA ZAKKA-BAJJANI, RAYMOND SIMMONDS, NIST — We have coupled a tunable cavity (an RF-SQUID resonator) to a phase qubit. The resonator can be used both for state transfer experiments as well as a measurement/readout device for the qubit. Specifically, it can be used in three different ways to help interrogate the state of the qubit. First, changes in the resonator frequency can be monitored in order to read out the qubit state after a conventional fast measure pulse is applied to the qubit bias flux. Second, we can perform a linear dispersive measurement of the qubit state using the coupled interaction between the qubit and the resonator. Here, the resonator will have a qubit-state dependent frequency shift. Finally, we can exploit the nonlinearity of the resonator by driving it into the bifurcated regime and performing a single-shot measurement of the state of the qubit. I will discuss the design, fabrication, and operation of this system.


11:15AM B29.00001 Trapped ion arrays for quantum simulation1, RICHARD SLUSHER, Georgia Tech Research Institute — Trapped ions have been used to demonstrate a broad range of quantum information processes with high fidelity and are an obvious choice for quantum simulations. Several quantum simulations have already been demonstrated with ions2. The present goal is to simulate quantum systems that cannot be achieved with classical computation using more than 20 ions. It is challenging to assemble more than 20 ions in suitable arrays for quantum simulation of arbitrary model systems. Present ion trap based quantum simulations with up to 20 ions are now in progress. This talk describes ion trap micro-fabrication techniques and designs that have the potential to increase the number of coupled ions to the range between 50 and 100 ions. High precision ion traps are fabricated using silicon VLSI techniques on silicon wafers with aluminum electrodes. At the Georgia Tech Research Institute we are designing, fabricating and testing ion trap arrays that will contain and accurately control at least 50 ions in linear chains of equally spaced ions. Large numbers of equally spaced ions have recently been shown to be stable in anharmonic trap potentials that are easily obtained in the micro-fabricated traps. The limits on quantum simulation accuracy due to errors in the ion trap parameters will be discussed.

1Supported by IARPA and DARPA.
11:51AM B29.00002 Laser-induced charging of microfabricated ion traps. GUANG HAO LOW, MIT, SHANNON X. WANG, sxwang@mit.edu, NATHAN LACHENMYER, YUFEI GE, PETER HERSKIND, ISAAC L. CHUANG, MIT — Microfabricated ion traps are promising candidates for realizing large-scale quantum computers, but small trap sizes leads to increased sensitivity of the trapped ions to surface effects, including localized charging of the trap electrodes. Laser-induced charging on microfabricated ion traps is studied by monitoring the ion micromotion over a period of up to 20 minutes that a laser is incident on the trap. The ion is trapped 100 µm above the metal surface and the trap is operated at 6K. The lasers used are at 405, 460, and 674 nm, which are relevant atomic transitions in Sr+ ions, and the typical intensity at the trap is $10^8$ photons/sec. The ion's micromotion signal is related to the number of charges created on the trap. A wavelength and material dependence of the charging behavior is observed: lasers at lower wavelengths cause more charging, and aluminum exhibits more charging than copper or gold. We describe the charging dynamic based on a rate equation approach.

12:03PM B29.00003 Superconducting microfabricated ion traps. SHANNON X. WANG, YUFEI GE, JAROSLAW LABAZIEWICZ, MIT, ERIC DAULER, MIT Lincoln Laboratory, KÄRLE BERGREN, ISAAC L. CHUANG, MIT — We fabricate superconducting ion traps with niobium and niobium nitride and trap single Sr+ ions at cryogenic temperatures. The superconducting transition is verified and characterized by measuring the resistance and critical current using a 4-wire measurement on the trap structure, and observing change in the rf reflection. The lowest observed heating rate is 2.1(3) quanta/sec at 800 kHz at 6 K and shows no significant change across the superconducting transition, suggesting that anomalous heating is primarily caused by noise sources on the surface. This demonstration of superconducting ion traps opens up possibilities for integrating trapped ions and molecular ions with superconducting devices.

12:15PM B29.00004 Microfabricated surface trap for scalable ion-photon interfaces. PETER HERSKIND, SHANNON WANG, MOLU SHI, YUFEI GE, MARKO CETINA, ISAAC CHUANG, MIT — The combination of high-finesse optical mirrors and ion traps is attractive for quantum light-matter interfaces, which represents an enabling resource for large-scale quantum information processing. We report on a scalable approach to ion-photon interfaces based on a surface electrode ion trap microfabricated on top of a highly reflective mirror. An aperture in the central electrode, directly below the ion, allows the mirror to interact with the ion. The integration of such mirrors is scalable as several mirror apertures may be added with no additional overhead for fabrication. Furthermore, the design provides a path for reaching the strong coupling regime of Cavity QED, where an ion-cavity system can be realized by adding a small concave mirror above the trap mirror. The quality of the mirror is not significantly compromised in the course of fabrication and we have measured an increase in losses for light at 422 nm at the level of 100 ppm. The functionality of the mirror has also been verified by light collection from, and imaging of, the ion 103 ± 4 µm above the mirror. Despite its proximity, we find that the presence of the mirror does not perturb the trap. Trapping is stable with laser cooled ion lifetimes of several hours and we observe only minimal sensitivity to laser-induced charging. Furthermore, through operation of the trap in a cryostat at 15 K the heating rate of the ion is a the level of only 0.1 quanta/ms.

12:27PM B29.00005 Ion crystal transducer for strong coupling between single ions and single photons. LUCAS LAMATA, Max-Planck-Institut fuer Quantenoptik, DAVID LEIBRANDT, National Institute of Standards and Technology, ISAAC CHUANG, Center for Ultracold Atoms, Department of Physics, MIT, IGNACIO CIRAC, Max-Planck-Institut fuer Quantenoptik, MIKHAIL LUKIN, ITAMP, Harvard-Smithsonian Center for Astrophysics, and Department of Physics, Harvard University, VLADAN VULETIC, Center for Ultracold Atoms, Department of Physics, MIT, SUSANNE YELIN, ITAMP, Harvard-Smithsonian Center for Astrophysics, and Department of Physics, University of Connecticut — A quantum interface between single photons and single ions in an ion crystal is proposed. The coupling between single photon and single particle is collectively enhanced via a collective internal ion state and a phonon state. Applications for this scheme include single-photon generation, a memory for a quantum repeater, and a deterministic photon-photon or photon-ion entangler.

12:39PM B29.00006 Temperature driven structural phase transition for trapped ions. ZHE-XUAN GONG, GUIN-DAR LIN, LU-MING DUAN — A Wigner crystal formed with trapped ion can undergo structural phase transition, which is determined only by the mechanical conditions on a classical level. Instead of this classical result, we show that through consideration of quantum and thermal fluctuation, a structural phase transition can be solely driven by change of the system’s temperature. We determine a finite-temperature phase diagram for trapped ions using the renormalization group method and the path integral formalism, and propose an experimental scheme to observe the predicted temperature-driven structural phase transition, which is well within the reach of the current ion trap technology.

12:51PM B29.00007 Differential Stark shift measurement of clock states of Yb+ using an optical frequency comb. QUDSIA QURAISHI*, DAVID HAYES, DAVID HUCIL, DZMITRY MATSUKEVICH, SHANTANU DEBNATH, SUSANNE YELIN, ITAMP, Harvard-Smithsonian Center for Astrophysics, and Department of Physics, MIT — Quantum information processing with trapped ions has traditionally involved state preparation, manipulation (eg. quantum gates) and detection using CW lasers. Quantum gates implemented with ions typically involve optical Raman transitions between two atomic levels. An optical frequency comb, emitted by a pulsed laser, is an excellent tool for bridging atomic frequency differences. Previously, we demonstrated quantum gates and separately, ultrafast spin manipulation, using pulsed lasers [1,2]. Unlike the CW case, employing pulsed lasers has the marked advantage of both low spontaneous emission and low AC Stark shifts, because the high powers available from pulsed lasers allow for larger detunings from optical resonance. Here, we show both experimentally and theoretically the scaling of the differential Stark shift with detuning (6 THz to 20 THz) of the Raman fields, achieving values of $10^{-3}$ of the Rabi frequency. [1] D. Hayes, et al., Phys. Rev. Lett. 104, 140501 (2010) [2] W. C. Campbell, et al., Phys. Rev. Lett. 105, 090502 (2010). *Currently NRC postdoc with SEDD, ARL, Adelphi, MD. Support: DARPA OLE under ARO contract, IARPA under ARO contract, NSF PIF Program, NSF PFC at JQI and *IC Postdoc administered by the NGA.

1:03PM B29.00008 “Tack” ion trap for efficient photon collection. CHEN-KUAN CHOU, GANG SHU, NATHAN KURZ, THOMAS NOEL, JOHN WRIGHT, BORIS BLINOV, University of Washington — Trapped, laser-cooled atoms and ions produce intense fluorescence of the order $10^7$ – $10^8$ photons per second. Detection of this fluorescence enables the efficient measurement of the quantum state of qubit based on the trapped atoms. Thus, it is desirable to collect a large fraction of the (isotropically emitted) photons to make the detection faster and more reliable. Additionally, efficient fluorescence collection can improve the signal and fidelity of remote ion entanglement and quantum gates. Refractive and reflective optics, as well as optical cavities, and, recently, bare multimode optical fibers have all been used to collect the trapped ion fluorescence with up to 10% efficiency. Here we show a novel ion trap design that incorporates a high numerical aperture metallic spherical mirror as the integral part of the trap itself (the RF electrode) which enables up to 35% solid angle collection of trapped ion fluorescence. The movable central needle-shaped electrode of this “tack” trap allows precise placement of the ion at the focus of the spherical mirror. We also study the properties of the images formed by the spherical mirror and comment on possible methods for aberration correction. Owning to the simplicity of its design, this trap structure can be adapted for microfabrication and integration into more complex trap architectures.

*Supported by National Science Foundation and IARPA.
1:15PM B29.00009 Towards laser cooling of a LC-resonator via trapped ions, SOENKE MOELLER, NIKOS DANIILIDIS, UC Berkeley, BOYAN TABAKOV, University of New Mexico, AARON BRADLEY, HARTMUT HAEFFNER, UC Berkeley — We will discuss our experimental progress towards coupling strings of trapped ions to a LC-resonator. The goal of our experiments is to cool the resonant mode of a superconducting high-quality resonant circuit to ultra-low temperatures. By continuously laser cooling a crystal of ions coupled to the circuit, energy is removed from the resonator. For quality factors on the order of $10^5$, the time-scale of the environment-to-mode coupling, i.e. the time for the resonant mode of the LC-resonator to thermalize, can be as long as the order of 1 second. Thus, engineering an ion-resonator coupling of $\sim 10^5 \text{kHz}$ results in a reduction of the electronic temperature by four orders of magnitude as compared to the ambient temperature of the resonator. The expected temperatures below 1mK are extremely low approaching even the vibrational ground state of the oscillator mode, enabling novel quantum electronics applications in the solid state.

1:27PM B29.00010 Micro-Fabricated Surface Electrode Y-Junction Ion Traps, DAVID MOEHRING, MATTHEW BLAIN, ROBERT COOK, KEVIN FORTIER, RAYMOND HALTLI, CLARK HIGHSTRETE, DANIEL STICK, CHRIS TIGGES, Sandia National Laboratories — We will present results of the design, operation, and performance of two different Y-Junction surface ion micro-traps fabricated at Sandia. Recent progress in the testing of the micro-traps will be highlighted, including the successful shuttling of single and multiple ions, ion-chain splitting and recombination, and the validation of simulations with experiments. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

1:39PM B29.00011 Emergent effective spin models in ion-trap-based quantum simulators, CHENG-CHING JOSEPH WANG, Georgetown University, UMD AND JQI COLLABORATION — We show how effective spin models emerge from the interaction of laser light with the ions in a linear Paul trap. It has been shown that quantum Ising models can be studied by adiabatic state evolution in a transverse magnetic field which is ramped from large to small values. The standard proof involves and adiabatic elimination of the phonons in the Lamb-Dicke regime. We discuss here that such an elimination can be problematic due to the inherent entanglement between the spins and the phonons. If the magnetic field is ramped over a longer time, the phonon-phonon interactions become stronger with the phonon number leading to an adiabatic elimination of the quantum states of the phonons. Nevertheless, the main effects are to change the spin entanglement of the quantum states and the occupation number of phonons. We present numerical evidence to illustrate these points.

2:03PM B29.00013 Scalable micro-scale optics for planar ion traps, TRUE MERRILL, Georgia Institute of Technology, HARLEY HAYDEN, CHIEN-SHING PAI, Georgia Tech Research Institute, RACHEL NOEK, JUNGSANG KIM, Duke University, CURTIS VOLIN, Georgia Tech Research Institute — Efficient collection of fluorescence from atomic ions is required for fast high-fidelity measurement in ion trap quantum information processing. Conventional multi-element lens stacks can achieve photon collection efficiencies as high as 5%, however these systems typically have restricted field-of-view and are not generally large enough to image large arrays of ions. We report progress towards integrating a MEMS beam steering system with an Yb ion trap experiment. The MEMS system will direct a ultraviolet beam with waist of $\sim 5 \mu$m at the ions across a 20um range. For a designed ion separation of 4um this allows addressing up to 5 ions. The far-detuned laser will induce an AC Stark shift on a single ion in the chain, and the induced phase shift can be measured by Ramsey spectroscopy.

Monday, March 21, 2011 11:15AM - 2:15PM — Session B45 DAMOP GQI: Optomechanics at the Quantum Limit

11:15AM B45.00001 Sideband cooling micromechanical motion to the quantum ground state, JOHN TEUFEL, NIST Boulder, TOBIAS DONNER, JILA, University of Colorado at Boulder, NIST, DALE LI, NIST Boulder, KONRAD LEHNERT, JILA, University of Colorado at Boulder, RAYMOND SIMMONDS, NIST Boulder — Accessing the full quantum nature of a macroscopic mechanical oscillator first requires elimination of its classical, thermal motion. The flourishing field of cavity opto- and electromechanics provides a nearly ideal architecture for both preparation and detection of quantum states of mechanical motion. We realized such a system by coupling the motion of an aluminum membrane to the resonance frequency of a superconducting, microwave circuit. By exciting the microwave circuit below its resonance frequency, we damp and cool the membrane motion and detection of mechanical motion at the quantum level. We realize such a system by coupling the motion of an aluminum membrane to the resonance frequency of a superconducting, microwave circuit. By exciting the microwave circuit below its resonance frequency, we damp and cool the membrane motion and detection of mechanical motion at the quantum level. The membrane mode is ramped more slowly, then the phonons and spins become entangled. Nevertheless, the main effects are to change the spin entanglement of the quantum states and the occupation number of phonons. We present numerical evidence to illustrate these points.

11:27AM B45.00002 Cavity Cooling of A Mechanical Resonator in Amorphous Systems, LIN TIAN, University of California, Merced — The quantum backaction force generated by a cavity coupled with a mechanical resonator can be exploited to achieve sideband cooling of the mechanical mode. By applying a red-detuned driving, the quantum ground state of the mechanical mode can be reached in the resolved-sideband regime, which has recently been demonstrated in experiments. However, in many of these materials, surface defects or adsorbates can couple with the mechanical mode and impair the cavity cooling. These defects can be treated as quantum two-level system (TLS). The mechanical vibration changes the local strain tensor and generates coupling with the TLS via the deformation potential. In this work, we study the cavity cooling of the mechanical mode in the presence of a TLS. By applying the adiabatic elimination technique widely used in quantum optics, we derive the cooling master equation for the resonator-TLS system in the eigenbasis of this system. Our results show that the stationary phonon number depends nonmonotonically on the energy of the TLS. We also show that the cooling depends strongly on the decoherence rate of the TLS.

This work is supported by the DARPA/MTO ORCHID program through AFOSR, NSF-DMR-0956064, NSF-CCF-0916303, and NSF COINS program.
11:39AM B45.00003 Quantum Interactions of a Torsional Nanomechanical Resonator with a Single Spin. BRIAN D’URS0, SHONALI DHINGRA, University of Pittsburgh — While the motions of macroscopic objects may ultimately be governed by quantum mechanics, the distinctive features of quantum mechanics can be hidden by thermal excitations and coupling to the environment. We present a system consisting of a torsional nanomechanical resonator with quantum behavior introduced to the system by coupling the resonator with a single spin through a uniform external magnetic field. The spin originates from a nitrogen vacancy (NV) center in a diamond nanocrystal which is positioned on the resonator. The quadratic coupling is maximized by utilizing a low moment of inertia resonator and an avoided level crossing. This coupling results in quantum non-demolition (QND) measurements of the resonator and spin states, enabling a bridge between the quantum and classical worlds. Furthermore, it provides a high-fidelity readout of the NV center spin and a potential means of observing the discrete states of the resonator. We will describe the potential for these measurements and report on the experimental progress made towards observing this coupling in the torsional resonator-NV system.

1This work is funded by a DARPA Young Faculty Award.

11:51AM B45.00004 Characterization of an oscillator’s mechanical impedance using photon pressure. PAUL WILKINSON, GORDON SHAW, JON PRATT, NIST Physical Measurements Lab — In recent years, there has been much progress in coupling optical cavities to mechanical oscillators, especially in the pursuit of the quantum ground state of a macroscopic oscillator. Photon pressure due to reflection is of particular interest, and such experiments must be carefully designed to minimize competing contributions. Typically, such unwanted contributions are estimated or modeled. We describe an experimental approach to place an upper bound on unwanted contributions. A fiber coupled superluminous light emitting diode is modulated at an optical power of 6.5 mW rms, driving a highly reflective cantilever at a displacement of over 10 nm rms at resonance (Q=4900) in vacuum (10⁻⁵ Torr). The optomechanical transfer function is measured and fit to a simple harmonic oscillator model. The stiffness of the oscillator determined from the fit (k=16.6 ±/− 1.3 N/m) is found to be in good agreement with that obtained by calibration against our SI-traceable nanoindenter (k=17.4 ±/− 0.5 N/m). We characterize the modal stiffness, mass, and dissipation of the first two eigenmodes of our oscillator with SI traceability. The quantitative agreement in our experiment indicates that our oscillator is actuated by photon pressure, and that all other contributions to the force must sum to less than 11%.

12:03PM B45.00005 Multi-stability in an optomechanical system with two-component Bose-Einstein condensate. YING DONG, Department of Physics and Astronomy, and Rice Quantum Institute, Rice University, Houston, Texas 77251-1892, USA, JINWU YE, Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA, HAN PU, Department of Physics and Astronomy, and Rice Quantum Institute, Rice University, Houston, Texas 77251-1892, USA — We investigate a system consisting of a two-component Bose-Einstein condensate interacting dispersively with a Fabry-Perot optical cavity where the two components of the condensate are resonantly coupled to each other by another classical field. The key feature of this system is that the atomic motional degrees of freedom and the internal pseudo-spin degrees of freedom are coupled to the cavity field simultaneously, hence an effective spin-rotational coupling within the condensate is induced by the cavity. The interplay among the atomic center-of-mass motion, the atomic collective spin and the cavity field leads to a strong nonlinearity, resulting in multi-stable behavior in both matter wave and light wave at the few-photon level.

1This work is supported by the NSF, the Welch Foundation (Grant No. C-1669) and by a grant from the Army Research Office with funding from the DARPA OLE Program. J. Ye is supported by NSF DMR-0966413.

12:15PM B45.00006 Optomechanical down-conversion. SIMON GROEBLACHER, SEBASTIAN HOFER, WITTEF WIECZOREK, MICHAEL VANNER, University of Vienna, Austria, KLEMENS HAMMERER, Leibniz University Hannover, Germany, MARKUS ASPELMEYER, University of Vienna, Austria — One of the central interactions in quantum optics is two-mode squeezing, also known as down-conversion. It has been used in a multitude of pioneering experiments to demonstrate non-classical states of light and it is at the heart of generating quantum entanglement in optical fields. Here we demonstrate first experimental results towards the optomechanical analogue, in which an optical and a mechanical mode interact via a two-mode squeezing operation. In addition, we make use of the fact that large optomechanical coupling strengths provide access to an interaction regime beyond the rotating wave approximation. This allows for simultaneous cooling of the mechanical mode, which will eventually enable the preparation of pure initial mechanical states and is hence an important precondition to achieve the envisioned optomechanical entanglement.

12:27PM B45.00007 Photothermally induced dynamics in partially coated loaded microcantilevers. SHOMEEK MUKHOPADHYAY, UMAR MOHIDEEN, University of California, Riverside — Cooling of microcantilevers in a Fabry-Perot cavity either by radiation pressure or using the photothermal effect has attracted significant attention lately. We present ongoing experimental results on partially coated microcantilevers which are either loaded (gold sphere) or have a coating only at the tip. In particular, we will compare the results with that of recent work on fully coated cantilevers.

12:39PM B45.00008 Micro-optomechanical trampoline resonators. BRIAN PEPPER, DUSTIN KLECKNER, UC Santa Barbara, PETRO SONIN, EVAN JEFFREY, University of Leiden, DIRK BOUWMEESTER, UC Santa Barbara, University of Leiden — Recently, micro-optomechanical devices have been proposed for implementation of experiments ranging from non-demolition measurements of phonon number to creation of macroscopic quantum superpositions. All have strenuous requirements on optical finesse, mechanical quality factor, and temperature. We present a set of devices composed of dielectric mirrors on Si₃N₄ trampoline resonators. We describe the fabrication process and present data on finesse and quality factor.

1The authors gratefully acknowledge support from NSF PHY-0804177 and Marie Curie EXT-CT-2006-042580.

12:51PM B45.00009 Proposal for detecting measurement-induced entanglement between remote mechanical oscillators. KJETIL BORKE, ANDREAS NUNNENKAMP, STEVEN M. GIRVIN, Yale University — In optomechanical systems where an optical cavity mode interacts with a mechanical oscillator, the light leaking out of the cavity has sidebands at the mechanical frequency. The photon statistics of these sidebands contain information about the mechanical oscillator. We consider driving two similar optical cavities, containing one mechanical system each, in such a way that the mechanical oscillators are laser cooled close to the ground state. When the output fields of the two cavities are made indistinguishable by combining them on a beamsplitter, the detection of sideband photons can lead to measurement-induced entanglement between the two non-interacting mechanical oscillators. We show how this short-lived entanglement between remote mechanical oscillators can be verified through measurements of higher-order coherences of the optical output field.

12:27PM B45.00007 Photothermally induced dynamics in partially coated loaded microcantilevers. SHOMEEK MUKHOPADHYAY, UMAR MOHIDEEN, University of California, Riverside — Cooling of microcantilevers in a Fabry-Perot cavity either by radiation pressure or using the photothermal effect has attracted significant attention lately. We present ongoing experimental results on partially coated microcantilevers which are either loaded (gold sphere) or have a coating only at the tip. In particular, we will compare the results with that of recent work on fully coated cantilevers.

12:39PM B45.00008 Micro-optomechanical trampoline resonators. BRIAN PEPPER, DUSTIN KLECKNER, UC Santa Barbara, PETRO SONIN, EVAN JEFFREY, University of Leiden, DIRK BOUWMEESTER, UC Santa Barbara, University of Leiden — Recently, micro-optomechanical devices have been proposed for implementation of experiments ranging from non-demolition measurements of phonon number to creation of macroscopic quantum superpositions. All have strenuous requirements on optical finesse, mechanical quality factor, and temperature. We present a set of devices composed of dielectric mirrors on Si₃N₄ trampoline resonators. We describe the fabrication process and present data on finesse and quality factor.

1The authors gratefully acknowledge support from NSF PHY-0804177 and Marie Curie EXT-CT-2006-042580.
1:03PM B45.00010 Investigation of radiation pressure shot-noise in a microwave circuit opto-mechanical system. JENNIFER HARLOW, JILA, University of Colorado and NIST. JOHN TEUFEL, RAYMOND SIMMONDS, NIST. KONRAD LEHNERT, JILA, University of Colorado and NIST — We examine the possibility of measuring the radiation pressure shot-noise of microwave light. When the motion of a nanomechanical oscillator is coupled to the microwave energy stored in a resonant circuit, the oscillator experiences a radiation pressure force. That force must have a random component associated with the quantum nature of the microwave field, a mechanical manifestation of the microwave photon. The variance of this random component increases with increasing circuit excitation power. Until recently, reaching powers where radiation pressure shot-noise would dominate over other random forces was unfeasible due to relatively weak optomechanical coupling and technical power limitations of microwave circuits. However, the recent advent of a mechanical oscillator coupled strongly to a microwave circuit [1] will enable exploration of this regime. We discuss the most favorable circuit parameters and measurement strategy for studying radiation pressure shot-noise.


1:15PM B45.00011 Levitated Quantum Nano-Magneto-Mechanical Systems. MAURO CIRIO, JASON TWAMELEY, GAVIN K. BRENKEN, Centre for Engineered Quantum Systems, Macquarie University, Sydney Australia. GERARD J. MILBURN, Centre for Engineered Quantum Systems, University of Queensland, Brisbane, Australia — Quantum nanomechanical systems have attracted much attention as they provide new macroscopic platforms for the study of quantum mechanics but may also have applications in ultra-sensitive sensing, high precision measurements and in quantum computing. In this work we study the control and cooling of a quantum nanomechanical system which is magnetically levitated via the Meissner effect. Supercurrents in nano-sized superconducting loops give rise to a motional restoring force (trap), when placed in an highly inhomogenous magnetic field, and can yield complete trapping of all translational and rotational motions of the levitated nano-object with motional oscillation frequencies $\nu \sim 10^{-10} - 100$ MHz. As the supercurrents experience little damping this system will possess unprecedented motional quality factors, with $Q_{\text{motion}} \sim 10^9 - 10^{13}$, and motional superposition states may remain coherent for days. We describe how to execute sideband cooling through inductive coupling to a nearby flux qubit, cooling the mechanical motion close to the ground state.

1:27PM B45.00012 Measurement of Casimir force with transparent conducting oxides. ALEXANDR BANISHEV, CHIA-CHENG CHANG, UMAR MOHIDENE — The Casimir force plays an important role in micro- and nano electronic mechanical systems (MEMS and NEMS) fabrication, because it can easily exceed the electrostatic forces used for actuators the systems at small electrode separation distances. The reduction of the Casimir force is a complicated problem that needs to be scientifically investigated to open opportunities for the full exploitation of MEMS and NEMS technology. One of the ways to tune the Casimir force is to properly choose the materials of which the interacting surfaces are made. According to the Lifshitz theory, the interaction between two objects depends on their dielectric permittivity. In that case the transparent dielectrics attract less than reflective materials. This can be used to decrease the Casimir force when the design requires a smaller short range interaction. To achieve low Casimir forces and avoid uncontrolled electrostatic forces as present in dielectrics, transparent but conductive materials can be used. An ideal choice is conductive Indium Oxide such as very low doped Indium Tin Oxide (ITO). In this report we present the results of the Casimir force using transparent electrodes such as Indium Tin Oxide coated SiO$_2$ plate.

1:39PM B45.00013 Precision measurements of the Casimir force at Low temperatures$^1$. RODRIGO CASTILLO-GARZA, UMAR MOHIDENE, Physics and Astronomy Dept. UC Riverside — We will present research involving the precision measurement of the Casimir force at low temperatures. The role of material losses in this force and its incorporation into the Lifshitz theory remains unresolved. The Casimir force results from the modification of the zero point photon spectrum due to the presence of boundaries. The problem arises when the Casimir force is calculated at non zero temperature, where the role of thermal photons have to be included to that of the zero point photons. We plan to address this problem by measuring the Casimir force for different materials as a function of the temperature. Currently we are involved in making precision measurements of the Casimir force at 6K, 77K, and 300K with a micro cantilever based system that we have designed and built at UC-Riverside. The high sensitivity of this instrument will provide us with the resolution to advance our understanding of the interactions of both virtual photons and real photons when confined to a semi-infinite cavity made out of real metals. The constructed apparatus will also provide a deeper understanding of the role vacuum fluctuations play when the cavity constituents are made of a combination of dielectric, superconductor, and metal surfaces.

$^1$The support of UCMEUX, NSF and DOE is acknowledged.

1:51PM B45.00014 Strong interactions of single atoms and photons near a dielectric boundary$^2$. N.P. STERN, D.J. ALTON, T. AOIKE, H. LEE, E. OSTBY, K.J. VAHALA, H.J. KIMBLE, California Institute of Technology, Pasadena, CA 91125, USA — Quantum control of strong interactions between a single atom and photon has been achieved within the setting of cavity quantum electrodynamics (cQED). To move beyond proof-of-principle experiments involving one or two conventional optical cavities to more complex scalable systems that employ $N > 1$ microscopic resonators requires localization of atoms on distances scales $\sim 100$ nm from a resonator’s surface where an atom can be strongly coupled to a single intracavity photon while at the same time experiencing significant radiative interactions with the dielectric boundaries of the resonator. As an initial step into this new regime of cQED, we use real-time detection and high-bandwidth feedback to select and monitor motion of single cesium atoms through the evanescent field of a microtoroid$^3$. Direct temporal and spectral measurements coupled with simulations reveal both the significant role of Casimir-Polder attraction and the manifestly quantum nature of the atom-cavity dynamics, here in a regime of strong coupling, setting the stage for trapping atoms near micro- and nano-scopic optical resonators.

$^2$Work supported by NSF PHY-0652914 and the NSSEFF.


2:03PM B45.00015 Distinct single photons strongly interacting at a single atom in a waveguide. PAVEL KOLCHIN, RUPERT F. OULTON, XIANG ZHANG, University of California at Berkeley — We propose a waveguide QED system where two distinct single photons can interact strongly. The system consists of a single ladder-type three level atom coupled to a waveguide. We show that the nonlinear interaction can be tremendously enhanced by the strong coupling of the cascade atomic transitions to the waveguide mode simultaneously. As a result, a control photon tuned to the upper transition induces a $\pi$ phase shift and tunneling of a probe photon tuned to the otherwise reflective lower transition. Waveguide QED schemes could be an alternative to high quality cavities or dense atomic ensembles in quantum information processing.

Monday, March 21, 2011 2:30PM - 5:30PM — Session D27 GQI: Focus Session: Superconducting Qubits - Gates and Algorithms C155

2:30PM D27.00001 Scaling Superconducting Qubits with the ResQu Architecture. JOHN MARTINIS, University of California at Santa Barbara — This abstract not available.
small scale quantum algorithms that require executing high-fidelity single qubit gates, quantum Fourier transform, Toffoli, CNOT, and other entangling gates.

Eight microwave lines drive the individual qubits, memory resonators, and coupling resonator. We demonstrate control over the quantum microprocessor via state to turn off stray coupling. Each qubit is coupled to a

of “off-the-shelf” qubit and resonator components in the RezQu (“rez-(,)kyoo”) architecture. The RezQu architecture uses resonators with qubits in the zero

JIAN ZHAO, ANDREW CLELAND, JOHN MARTINIS — We present our newly designed and fabricated 4-qubit/5-resonator quantum microprocessor composed

GRANT, AARON O’CONNELL, PETER O’MALLEY, DANIEL SANK, AMIT VAINSENCHER, HAUHOA WANG, JAMES WENNER, TED WHITE, YI YIN, ERIK LUCERO, RAMI BARENDS, RADOSLAW BIALCZAK, YU CHEN, JULIAN KELLY, MIKE LENANDER, MATTEO MARIANTONI, ANTHONY ME-

near-resonant overshoot, and an arbitrary rear ramp.

can be realized perfectly using a tune/detune pulse with four adjustable parameters. The pulse consists of the front ramp (with proper shaping), a constant

the single-excitation transfer (which we call MOVE) between a phase qubit and its memory. We show that the idling error is negligible, being proportional to

architecture for superconducting phase qubits recently proposed by John Martinis, concentrating on the idling error, generation of single-excitation states, and

qubits

STRAUCH, Williams College — Superconducting resonators are a promising element for many applications in quantum information processing, such as memory, state transfer, and qubit-qubit coupling. Here I introduce a new application—multi-level quantum logic using superpositions of Fock states. A circuit-QED implementation of single and coupled-resonator gates will be presented and theoretically analyzed. This scheme, using experimentally demonstrated interactions, will be compared with traditional qubit operations.

Two-qubit gates and coupling with low-impedance flux qubits . JERRY CHOW, ANTONIO CORCOLES, CHAD RIGETTI, JIM ROZEN, GEORGE KEEFE, MARY-BETH ROTHWELL, JOHN ROHRS, MARK BORSTELMANN, DAVID DIVINCENZO, MARK KETCHEN, MATTHIAS STEFFEN, IBM Research — We experimentally demonstrate the coupling of two low-impedance flux qubits mediated via a transmission line resonator. We explore the viability of experimental coupling protocols which involve selective microwave driving on the qubits independently as well as fast frequency tuning through on-chip flux-bias. Pulse-shaping techniques for single-qubit and two-qubit gates are employed for reducing unwanted leakage and phase errors. A joint readout through the transmission line resonator is used for characterizing single-qubit and two-qubit states.

ABSTRACT WITHDRAWN –

Entangling ISWAP gate using frequency shifted anharmonic qubits . FELIX MOTZOI, JAY GAMBITTA, SETH MERKEL, AMIRA ELTONY, FRANK WILHELM, University of Waterloo — In this talk, we examine the coupling between frequency separated qubits, typical of superconducting implementations. We show how to correct for errors coming from finite turn-on time (corresponding to bringing the qubits into resonance) as well as leakage error (corresponding to exciting population out of the qubit manifold), namely by bringing the qubits in and out of resonance repeatedly to cancel out the unwanted implementations of the Hamiltonian. The gates presented are smooth and robust and represent a whole class of analytic and numeric solutions for the evolution of the composite system.

Analytic control methods for high fidelity unitary operations in a weakly nonlinear oscillator , SETH MERKEL, JAYDE GAMBITTA, FELIX MOTZOI, FRANK WILHELM, University of Waterloo — In qubits made from a weakly anharmonic oscillator the leading source of error at short gate times is leakage of population out of the two dimensional Hilbert space that forms the qubit. In this talk we explore a general technique based on an adiabatic expansion to find pulse shapes that correct this type of error. This leads to a family of solutions that can be further refined based on what is feasible for a particular application. This set of pulses contains and improves upon the previously developed DRAG solution [F. Motzoi, et. al., Phys. Rev. Lett. 103, 110501 (2009)] and can be further generalized to more complicated systems with additional leakage channels.

CNOT gate for superconducting qubits biased at their symmetry points , SAHEL ASHHAB, FRANCO NORI, Advanced Science Institute, RIKEN, Wako-shi, Japan, PIETER DE GROOT, KEES HARMANS, HANS MOOIJ, Kavli Institute of Nanoscience, Delft University of Technology, The Netherlands, JÜRGEN LISENFIELD, Karlsruher Institute of Technology, Germany, ADRIAN LUPASCU, Institute for Quantum Computing, University of Waterloo, Canada — A number of different techniques have been proposed and demonstrated in the past few years for implementing two-qubit gates in a system of two coupled superconducting qubits biased at their symmetry points. Most of these techniques implement the ISWAP gate. I will discuss a new technique that implements the CNOT gate. The two qubits are driven at the frequency of the target qubit, and the amplitudes applied to the two qubits are chosen such that the target qubit undergoes Rabi oscillations for only one of the two possible states of the control qubit. As a result a CNOT gate can be implemented.

Controlled-NOT logic gate based on conditional spectroscopy , MICHAEL GELLER, JOYDIP GHOSH, University of Georgia, Athens — A controlled-NOT logic gate based on conditional rotation of a target qubit by applying a microwave pulse of appropriate frequency has been demonstrated experimentally for a pair of superconducting flux qubits [Plantenberg et. al., Nature 447, 836 (2007)]. Here we discuss a related construction appropriate for coupled phase qubits or a phase qubit coupled to a resonator. Our results show that an intrinsic fidelity of more than 99% is achievable in about 45ns.

Quantum Logic Gates for the Rezqu Architecture , JOYDIP GHOSH, MICHAEL GELLER, University of Georgia, Athens — A promising quantum computing architecture has been recently proposed by the UCSB superconducting quantum computation group. In this architecture, n phase qubits are capacitively coupled to individual memory resonators as well as a common bus. In this talk we discuss the design of quantum logic gates for this architecture and discuss the intrinsic fidelities.

Idling error and SWAP/MOVE operation in RezQu architecture for phase qubits1 , ANDREI GALIUTHDINOV, ALEXANDER KOROTKOV, University of California - Riverside — We analyze several basic operations in the RezQu architecture for superconducting phase qubits recently proposed by John Martinis, concentrating on the idling error, generation of single-excitation states, and the single-excitation transfer (which we call MOVE) between a phase qubit and its memory. We show that the idling error is negligible, being proportional to the sixth power of the coupling strength. We also show that in the rotating wave approximation the MOVE operation, which is simpler than the usual SWAP, can be realized perfectly using a tune/detune pulse with four adjustable parameters. The pulse consists of the front ramp (with proper shaping), a constant near-resonant overshoot, and an arbitrary rear ramp.

Experimental demonstration of quantum algorithms on a 4-qubit/5-resonator quantum microprocessor utilizing superconducting qubits in the RezQu architecture , ERIK LUCERO, RAMI BARENDS, RADOSLAW BIALCZAK, YU CHEN, JULIAN KELLY, MIKE LENANDER, MATTEO MARIANTONI, ANTHONY MEGRANT, AARON O’CONNELL, PETER O’MALLEY, DANIEL SANK, AMIT VAINSENCHER, HAUHOA WANG, JAMES WENNER, TED WHITE, YI YIN, JIAN ZHAO, ANDREW CLELAND, JOHN MARTINIS — We present our newly designed and fabricated 4-qubit/5-resonator quantum microprocessor composed of “off-the-shelf” qubit and resonator components in the RezQu (“rez-(,)kyoo”) architecture. The RezQu architecture uses resonators with qubits in the zero state to turn off stray coupling. Each qubit is coupled to a 3/4 memory resonator and coupling between the qubits is mediated by a common λ/2 resonator bus. Eight microwave lines drive the individual qubits, memory resonators, and coupling resonator. We demonstrate control over the quantum microprocessor via small scale quantum algorithms that require executing high-fidelity single qubit gates, quantum Fourier transform, Toffoli, CNOT, and other entangling gates.

This work was supported by NSA and IARPA under ARO grant No. W911NF-10-1-0334.

ABSTRACT WITHDRAWN —

1 Experimental demonstration of quantum algorithms on a 4-qubit/5-resonator quantum microprocessor utilizing superconducting qubits in the RezQu architecture.
5:06PM D27.00012 Efficient Toffoli Gate in Circuit Quantum Electrodynamics†, MATTHEW REED, Department of Applied Physics and Physics, Yale University, New Haven, Connecticut 06520, USA, LEONARDO DICARLO, Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands, LUYAN SUN, LUIGI FRUNZIO, ROBERT SCHOELKOPF, Department of Applied Physics and Physics, Yale University, New Haven, Connecticut 06520, USA — The fidelity of quantum gates in circuit quantum electrodynamics is typically limited by qubit decoherence. As such, significant improvements can be realized by shortening gate duration [1, 2]. The three-qubit Toffoli gate, also called the controlled-controlled NOT, is an important operation in basic quantum error correction. We report a scheme for a Toffoli gate that exploits interactions with non-computational excited states of transmon qubits which can be executed faster than an equivalent construction using one- and two-qubit gates. The application of this gate to efficient measurement-free quantum error correction will be discussed.


†Research supported by NSF, NSA, and ARO.

5:18PM D27.00013 Progress towards a microwave-based high-fidelity Toffoli gate with superconducting qubits, CHAD RIGETTI, JERRY CHOW, ANTONIO CORCOLES, JIM ROZEN, GEORGE KEEFE, MARY BETH ROTHWELL, JACK ROHRS, MARK BORSTELMANN, DAVID DIVINCENZO, MARK KETCHEN, MATTHIAS STEFFEN, IBM Research — We describe recent progress at IBM towards a microwave-based implementation of the Toffoli gate using three capacitively shunted flux qubits dispersively coupled to a resonator. We discuss the device architecture and the microwave protocol, along with expected limits to gate fidelity and scaling.


2:30PM D29.00001 Scalable Quantum Computing Over the Rainbow, OLIVIER PFISTER, University of Virginia, NICOLAS C. MENICUCCI, Perimeter Institute, Waterloo, Canada, STEVEN T. FLAMMAF, IQI, Caltech — The physical implementation of nontrivial quantum computing is an experimental challenge due to decoherence and the need for scalability. Recently we proved a novel theoretical scheme for realizing a scalable quantum register of very large size, entangled in a cluster state, in the optical frequency comb (OFC) defined by the eigenmodes of a single optical parametric oscillator (OPO). The classical OFC is well known as implemented by the femtosecond, carrier-envelope-phase- and mode-locked lasers which have redefined frequency metrology in recent years. The quantum OFC is a set of harmonic oscillators, or Qmodes, whose amplitude and phase quadratures are continuous variables, the manipulation of which is a mature field for one or two Qmodes. We have shown that the nonlinear optical medium of a single OPO can be engineered, in a sophisticated but already demonstrated manner, so as to entangle in constant time the OPO’s OFC into a finitely squeezed, Gaussian cluster state suitable for universal quantum computing over continuous variables. Here we summarize our theoretical result and survey the ongoing experimental efforts in this direction.

2:42PM D29.00002 Implementing quantum gates through scattering between a static and a flying qubit, GUILLERMO CORDOURIER-MARURI, Cinvestav, Department of Applied Physics, Cordemex 97310, Merida, Mexico, FRANCESCO CICCARELLO, Universitat’a degli Studi di Palermo, CNISM, I-90128 Palermo, Italy, YASSER OMAR, Universidade Tecnica de Lisboa, P-1200-781 Lisbon, Portugal, MICHELANGELO Z, Universitat’a degli Studi di Palermo, Palermo, Italy, ROMEO DE COSS, Cinvestav, Department of Applied Physics, Cordemex 97310, Merida, Mexico, SOUGATO BOSE, UCL, Department of Physics and Astronomy, London WC1E 6BT, UK — We investigate whether a two-qubit quantum gate can be implemented in a scattering process involving a flying and a static qubit. We focus on a paradigmatic setup made out of a mobile particle and a quantum impurity, whose respective spin degrees of freedom couple to each other during a one-dimensional scattering process. A condition for the occurrence of quantum gates is derived in terms of spin-dependent transmission coefficients. This can be fulfilled through the insertion of an additional narrow potential barrier. Under resonance conditions this procedure enables a gate only for Heisenberg interactions and fails for an XY interaction. We show the existence of parameter regimes for which gates able to establish a maximum amount of entanglement can be implemented. The gates are found to be robust to variations of the optimal parameters.

2:54PM D29.00003 The 2D AKLT state is a universal quantum computational resource, TZU-CHIEH WEL, University of British Columbia, IAN AFFLECK, ROBERT RAUSSENDORF, University of British Columbia — We demonstrate that the two-dimensional AKLT state on a honeycomb lattice is a universal resource for measurement-based quantum computation. Our argument proceeds by reduction of the AKLT state to a 2D cluster state, which is already known to be universal, and consists of two steps. First, we devise a local POVM by which the AKLT state is mapped to a random 2D graph state. Second, we show by Monte Carlo simulations that the connectivity properties of these random graphs are governed by percolation, and that typical graphs are in the connected phase. The corresponding graph states can then be transformed to 2D cluster states.

3:06PM D29.00004 Robust benchmarking of quantum processes, EASWAR MAGESAN, JAY GAMBETTA, JOSEPH EMERSON, Institute for Quantum Computing, University of Waterloo — Fault-tolerant threshold theorems show that as long as the noise affecting a quantum system is below some threshold, reliable quantum computation can take place. As a result, methods for noise characterization are of great interest in quantum information theory. Unfortunately, methods for complete noise characterization scale exponentially in the number of qubits comprising the system. This non-scalability highlights the importance of developing mathematical methods for scalable partial characterization of the noise affecting a quantum system. We discuss a randomized benchmarking protocol that provides fitting models for the fidelity decay of the noisy gates used in quantum information processing. We show that when the average variation of the noise is not too large the first order model gives a robust estimate of both the average error affecting the gate set and the gate-dependence of the noise. We also show that the protocol is scalable in the number of qubits comprising the system. The protocol allows the noise to be both time and gate-dependent, and takes into account state preparation and measurement errors.

3:18PM D29.00005 Universal Quantum Computation within the Bose-Hubbard Model†, MICHAEL S. UNDERWOOD, DAVID L. FEDER, Institute for Quantum Information Science at the University of Calgary — We present a novel scheme for universal quantum computation based on spinless bosons hopping on a two-dimensional lattice with on-site interactions. Our setup is comprised of a \( 2 \times n \) lattice for an \( n \)-qubit system; the two rows correspond to the computational basis states, and a boson in each column encodes a qubit. The system is initialized with \( n \) sites of the \( |0\rangle \) row, and the lattice deep enough to prevent tunneling. Arbitrary single-qubit \( X \) rotations are implemented by tuning the tunneling strength between the \( |0\rangle \) and \( |1\rangle \) sites of the appropriate column, and \( Z \) rotations by applying a local potential to the \( |1\rangle \) site. Entanglement is generated by hopping between the \( |1\rangle \) sites of adjacent qubits; by tuning the on-site interaction strength of the bosons, a non-trivial controlled phase is acquired if these two qubits are in the state \( |11\rangle \). Because the quantum information is encoded entirely in the lattice positions of the bosons, the encoded qubits are inherently robust against decoherence. An implementation in terms of ultracold atoms in optical lattices is suggested.

†This work was supported by NSERC and iCORE.
3:30PM D29.00006 Optimal Trajectories for Quantum Adiabatic Factoring  | JORDAN KYRIAKIDIS, ROBERT ARCHIBALD, Dalhousie University, WILLIAM MACREADY, D-Wave Systems, Inc. — We show how a classical multiplication circuit can be expressed as an optimization problem. The circuit can then be effectively run backwards by fixing the output states in the optimization problem and determining the corresponding input states, thereby factoring the output state. This can in turn be expressed as a problem in adiabatic quantum computing. We show by solving a coupled set of Euler-Lagrange equations how (locally) optimal trajectories from initial to final Hamiltonians can be found whose efficacy vastly exceeds that of the usual linear scaling trajectory. Explicit examples will be given for factoring 6-bit integers.

3:42PM D29.00007 Deterministic Random-Length Computation with Weakly Entangled Cluster States | ADAM G. D’SOUZA, DAVID L. FEDER, Institute for Quantum Information Science, University of Calgary — Universal quantum computation can be accomplished via single-qubit measurements on a highly entangled resource state, together with classical feedback of the measurement results. The best-known example of such a resource state is the cluster state, on which judiciously chosen single-qubit measurements can be used to simulate an arbitrary quantum circuit with a number of measurements that is linear in the number of gates. We examine the power of the orbit of the cluster states under GL(2,C), also known as the SLOCC equivalence class of the cluster state, as a resource for deterministic universal computation. We find that, under certain circumstances, these states do indeed constitute resources for such computations, but of random length.

3:54PM D29.00008 Logical operator tradeoff for local quantum codes | JEONGWON HAAH, JOHN PRESKILL, I-QI, Caltech — We study the structure of logical operators in local D-dimensional quantum codes, considering both subsystem codes with geometrically local gauge generators and codes defined by geometrically local commuting projectors. We show that if the code distance is d, then any logical operator can be supported on a set of specified geometry containing d qubits, where d!/(D−1)! = O(n) and n is the code length. Our results place limitations on partially self-correcting quantum memories, in which at least some logical operators are protected by energy barriers that grow with system size. We also show that two-dimensional codes defined by local commuting projectors admit logical “string” operators and are not self correcting.

4:06PM D29.00009 ABSTRACT WITHDRAWN

4:18PM D29.00100 Simulating Concordant Computations | BRYAN EASTIN, Northrop Grumman — A quantum state is called concordant if it has zero quantum discord with respect to any part. By extension, a concordant computation is one such that the state of the computer, at each time step, is concordant. In this talk, I describe a classical algorithm that, given a product state as input, permits the efficient simulation of any concordant quantum computation having a conventional form and composed of gates acting on two or fewer qubits. This shows that such a quantum computation must generate observable discord if it is to efficiently solve a problem that requires super-polynomial time classically. While I employ the restriction to two-qubit gates sparingly, a crucial component of the simulation algorithm appears not to be extensible to gates acting on higher-dimensional systems.

4:30PM D29.00111 Photonic Phase Gate via an Exchange of Fermionic Spin Waves in a Spin Chain | ALEXEY GORSHKOV, California Institute of Technology, USA, JOHANNES OTTERBACH, Universität Kaiserslautern, Germany, EUGENE DEMLER, Harvard University, USA, MICHAEL FLEISCHHAUER, Universität Kaiserslautern, Germany, MIKHAIL LUKIN, Harvard University, USA — We propose a new protocol for implementing the two-qubit photonic phase gate. In our approach, the π phase is acquired by mapping two single photons into atomic excitations with fermionic character and exchanging their positions. The fermionic excitations are realized as spin waves in a spin chain, while photon storage techniques provide the interface between the photons and the spin waves. Possible imperfections and experimental systems suitable for implementing the gate are discussed. [Reference: Phys. Rev. Lett. 105, 066502 (2010)]

4:42PM D29.00112 Scalable Neutral Atom Quantum Computer with Interaction on Demand | MIKIO NAKAHARA, ELHAM HOSSEINI LAPASAR, KENICHI KASAMATSU, TETSUO OHMI, YASUSHI KONDO, Department of Physics, Kinki University — We propose a scalable neutral atom quantum computer with an on-demand interaction. Artificial lattice of near-field optical traps is employed to trap atomic qubits. Interactions between atoms can be turned off if the atoms are separated by a high enough potential barrier so that the size of the atomic wave function is much less than the interatomic distance. One-qubit gate operation is implemented by a gate control laser beam which is attached to an individual atom. Two-qubit gate operation between a particular pair of atoms is introduced by leaving these atoms in an optical lattice and making them collide so that a particular two-qubit state acquires a dynamical phase. Our proposal is feasible within existing technology developed in cold atom gas, MEMS, nanolithography, and various areas in optics.

1 Work partially supported by “Open Research Center” Project for Private Universities: matching fund subsidy from MEXT, Japan.

4:54PM D29.00113 General-Purpose Quantum Simulation with Prethreshold Superconducting Qubits | EMILY PRITCHETT, IQC Waterloo, COLIN BENJAMIN, University of Georgia, ANDREI GALIAUTDINOV, UC Riverside, MICHAEL GELLER, ANDREW SORNBORGER, PHILLIP STANCIL, University of Georgia, JOHN MARTINIS, UC Santa Barbara — We introduce a protocol for the fast simulation of n-dimensional quantum systems on n-qubit quantum computers with tunable couplings. A mapping is given between the control parameters of the quantum computer and the matrix elements of an n-dimensional real (but otherwise arbitrary) Hamiltonian that is simulated in the n-dimensional single-excitation subspace of the quantum simulator. A time-dependent energy/time-rescaling minimizes the simulation time on hardware having a fixed coherence time. We demonstrate how three tunnelly coupled superconducting phase qubits can simulate a three-channel molecular collision using this protocol. The method makes a class of general-purpose time-dependent quantum simulation practical with today’s sub-threshold-fidelity qubits.

5:06PM D29.00114 Currently Realizable Quantum Error Detection/Correction Algorithms for Superconducting Qubits | KYLE KEANE, Department of Physics and Astronomy, University of California, Riverside, ALEXANDER N. KOROTKOV, Department of Electrical Engineering, University of California, Riverside — We investigate the efficiency of simple quantum error correction/detection codes for zero-temperature energy relaxation. We show that standard repetitive codes are not effective for error correction of energy relaxation, but can be efficiently used for quantum error detection. Moreover, only two qubits are necessary for this purpose, in contrast to the minimum of three qubits needed for conventional error correction. We propose and analyze specific two-qubit algorithms for superconducting phase qubits, which are currently realizable and can demonstrate quantum error detection; each algorithm can also be used for quantum error correction of a specific known error. In particular, we analyze needed requirements on experimental parameters and calculate the expected fidelities for these experimental protocols.

1 This work was supported by NSA and IARPA under ARO grant No. W911NF-10-1-0334.
Quantum dots is complicated by valley degeneracy, the larger effective electron mass, and the difficulty of obtaining high quality samples [3]. Here we develop a...
Double quantum dot with tunable coupling in an enhancement-mode silicon metal-oxide semiconductor device with lateral geometry. L.A. TRACY, R.W. YOUNG, G.A. TEN YECK, K. ENG, K.D. CHILDS, J.R. WENDT, R.K. GRUBBS, J. STEVENS, M.P. LILLY, M.S. CARROLL, Sandia National Labs; University of Wisconsin-Madison, C. BORRAS PINILLA, Universidad Industrial de Santander-Colombia, H.L. STALFORD, Sandia National Laboratories; University of Oklahoma-Norman, M.A. ERIKSSON, University of Wisconsin-Madison — We present transport measurements of a tunable silicon metal-oxide-semiconductor double quantum dot device with lateral geometry. Experimentally extracted gate-to-dot capacitances show that the device is largely symmetric under the gate voltages applied. Intriguingly, these gate voltages themselves are not symmetric. Comparison with numerical simulations indicates that the applied gate voltages serve to offset an intrinsic asymmetry in the physical device. We also show a transition from a large single dot to two well isolated coupled dots, where the central gate of the device is used to controllably tune the interdot coupling. This work was supported by the LDRD program at Sandia National Laboratories, a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary Lockheed-Martin Company, for the U. S. DOE NNSA under Contract No. DE-AC04-94AL85000.

The effect of donors on lateral gated quantum-devices in Si/SiGe heterostructures1, XI LIN, JINGSHI HU, A. LAI, MIT, Z. ZHANG, UCLA, K. MACLEAN, MIT, Y.H. XIE, UCLA, M.A. KASTNER, MIT — Much activity has focused on the development of quantum dots in Si/SiGe because of its potentially very long decoherence times (T2). However, to fabricate well-controlled quantum dots in Si/SiGe heterostructures, one must overcome complications that do not arise in GaAs/AlGaAs heterostructures. We demonstrate that switching charge noise and donor-layer conduction can lead to instability and cross-coupling among the tunnel barriers, thus making it difficult to achieve highly stable and tunable quantum devices in a Si/SiGe heterostructure. In particular, we have used an integrated charge-sensing quantum point contact to investigate the charge motion that originates from the excess donars, and present a systematic capacitance measurement to show how the donor layer affects device function in devices with large (~100 μm²) gates as well as nanometer-size ones.

Pauli Spin Blockade and Lifetime-Enhanced Transport in a Si/SiGe double quantum dot1, TECK SENG KOH, C.B. SIMMONS, NAKUL SHAJI, MADHU THALAKULAM, L.J. KLEIN, HUA QIN, H. LUO, D.E. SAVAGE, M.G. LAGALLY, University of Wisconsin-Madison, A.J. RIMBERG, Dartmouth College, ROBERT JOYNT, ROBERT BLICK, MARK FRIESEN, S.N. COPPERSMITH, M.A. ERIKSSON, University of Wisconsin-Madison — We analyze electron transport data through a Si/SiGe double quantum dot in terms of spin blockade and lifetime-enhanced transport (LET), which is transport through excited states that is enabled by long spin relaxation times. We present a series of low-bias voltage measurements showing the suppression of a particular signal leading to an unambiguous signature of LET appearing when the bias voltage becomes greater than the singlet-triplet splitting for the (2,0) electron state. We present eight independent data sets, in both forward and reverse bias regimes, and show that excellent fits to all data sets were obtained using one consistent set of parameters. We also obtain quantitative estimates for the tunneling rates and currents in the reverse bias regime using the Lindblad formalism. [Ref: arXiv:1008.5398v1]

Fabrication of Few-Electron Carbon Nanotube Single and Double Quantum Dots, HUGH CHURCHILL, PATRICK HERRING, RUBY LAI, CHARLES MARCUS, Harvard University — We discuss fabrication methods for carbon nanotube quantum dot devices designed to satisfy the requirements of spin qubit applications. These requirements include low disorder for reliable access to the few-electron regime, detection of charge states, and rapid manipulation with multiple gates. Nanotube growth occurs at or near the end of the fabrication process, a scheme that has been shown previously to produce clean devices for transport studies. In our devices the nanotubes are grown over pre-patterned m gates as well as nanometer-size ones.

Undoped Heterostructure Materials for SiGe Quantum Devices, R.S. ROSS, M.G. BORESLLI, B. HUANG, K.S. HOLABIRD, T.M. HAZARD, A.A. KISELEV, P.W. DEELMAN, I. ALVARADO-RODRIGUZ, A.E. SCHMITZ, M. SOKOLICH, A.T. HUNTER, M.F. GYURE, HRL Laboratories LLC, 3011 Malibu Canyon Road, Malibu CA 90265 — Quantum well heterostructures, widely used for the fabrication of quantum dots and related devices, typically make use of modulation doping. Removal of the dopants, by use of globally “field-gated” and/or back-gated heterostructure designs, eliminates the dominant sources of scattering, charge noise and instability in devices intended for low-temperature operation. In this talk we present recent progress in designing and fabricating undoped quantum well heterostructures in Si/SiGe. A combination of simulation based modeling and experimental work has enabled us to successfully engineer materials for stable and quiet quantum dot operation. Specific topics to be presented include the important role of substrate and buffer layer background doping, concurrent MOS accumulation, leakage to front and back gates via barrier tunneling, and the expected range of electric fields that determine valley mixing in quantum dots. Sponsored by United States Department of Defense. Approved for Public Release, Distribution Unlimited.

Heterostructure surface effects on Si/SiGe 2DEGs, XIAN WU, C.B. SIMMONS, J.R. PRANCE, D.E. SAVAGE, M.G. LAGALLY, M.A. ERIKSSON, University of Wisconsin-Madison — We present the results of Hall and Shubnikov-de Haas measurements of the two-dimensional electron gas (2DEG) in Si/SiGe heterostructures at 2 K. We demonstrate that the condition of the surface has significant effects on the carrier density and mobility of electrons in the quantum well. Results from multiple samples show that the carrier density and mobility decrease with the amount of time that the samples are exposed to air. Surface treatment via a forming gas anneal or by dipping the samples in HF restores the carrier density and mobility of the degraded samples, and storing the samples in vacuum slows the rate of degradation. We believe that the reduction in carrier density of the 2DEG is a result of interface traps that form in the surface native oxide. Forming gas anneal passivates the interface traps, and HF strips the oxide. Illuminating the degraded samples at 2 K also improves the carrier density and mobility, possibly by activating electrons out of trap states. Deposition of Al2O3 on the surface using ALD caused a severe reduction in carrier density, which we believe is the result of a high trap density.
10:24AM H27.00013 Density and Depth of Natural Quantum Dots in Silicon MOS Structures, R.M. JOCK, S. SHANKAR1, A.M. TYRYSHKIN, J.-H. HE, S.A. LYON, Princeton University, K. ENG2, K. CHILDS, L. TRACY, M. LILLY, M. CARROLL, Sandia National Laboratories — Electron spins in MOS structures have shown promise as qubits for quantum information processing. Typically, characteristics such as mobility, mid-gap interface states and oxide fixed charge are considered figures of merit for the Si/SiO2 interface, however, other properties may be important. Recently, we have shown that, by biasing the gate above threshold and then reducing V_G to 0V, we freeze electrons into natural quantum dots, where 2D electrons are confined by interface disorder. The depth of these dots is determined by the temperature and can be extracted using a Schottky-Hall-Read model. Additionally, we measure the density of confined electron states. This measurement offers useful constraints to characterize the interface disorder in these MOS structures. Experiments have been performed on devices from different labs. Preliminary results from industrial quality devices fabricated at Sandia National Laboratories indicate a shallower dot depth, though a similar mobility. The shallower confinement suggests a higher quality for single-electron quantum devices.

1 Now at Yale
2 Now at HRL

10:36AM H27.00014 Real time electron counting through wavelet edge detection1, BJORN VAN BAEL, JONATHAN PRANCE, CHRISTIE SIMMONS, TECK SENG KOH, ZHAN SHI, DON SAWAGE, MAX LAPELL, ROBERT JOYNT, MARK FRIESEN, SUSAN COPPERSMITH, MARK ERIKSSON, University of Wisconsin-Madison — We have recently demonstrated single-shot measurements of individual electron spins in a Si/SiGe quantum dot. These experiments were analyzed using a wavelet-based technique that allows detection of charging events in real time. An alternative method, based on level thresholding, is not well suited for real time detection, due to drifting background currents in the charge sensor. In contrast, the wavelet technique relies on edge detection and is hence robust against drifting currents levels. In this talk, we describe our wavelet algorithm and its applications for charge sensing. We benchmark the performance of the algorithm under realistic signal noise conditions.

1 This work was supported by ARO, LPS, NSF and DARPA.

10:48AM H27.00015 Triangulating the source of tunneling resonances in a point contact with nanometer scale sensitivity, N.C. BISHOP, Sandia National Labs, C. BORAS PINILLA, Universidad Industrial de Santander-Colombia, H.L. STALFORD, University of Oklahoma, R.W. YOUNG, G.A. TEN EYCK, J.R. WENDT, K. ENG, M.P. LILLY, M.S. CARROLL, Sandia National Labs — We observe resonant tunneling in split gate point contacts defined in a double gate enhancement mode Si-MOS device structure. We determine the capacitances from the resonant feature to each of the conducting gates and the source/drain two dimensional electron gas regions. In our device, these capacitances provide information about the resonance location in three dimensions. Semi-classical electrostatic simulations of capacitance, already used to map quantum dot size and position [Stalford et al., IEEE Nanotechnology], identify a combination of location and confinement potential size that satisfy our experimental observations. The sensitivity of simulation to position and size allow us to triangulate possible locations of the resonant level with nanometer resolution. We discuss our results and how they may apply to resonant tunneling through a single dot. This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Tuesday, March 22, 2011 8:00AM - 11:00AM –
Session H29 GQI: Focus Session: Quantum Information for Quantum Foundations - Axiomatics and Toy Models C148

8:00AM H29.00001 Toward a conceptual foundation of Quantum Information Processing, GIULIO CHIRIBELLA, Perimeter Institute for Theoretical Physics — Quantum Information Science has brought to light an enormous amount of new protocols showing that the structure of quantum theory dramatically impacts the way in which information can be processed. It also made clear that the rules of information processing are dictated by physics and that different physical theories entail different models of information processing. Quantum Information poses an exciting challenge to foundational research: the challenge is to understand the multiplicity of quantum protocols to a small number of basic physical principles and to answer questions like “What are the physical roots of the power of quantum information?” A satisfactory answer to these questions calls for the solution of a long-standing problem: deriving quantum theory from physical principles, as opposed to the abstract mathematical principles of the Hilbert space formulation. In this talk I will show that quantum theory can be derived from few principles about information processing. The central principle of the derivation will be the purification principle, stating that ignorance about a part (subsystem) is always compatible with maximal knowledge of the whole (compound system). A large number of quantum information features, including e.g. teleportation and no-cloning, are direct consequences of the purification principle, which appears as a strong candidate for the conceptual foundation of Quantum Information Processing. Moreover, the derivation of quantum theory from purely informational principles provides a rigorous justification of the diffuse claim that quantum theory is ultimately a theory of information.

8:36AM H29.00002 Physics as Information, GIACOMO MAURO D’ARIANO, Università di Pavia — The experience from Quantum Information has lead theorists to look at Quantum Theory and the whole Physics from a different angle. A new information-theoretic paradigm is emerging, long time ago prophesied by John Archivald Wheeler with his popular coinage “It from bit.” Theoretical groups are now addressing the problem of deriving Quantum Theory from informational principles, and similar lines are investigated e.g. in new approaches to Quantum Gravity. In my talk I will review some recent advances on these lines. The general idea synthesizing the new paradigm is that there is only Quantum Theory (without quantization rules), and the whole Physics—including space-time and relativity—is emergent from the quantum-information processing. And, since Quantum Theory itself is made with purely informational principles, the whole Physics must be reformulated in information-theoretical terms. The review is divided into four parts: a) Very short review of the informational axiomatization of Quantum Theory; b) How space-time and relativistic covariance emerge from the quantum computation; c) What is the information-theoretical meaning of inertial mass and Planck constant, and how the Dirac field emerges; d) Observable consequences of the new theory. I will then conclude with some possible future research lines.

8:48AM H29.00003 A derivation of quantum theory from physical requirements, MARKUS MUELLER, Perimeter Institute for Theoretical Physics, Waterloo (ON), Canada, LUIS MASANES, ICF0-Institut de Ciencies Fotoniques, Barcelona, Spain — Quantum theory is usually formulated by postulating the mathematical structure and representation of states, transformations, and measurements. The general physical consequences that follow (like violation of Bell-type inequalities, the possibility of performing state tomography with local measurements, or factorization of integers in polynomial time) come as theorems which use the postulates as premises. In this work, this procedure is reversed: we impose five simple physical requirements, and this suffices to single out quantum theory and derive its mathematical formalism uniquely. This is more similar to the usual formulation of special relativity, where two simple physical requirements—the principles of relativity and light speed invariance—are used to derive the mathematical structure of Minkowski space-time and its transformations.
9:00AM H29.00004 Homogeneous Self-Dual Cones and the Structure of Quantum Theory. ALEXANDER WILCE, Susquehanna University — This talk reviews recent and ongoing work with Howard Barnum on the origins of the Jordan-algebraic structure of finite-dimensional quantum theory. I begin by surveying various principles — e.g., that every state of a bipartite system arises as the marginal of a “steering” bipartite state — that force the cone of (un-normalized) states of a finite-dimensional probabilistic system to be homogeneous and weakly self-dual, that is, isomorphic to its dual cone. Where this weak self-duality can be implemented by an inner product, the cone is strongly self-dual. In this case, classical results of Koecher and Vinberg show that it is isomorphic to the cone of squares in a formally real Jordan algebra. If this is the case, then (using a theorem of H. Hanche-Olsen) one can show that the only locally-tomographic theory containing at least one qubit is finite-dimensional Complex QM. I conclude with a brief discussion of how one might motivate strong self-duality.

9:12AM H29.00005 Quaternions and the Quantum. MATTHEW GRAYDON, University of Waterloo and Perimeter Institute for Theoretical Physics — Birkhoff and von Neumann pointed out that quantum probability calculi could be formulated over rings admitting involutory anti-automorphisms [1]. We discuss a model for generalized quantum measurements and quantum states based on quaternionic matrix algebras. We show that the usual Born rule for calculating probabilities for outcomes of quantum measurements can be carried over into quaternionic quantum theories within a Jordan-algebraic framework. We exploit a group isomorphism between Sp(1) and SU(2) to show that single-system unitary dynamics and generalized measurements in a quaternionic quantum theory can be simulated by corresponding processes in usual quantum mechanics. We resurvey the divide between quaternionic and complex quantum theories given this quadit-qudit correspondence. Reference: [1] G. Birkhoff and J. Von Neumann, “The logic of quantum mechanics”, Ann. Math., 37, 823-843 (1936).

This work was supported in part by the U. S. Office of Naval Research (Grant No. N00014-09-1-0247).

9:24AM H29.00006 Quantum theory cannot be extended. ROGER COLBECK, Perimeter Institute, Canada, RENATO RENNER, ETH Zurich, Switzerland — Predictions made by quantum theory are generally not deterministic: the theory tells us only how to calculate the probabilities with which measurement outcomes occur. This indeterminism is one of the key differences from classical mechanics and one can ask whether this is the best any theory can offer, or whether observable quantities could be better predicted by some higher theory. In a famous work, Bell considered extensions of quantum theory in the form of local hidden variables and showed that these cannot determine the outcomes of measurements on maximally entangled particles. Here, we go beyond the case of such classical extensions and ask whether any improved predictions can be achieved by any extension of quantum theory. We answer this question in the negative. More precisely, under the assumption that measurement settings can be chosen freely, there cannot exist any extension of quantum theory that provides us with any additional information about the outcomes of future measurements.

9:36AM H29.00007 Eliminating remnants of classical mechanics and the birth of the Schrödinger equation. WOLFGANG P. SCHLEICH, Institute of Quantum Physics, Ulm University, DANIEL GREENBERGER, City College, City University of New York, DONALD H. KOBE, Department of Physics, University of North Texas — We show that the Schrödinger equation emerges from the Hamilton-Jacobi equation for a specific choice of the amplitude $R$ of a wave $\psi \equiv \exp(iS/h)$ where $S$ is the classical action. This choice eliminates in the wave equation for $\psi$ all remnants of classical mechanics associated with $S$ but at the same time builds via the wave equation for $R$ a bridge to classical mechanics and to the de Broglie pilot wave theory.

9:48AM H29.00008 Modal Quantum Theory. MICHAEL WESTMORELAND, Denison University, BENJAMIN SCHUMACHER, Kenyon College — We present a class of toy model theories similar in structure to ordinary quantum mechanics. Some of these models are based on finite fields instead of complex amplitudes. The interpretation of such theories involves only the “modal” concepts of possibility and necessity rather than quantitative probability measures. Despite its very simple structure, our toy model nevertheless includes many of the key phenomena of actual quantum systems: interference, complementarity, entanglement, nonlocality, and the impossibility of cloning. These results are detailed in arXiv:1010.2929 and arXiv:1010.5452.

10:00AM H29.00009 Time-asymmetry and causal structure. BOB COECKE, RAYMOND LAL, Oxford University — We consider devices with two inputs and two outputs, Alice and Bob each having access to one input and one output. To such a device we associate time-reverses by exchanging the roles of the inputs and the outputs. We find that there are devices which admit a local hidden variable representation, but for which time-reverses enable perfect signaling between Alice and Bob. That is, a “perfect channel in one time direction” becomes a “non-channel in the other direction.” Also, for PR boxes time-reverses enable signaling between Alice and Bob, but never as a perfect channel. This result has several consequences. Firstly, it establishes that the arrow of time can be read from signaling structure: signaling means backward in time. It undermines the representation of causal structures as partial orders or similar “time-symmetric structures”, as is often assumed in search of a theory of quantum gravity. They also provide new insights into the structure of the polytope of generalized probabilistic correlations, hence on theories more general than quantum theory. Finally, it contributes to the growing area of research into quantum information processing in relativistic spacetimes. Ref: arXiv:1010.4572

10:12AM H29.00010 Topos formulation of History Quantum Theory. CECILIA FLORI, Perimeter Institute — In this talk I will describe a topos formulation of consistent histories obtained using the topos reformulation of standard quantum mechanics put forward by Doering and Isham. Such a reformulation leads to a novel type of logic with which to represent propositions. In the first part of the talk I will introduce the topos reformulation of quantum mechanics. I will then explain how such a reformulation can be extended so as to include temporally-ordered collection of propositions as opposed to single time propositions. Finally I will show how such an extension will lead to the possibility of assigning truth values to temporal propositions.

10:24AM H29.00011 Causal Tapestries. WILLIAM SULIS, McMaster University — Causal sets provide one of many approaches to the problem of quantum gravity. Causal tapesries generalize the concept of a causal set, extending the range of putative dynamics from sequential growth to include iterative and non deterministic methods, and the range of embedding manifolds to include those with curvature. Like causal sets, causal tapesries are manifestly Lorentz invariant in spite of possessing a form of “transient now”. It is shown that the order relations of the local causal structures must possess an order theoretic (Dushnik & Miller) dimension not exceeding the topological dimension of the embedding manifold and the finite free dimension is bounded by the number of elementary processes generating the causal relations.

10:36AM H29.00012 ABSTRACT WITHDRAWN —
The quantal algebra and abstract equations of motion

Classical and quantum mechanics common characteristics reveal core physics features that are hidden by the details related to the realizations of those theories in phase and Hilbert space respectively. The quantal algebra combines classical and quantum mechanics into an abstract structurally unified structure. It is based on two observations which can be made about classical and quantum mechanics. The first observation is that classical and quantum mechanics use two products: one symmetric and one anti-symmetric. The second observation is that classical and quantum mechanics obey the so-called composability principle: any two physical systems can interact with each other. The local structure of spacetime is contained in the quantal algebra without having been postulated. We will generalize classical and quantum mechanics equations of motion to abstract equations of motion in which the anti-symmetric product of the quantal algebra plays a central role. We will express the defining identities of the quantal algebra in terms of the abstract derivation. In this form it is easy to see that the first defining identity (the Jacobi identity) captures the essence of the Bianchi identity in general relativity which is one set of gravitational field equations for the curvature tensor.

Tuesday, March 22, 2011 11:15AM - 2:15PM
Session J27 GQI: Focus Session: Quantum Optics with Superconducting Circuits II C155

11:15AM J27.00001 Tomography and Correlation Function Measurements of Itinerant Microwave Photons

ANDREAS WALLRAFF, ETH Zurich — At optical frequencies the radiation produced by a source, such as a laser, a black body or a single-photon emitter, is frequently characterized by analysing the temporal correlations of emitted photons using single-photon counters. At microwave frequencies, however, there are no efficient single-photon counters yet. Instead, well-developed linear amplifiers allow for efficient measurement of the amplitude of an electromagnetic field. Here, we demonstrate first- and second-order correlation function measurements of a pulsed microwave-frequency single-photon source integrated on the same chip with a 50/50 beam splitter followed by linear amplifiers and quadrature amplitude detectors [1]. We clearly observe single-photon coherence in first-order and photon antibunching in second-order correlation function measurements of the propagating fields [2]. We also present first measurements in which we reconstruct the Wigner function of itinerant single photon Fock states and their superposition with the vacuum. To perform these measurements we have developed efficient methods to separate the detected single photon signal from the noise added by the amplifier by analyzing the moments of the measured amplitude distribution up to 4th order. The techniques and methods demonstrated in this work may find application in quantum optics and quantum information processing experiments at microwave frequencies.


Work done in collaboration with D. Bozyigit, C. Lang, C. Eichler, M. P. da Silva, A. Blais, and members of the Quantum Device Lab at ETH Zurich and supported in part by the EU through an ERC starting grant.

11:51AM J27.00002 An integrated circuit for generating distributable and unconditional entanglement at microwave frequencies

HSIANG-SHENG KU, University of Colorado at Boulder, FRANCOIS MALLET, JILA, WILLIAM F. KINDEL, University of Colorado at Boulder, KONRAD W. LEHNERT, JILA and NIST, KENT D. IRWIN, GENE C. HILTON, LEILA R. VALE, EMANUEL KNILL, SCOTT C. GLANCY, NIST, JILA TEAM, NIST TEAM — Entanglement, the unique feature of quantum mechanics, is the central resource of quantum information. In the strategy of continuous-variables quantum information processing, unconditional and distributable entanglement can be obtained by combining two squeezed states on a balanced beam splitter. Our group has recently demonstrated the generation of squeezed microwave fields using a Josephson Parametric Amplifier [1] and implemented on-chip balanced beam splitters [2]. This talk will present a device that combines all these components on a single chip. The design requirements for such an “on-chip entangler” of the electromagnetic field modes will be discussed.


12:03PM J27.00003 Measuring on-chip distributable and unconditional entanglement at microwave frequencies

FRANCOIS MALLET, HSIAH-SHENG KU, JILA, WILL KINDEL, SCOTT GLANCY, EMANUEL KNILL, KENT D. IRWIN, GENE C. HILTON, LEILA R. VALE, NIST — A squeezed mode of the light field exhibits reduced fluctuations, below the vacuum level, along one of its quadratures and conversely amplified fluctuations along the conjugate quadrature. In that sense, it is the electromagnetic analog of the particle modes used by Einstein-Podolsky-Rosen to derive their famous paradox. Indeed, by combining two such squeezed modes on a balanced beam splitter, entanglement can be generated, in an unconditional and distributable way. Such experiments have been performed for some years at optical frequencies. This talk will present an experimental attempt to generate and characterize entanglement with squeezed light at microwave frequencies, using superconducting electrical circuits. We will discuss the achieved degree of entanglement from the perspective of implementing quantum teleportation protocols at microwave frequencies.

12:15PM J27.00004 Observation of photon blockade in circuit QED using second-order correlation function measurements

C. LANG, D. BOZYIGIT, C. EICHLER, L. STEFFEN, J.M. FINK, A.A. ABDUMALIKOV JR., M. BAUR, S. FILIPP, A. WALLRAFF, ETH Zurich — Circuit quantum electrodynamics (QED) provides an attractive platform to effectively study photon-photon interactions mediated by their strong and resonant coupling to a superconducting qubit embedded into a transmission line resonator. Driving the coupled system with a coherent microwave frequency tone the anharmonicity of the Jaynes-Cummings ladder blocks the transmission of more than a single photon through the resonator at a time. Using on-chip microwave beam splitters, linear amplifiers, and quadrature amplitude detectors we observe fluorescence and Rayleigh scattering in Mollow-triplet-like spectra. We investigate the phenomenon of photon blockade in second-order correlation function measurements which show antibunching and signatures of Rabi oscillations induced by the continuous drive coupling the ground and first excited states of the Jaynes-Cummings ladder.

12:27PM J27.00005 Generation and reconstruction of two mode squeezed states in the microwave domain

CHRISTOPHER EICHLER, DENIZ BOZYIGIT, CHRISTIAN LANG, MATTHIAS BAUR, LARS STEFFEN, JOHANNES FINK, STEFAN FILIPP, ANDREAS WALLRAFF, ETH Zurich — Squeezing between two radiation field modes at optical frequencies has already been used to realize various quantum information processing tasks such as teleportation and quantum key distribution. Here we present measurements at microwave frequencies in which we generate and reconstruct a two mode squeezed state in a circuit QED setup. We prepare the desired state with a Josephson parametric amplifier and detect all four quadrature components simultaneously in a two channel heterodyne setup using amplitude detectors. Recording two dimensional phase space histograms for all possible pairs of quadratures allows for the reconstruction of the full covariance matrix and the four dimensional Wigner function of the squeezed state which shows strong correlations between the quadrature noise in the two modes. Combining parametric amplifier devices in networks with beamsplitters and superconducting qubits could allow for future linear optics quantum computation with propagating microwave photons.
12:39PM J27.00006 Using Superconducting Qubit Circuits to Engineer Exotic Lattice Systems  
DIMITRIS TSOMOKOS1, Royal Holloway University of London, SAHEL ASHHAB2, FRANCO NORI3, Institute of Physical and Chemical Research (RIKEN) Japan and Physics Department, University of Michigan — We propose an architecture based on superconducting qubits and resonators for the implementation of a variety of exotic lattice systems, such as spin and Hubbard models in higher or fractal dimensions and higher-genus topologies. Spin systems are realized naturally using qubits, while superconducting resonators can be used for the realization of Bose-Hubbard models. Fundamental requirements for these designs, such as controllable interactions between arbitrary qubit pairs, have recently been implemented in the laboratory, rendering our proposals feasible with current technology.

12:51PM J27.00007 Microwave Cavity Lattices for Simulating Condensed Matter Systems  
DEVIN UNDERWOOD, ARTHUR SAFIRA, SRIKANTH SRINIVASAAN, ANTHONY HOFFMAN, Princeton University, JENS KOCH, Northwestern University, ANDREW HOUCK, Princeton University — Recently, quantum phase transitions of light have been the focus of much theoretical attention. One possible experimental realization relies upon the circuit quantum electrodynamic architecture (cQED); however, in order for this to be successful, coupled arrays of superconducting resonators must first be realized with low disorder. Here we fabricate and characterize an array with low disorder consisting of 12 niobium resonators on a sapphire substrate in a honeycomb pattern with the photonic lattice sites forming a Kagome star. The structure is characterized by measuring transmission through different input-output port pairs and by varying the hopping rate between resonators. A family of resonant peaks corresponding to the various modes of the coupled array is identifiable and agrees well with both a tight-binding Hamiltonian and simulations from a commercial microwave software package. These experiments are an important step in realizing strongly correlated interactions in cQED.

1:03PM J27.00008 Synthetic gauge fields in Jaynes-Cummings-Hubbard ring lattices  
ANDREAS NUNNENKAMP, Yale University, JENS KOCH, Northwestern University, STEVEN GIRVIN, Yale University — Recently there has been much interest in many-body physics with photons in circuit-QED arrays. Here we explore the physics of a Jaynes-Cummings-Hubbard ring lattice subject to a synthetic gauge field, i.e. where the hopping terms carry a complex phase factor due to Josephson couplers between the resonators. There are critical phase twists at which the single-particle spectrum is degenerate so that even weak interactions can give rise to strong correlations. We compare to ultracold bosons in rotating ring lattices and study the out-of-equilibrium physics as relevant for current experiments.

1:15PM J27.00009 Multi-Resonator Circuit QED Part I: The Photon Shell  
MATTEO MARIANTONI, H. WANG, RADOSLAW C. BIALCZAK, M. LENANDER, ERIK LUCERO, M. NEELEY, A.D. O’CONNELL, D. SANK, M. WEIDES, J. WENNER, T. YAMAMOTO, Y. YIN, J. ZHAO, JOHN M. MARTINIS, A.N. CLELAND, Department of Physics, UC Santa Barbara — The generation and control of quantum states of light constitute fundamental tasks in cavity quantum electrodynamics (QED). The superconducting realization of cavity QED, circuit QED, enables on-chip microwave photonics, where superconducting qubits control and measure individual photon states. A long-standing issue in cavity QED is the coherent transfer of photons between two or more resonators. Here, we use circuit QED to implement a three-resonator architecture on a single chip, where the resonators are interconnected by two superconducting phase qubits. We use this circuit to shuffle one- and two-photon Fock states between the three resonators, and demonstrate qubit-mediated vacuum Rabi swaps between two resonators. This illustrates the potential for using multi-resonator circuits as photon quantum registries and for creating multipartite entanglement between delocalized bosonic modes.

1:27PM J27.00010 Multi-resonator circuit QED - Part 2: Generation and detection of NOON states  
FRANK WILHELM, fwilhelm@iqc.ca, SETH MERKEL, University of Waterloo — NOON states, states between two modes of light of the form \( |N, 0⟩ + e^{i\phi} |0, N⟩ \) allow for super-resolution interferometry. We show how NOON states can be efficiently produced in circuit quantum electrodynamics using superconducting phase qubits and resonators. We propose a protocol where only one interaction between the two modes is required, creating all the necessary entanglement at the start of the procedure. This protocol makes active use of the first three states of the phase qubits. Additionally, we show how to efficiently verify the success of such an experiment, even for large NOON states, using randomly sampled measurements and semidefinite programming technique. This is more efficient if the full tomography implemented to-date, allowing to reliably verify higher NOON-states. Based on New J. Phys. 12, 093036 (2010).

1:39PM J27.00011 Multi-Resonator Circuit QED Part III: Two-Resonator Entanglement  
HAOHUA WANG, MATTEO MARIANTONI, RADOSLAW C. BIALCZAK, M. LENANDER, ERIK LUCERO, M. NEELEY, A.D. O’CONNELL, D. SANK, M. WEIDES, J. WENNER, Y. YIN, J. ZHAO, JOHN M. MARTINIS, A.N. CLELAND, Department of Physics, UC Santa Barbara, T. YAMAMOTO, Green Innovation Research Laboratories, NEC, Japan — Quantum entanglement, a defining feature of quantum mechanics, has been demonstrated in a variety of nonlinear spin-like systems. Quantum entanglement in linear systems has proven significantly more challenging, as the intrinsic energy level degeneracy associated with linearly makes quantum control more difficult. Here we demonstrate the quantum entanglement of photon states in two independent linear microwave resonators utilizing two superconducting phase qubits coupled through a band-pass resonator. After entangling two qubits into a Bell state, we demonstrate the controlled sequential photon amplification and transferring procedures, creating N quanta excitations distributed in two resonators. We completely characterize the two-resonator states with bipartite Wigner tomography and prove the existence of entanglement.

1:51PM J27.00012 Observation of Collective Strong Coupling between a Superconducting Resonator and Bismuth Dopants in Silicon  
NATANIA ANTLER, R. VIJAY, UC Berkeley, CHRISTOPH WEIS, Lawrence Berkeley National Laboratory, ELI LEVENSON-FALK, UC Berkeley, THOMAS SCHENKEL, Lawrence Berkeley National Laboratory, IRFAN SIDDIQI, UC Berkeley — All electrical readout and control of spin systems with superconducting circuitry is an attractive route for implementing hybrid quantum information processing. Isolated spins, in general, have much longer coherence times than present day superconducting qubits, and thus could be utilized as memory elements. Species with a zero-field splitting (ZFS), such as bismuth doped silicon or NV centers in diamond, are particularly attractive as the absence of a strong magnetic bias field facilitates compatibility with low loss superconducting circuitry. We present results on the interaction of a tunable superconducting resonator and an ensemble of Bi spins implanted in an epitaxial layer of 28Si. As the resonator tunes through the ZFS, we observe an avoided crossing indicative of collective strong coupling. We discuss coherence properties as a function of spin density as well as progress on the detection of a small number of spins using a dispersive nanoSQUID magnetometer.
The observables for a pair of qubits yield a system of 60 rays and 75 bases derived from the vertices of a 600-cell (a regular polytope in four dimensions) contains over a hundred million parity proofs of the Kochen-Specker theorem. An overview of these proofs is given and they are compared with those in other 4-d systems, such as the 600-cell. The significance of the results is discussed.

We thank support from DARPA, AFOSR, NSA, LPS, ARO, NSF, MEXT, JSPS, FIRST, and JST

Tuesday, March 22, 2011 11:15AM - 2:15PM —
Session J29 GQI: Focus Session: Quantum Information for Quantum Foundations - Structures in Hilbert Space  C148

11:15AM J29.00001 Proofs of the Kochen-Specker theorem based on two qubits  MORDECAI WAEGELL, P.K. ARAVIND, Worcester Polytechnic Institute — The observables for a pair of qubits yield a system of 60 rays and 105 bases in a complex Hilbert space of four dimensions that contains over a hundred million parity proofs of the Kochen-Specker theorem. An overview of these proofs is given and they are compared with those in other 4-d systems, such as the 600-cell. The significance of the results is discussed.

11:27AM J29.00002 Proofs of the Kochen-Specker theorem based on the 600-cell  P.K. ARAVIND, MORDECAI WAEGELL, Worcester Polytechnic Institute, NORMAN MEGILL, Boston Information Group, MLADEN PAVICIC, ITAMP, Harvard University — It is shown that the system of 60 rays and 75 bases derived from the vertices of a 600-cell (a regular polytope in four dimensions) contains over a hundred million parity proofs of the Kochen-Specker theorem. An overview of the proofs is given, some examples of them are presented and the significance of the results is discussed.

11:39AM J29.00003 MUB Entanglement Patterns by Transformations in Phase Space  JAY LAWRENCE, Dartmouth College, Hanover, NH 03755 — All possible MUB entanglement patterns for systems of N prime-state particles are obtained from standard ones by unitary transformations in the Hilbert space, thus preserving the relationships between the generalized Pauli operators, the phase point operators, and the MUB projectors. The transformations are described geometrically in discrete phase space. Illustrative examples show the invariance of the total entanglement content and the connection of entanglement with Galois fields. Different field representations for the same dimension may produce inequivalent MUB sets. This work provides alternative constructions and generalizes previous work on qubit systems [1,2].


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11:51AM J29.00004 Entanglement in Mutually Unbiased Bases1  MARCIN WIESNIAK, University of Vienna, TOMASZ PATEREK, CQT Singapore, ANTON ZEILINGER, University of Vienna — Higher-dimensional Hilbert spaces are still not fully explored. One issue concerns mutually unbiased bases (MUBs). For primes [1] and their powers (e.g. [2]), full sets of MUBs are known. The question of existence of all MUBs in composite dimensions is still open. We show that for all full sets of MUBs of a given dimension a certain entanglement measure of the bases is constant. This fact could be an argument either for or against the existence of full sets of MUBs in some dimensions and tells us that almost all MUBs are maximally entangled for high-dimensional composite systems, whereas this is not the case for prime dimensions. We present a new construction of MUBs in prime dimensions. We use only one entangling operation, which simplifies possible experiments. The construction gives only product states and maximally entangled states.


Research supported by ERC Advanced Grant QIT4QAD and FWF SFB-grant F4007 of the Austrian Science Fund.

12:03PM J29.00005 Qutrits under a microscope1  GELO NOEL TABIA, University of Waterloo, Perimeter Institute for Theoretical Physics, Institute for Quantum Computing — Gleason’s theorem states that the set of quantum states is complete, in the sense that density operators, and the MUB projectors. The transformations are described geometrically in discrete phase space. Illustrative examples show the invariance of the total entanglement content and the connection of entanglement with Galois fields. Different field representations for the same dimension may produce inequivalent MUB sets. This work provides alternative constructions and generalizes previous work on qubit systems [1,2].


This work was supported in part by the U. S. Office of Naval Research (Grant No. N00014-09-1-0247).

12:15PM J29.00006 A Linear Dependency Structure ARISING FROM Weyl-Heisenberg Symmetry1  HOAN BUI DANG, Perimeter Institute and University of Waterloo, MARCUS APPLEBY, Perimeter Institute, INGEMAR BENGTSSON, KATE BLANCHFIELD, Stockholm University, ASA ERICSSON, CHRISTOPHER FUCHS, Perimeter Institute, MATTHEW GRAYDON, GELO TABIA, Perimeter Institute and University of Waterloo — The Weyl-Heisenberg (WH) group was used by Hermann Weyl to construct finite-dimensional quantum mechanics in the earliest days of the theory and, through its ubiquitous use in quantum information theory, is even more important today. While investigating properties of symmetric informationally-complete (SIC) measurements, we found a linear dependency structure in a class of Weyl-Heisenberg covariant sets when certain conditions on the dimensionality of the Hilbert space are met. This result reveals more structure in WH symmetry than previously noted and helps us gain a better understanding of quantum state space. For example in the Quantum Bayesian framework of Fuchs and collaborators, the number of zeros of a quantum state in a SIC representation is directly related to this linear dependency.

This work was supported in part by the U. S. Office of Naval Research (Grant No. N00014-09-1-0247).
12:27PM J29.00007 Regrouping phenomena of SIC POVMs covariant with respect to the Heisenberg–Weyl group, HUANGJUN ZHU, Centre for Quantum Technologies, National University of Singapore — Symmetric informationally complete positive operator valued measures (SIC POVMs) covariant with respect to the Heisenberg–Weyl (HW) group form disjoint orbits under the action of the normalizer of the HW group—the (extended) Clifford group. Additional SIC POVMs can be obtained by a suitable regrouping of the fiducial vectors on certain orbits, for example, in Hilbert spaces of dimension three, four, eight and twelve. To understand these SIC POVM regrouping phenomena, we need to go beyond the Clifford group and consider a larger group, in particular the normalizer of the Clifford group. We prove that, when the dimension of the Hilbert space is not a multiple of four, the HW group is a characteristic subgroup of the Clifford group, and the normalizer of the Clifford group is itself; when the dimension is a multiple of four, there are exactly two normal subgroups in the Clifford group that are isomorphic to the HW group, which are conjugated to each other in the normalizer of the Clifford group. Based on this observation, we provide a unified framework for understanding the regrouping phenomena mentioned above and those potential candidates.

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

12:39PM J29.00008 Quantum Computational Geodesic Derivative, HOWARD BRANDT, U.S. Army Research Laboratory — In recent developments in the differential geometry of quantum computation, the quantum evolution is described in terms of the special unitary group of n-qubit unitary operators with unit determinant. The group manifold is taken to be Riemannian. In the present work the geodesic derivative is clarified. This is applicable to investigations of conjugate points and the global characteristics of geodesic paths in the group manifold, and the determination of optimal quantum circuits for carrying out a quantum computation.

12:51PM J29.00009 Affine Maps of the Polarization Vector for Quantum Systems of Arbitrary Dimension, MARK BYRD, Southern Illinois University, C. ALLEN BISHOP, YONG-CHENG OU, Physics Department, Southern Illinois University — The operator-sum decomposition (OS) of a mapping from one density matrix to another has many applications in quantum information science. To this mapping there corresponds an affine map which provides a geometric description of the density matrix in terms of the polarization vector representation. This has been thoroughly explored for qubits since the components of the polarization vector are measurable quantities (corresponding to expectation values of Hermitian operators) and also because it enables the description of map domains geometrically. Here we extend the OS-affine map correspondence to qudits, briefly discuss general properties of the maps, the form for particular important cases, and provide several explicit results for qudit maps. We use the affine map and a singular-value-like decomposition, to find positivity constraints that provide a symmetry for small polarization vector magnitudes (states which are closer to the maximally mixed state) which is broken as the polarization vector increases in magnitude (a state becomes more pure). The dependence of this symmetry on the magnitude of the polarization vector implies the polar decomposition of the map can not be used as it can for the qubit case. However, it still leads us to a connection between positivity and purity for general d-state systems.

This material is based upon work supported by NSF-Grant No. 0545798 to MSB.

1:03PM J29.00010 Pseudo-unitary freedom in the operator-sum representation, YONG CHENG OU, Department of Chemistry, Texas Tech University, Lubbock, Texas 79409, MARK S. BYRD, Department of Physics and Department of Computer Science, Southern Illinois University, Carbondale, Illinois 62901 — A general dynamical map can be written in an operator-sum representation (OSR) by using a spectral decomposition, which needs not be completely positive. The OSR is not unique; there is freedom to choose a different set of operators in the OSR, yet still obtain the same map. We will show that, whereas the freedom for completely positive maps is unitary, the freedom for not completely positive maps is pseudo-unitary.

1:15PM J29.00011 Long-range spin-coupled interactions: a Gedankenexperiment on the nature of spin, IAN DURHAM, Saint Anselm College — What is intrinsic spin? It is at the heart of the quantum information revolution and yet it defies many of the efforts to better understand it, even to the point of pushing particle physics beyond the Standard Model. Long assumed to require the relativistic theory of Dirac, in 1967 Lévy-Lablond demonstrated that this was not the case: it is not necessarily a relativistic effect. In this article, we apply the Lévy-Lablond model to a simple Gedankenexperiment that suggests the existence of a quasi-fundamental long-range spin-coupled interaction. Calculations of the eigenfunctions of a test particle and the coupling constant of the force gives insight into the behavior of the potential that gives rise to this interaction. For large separation distances the potential looks like a simple potential well while for very small separation distances it exhibits a more complex nature. This, in turn, sheds additional light on the nature of intrinsic spin and suggests a path for future research.

1:27PM J29.00012 Quantum simulation of time-dependent Hamiltonians and the convenient illusion of Hilbert space, ROLANDO SOMMA, Los Alamos National Laboratory, DAVID POULIN, University of Sherbrooke, ANGIE QARRY, FRANK VERSTRAEETE, University of Vienna — We consider the manifold of all quantum many-body states that can be generated by arbitrary time-dependent local Hamiltonians in a time that scales polynomially in the system size, and show that it occupies an exponentially small volume in Hilbert space. This implies that the overwhelming majority of states in Hilbert space are not physical as they can only be produced after an exponentially long time. We establish this fact by making use of a time-dependent generalization of the Suzuki-Trotter expansion, followed by a counting argument. This also demonstrates that a computational model based on arbitrarily rapidly changing Hamiltonians is no more powerful than the standard quantum circuit model.

3 We acknowledge support from NSF, NSERC, and FQRNT.

1:39PM J29.00013 Mathematical Constraint on Realistic Theories, JAMES FRANSON, University of Maryland at Baltimore County — We consider realistic theories in which some physical property $f(r,t)$ is assumed to exist regardless of whether or not we measure it. It is shown that the value of $f(r,t)$ at position $r$ and time $t$ is completely determined by its value at all other locations $r'$ and earlier times $t' < t$ provided that $f(r,t)$ has continuous second partial derivatives [1]. Mathematical functions of this kind are sufficiently general to describe many situations of physical interest. These results are based on a mathematical identity that is similar in some respects to Cauchy’s integral theorem and it can be viewed as a generalization of Green’s third identity. The physical implications of weak determinism of this kind will be discussed and it will be contrasted with the properties of quantum systems.


1:51PM J29.00014 Construction of optimal witness for unknown two-qubit entanglement, S.-S.B. LEE, Department of Physics, Korea Advanced Institute of Science and Technology, H.S. PARK, H. KIM, S.-K. CHOI, Korea Research Institute of Standards and Science, H.-S. SIM, Department of Physics, Korea Advanced Institute of Science and Technology — Whether entanglement in a state can be detected, distillled, and quantified without full state reconstruction is a fundamental open problem. We demonstrate a new scheme encompassing these three tasks for arbitrary two-qubit entanglement, by constructing the optimal entanglement witness for polarization-entangled mixed-state photon pairs without full state reconstruction. With better efficiency than quantum state tomography, the entanglement is maximally distilled by newly developed tunable polarization filters, and quantified by the expectation value of the witness, which equals the concurrence. This scheme is extendible to multi-qubit Greenberger-Horne-Zeilinger entanglement. This work is to appear in Physical Review Letters.
Entanglement of spin waves among four quantum memories

3:42PM L4.00003 Quantum-logic clocks for fundamental physics and geodesy

Supported by ONR, NIST, AFOSR, and DARPA.

4:18PM L4.00002 Quantum Networks with Atoms and Photons

Supported by ONR, NIST, AFOSR, and DARPA.

3:06PM L4.00001 Entanglement of spin waves among four quantum memories

3:36PM L4.00004 Towards Quantum Information Processing with Superconducting Circuits

2:30PM L4.00005 Quantum Information and the Foundations of Quantum Mechanics: a story of mutual benefit

2:03PM J29.00015 ABSTRACT WITHDRAWN

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2:30PM L4.00005 Quantum Information and the Foundations of Quantum Mechanics: a story of mutual benefit
2:30PM L29.00001 Entanglement entropy between two coupled Tomonaga-Luttinger liquids. SHUNSUKE FURUKAWA, YONG BAEK KIM, Dept. of Physics, University of Toronto — We consider a system of two coupled Tomonaga-Luttinger liquids (TLL) on parallel chains and study the Rényi entanglement entropy $S_n$ between the two chains. The limit $n \to 1$ corresponds to the von Neumann entanglement entropy. The system is effectively described by two-component bosonic field theory with different TLL parameters in the symmetric/antisymmetric channels. We argue that in this system, $S_n$ is a linear function of the length of the chains followed by a universal subleading constant $\gamma_n$ determined by the ratio of the two TLL parameters. We derive the formula of $\gamma_n$ for integer $n \geq 2$ using (a) ground-state wave functionals of TLLs and (b) conformal boundary states, which lead to the same result. These predictions are checked in a numerical diagonalization analysis of a hard-core bosonic model on a ladder. Although our formulae of $\gamma_n$ are not analytic in the limit $n \to 1$, our numerical result suggests that the subleading constant in the von Neumann entropy is also universal.

2:42PM L29.00002 Entanglement from Charge Statistics: Exact Relations for Many-Body Systems. FRANCIS SONG, Yale University, CHRISTIAN FLINDT, Universite de Geneve, STEPHAN RACHEL, Yale University, ISRAEL KLIICH, University of Virginia, KARYN LE HUR, Yale University — We present exact formulas for the entanglement and Rényi entropies generated at a quantum point contact (QPC) in terms of the statistics of charge fluctuations, which we illustrate with examples from both equilibrium and non-equilibrium transport. The formulas are also applicable to groundstate entanglement in systems described by non-interacting fermions in any dimension, which in one dimension includes the critical spin-1/2 XX and Ising models where conformal field theory predictions for the entanglement and Rényi entropies are reproduced from the full counting statistics. These results may play a crucial role in the experimental detection of many-body entanglement in mesoscopic structures and cold atoms in optical lattices.

2:54PM L29.00003 Quantum Monte Carlo Calculation of the Topological Entanglement Entropy in a Kagome Spin Liquid. ROGER MELKO, Waterloo, SERGEI ISAKOV, ETH Zurich, ANN KALLIN, Waterloo, MATTHEW HASTINGS, Microsoft Research and Duke — We develop a quantum Monte Carlo procedure to compute the Rényi entanglement entropy of interacting quantum many-body systems at nonzero temperature. We illustrate the method by calculating the topological entanglement entropy in a featureless Mott Insulating phase of a Bose-Hubbard model on the kagome lattice. The topological entanglement entropy displays a characteristic finite-temperature crossover behavior discussed previously in the context of the toric code. At zero-temperature it becomes the log of the quantum dimension of the topological order, confirming the existence of a Z2 spin liquid phase in the groundstate of this model.

3:06PM L29.00004 Entanglement entropy and boundary operators in quantum impurity systems. ERIK ERIKSSON, HENRIK JOHANNESSON, University of Gothenburg — Entanglement in quantum impurity systems can be studied analytically using boundary conformal field theory (BCFT). In particular, the effect from an impurity on the entanglement entropy of a surrounding region is governed by the boundary operator content of the model. We present general results for the corrections to scaling of the Rényi entanglement entropies when perturbing the BCFT with boundary operators [arXiv:1011.0446]. These results are then used to predict the asymptotic large-block behavior of the impurity contribution to the entanglement entropy in various Kondo systems.

3:18PM L29.00005 Global quantum correlations in the spin-1 bilinear-biquadratic chain. ROMAN ORUS, University of Queensland and Max Planck Institute of Quantum Optics, TZU-CHIEH WEI, University of British Columbia — We investigate global properties of the ground state of the spin-1 bilinear-biquadratic quantum spin chain in the thermodynamic limit, focusing on the geometric entanglement and fidelity diagram. The two quantities are computed via iTEBD and they appear to be capable of detecting the various well-known phase transitions in the system, including a Kosterlitz-Thouless one. The two quantities also behave distinctively at other points in the phase diagram. In particular, this is the case for the fidelity diagram at $\theta \approx 1.34\pi$ (around a possible transition to a spin nematic phase), and also for the geometric entanglement at the integrable gapped point $\theta = 3\pi/2$, where we conjecture an infinite entanglement length in the system.

3:30PM L29.00006 Definitions of entanglement entropy of spin systems in the valence-bond basis. YU-CHENG LIN, Applied Physics, National Chengchi University, ANDERS SANDVIK, Physics, Boston University — The valence-bond structure of spin-1/2 Heisenberg antiferromagnets is closely related to quantum entanglement. We investigate definitions of entanglement entropy based on individual valence bonds connecting two subsystems, as well as shared loops of the transposition graph (overlap) of two valence-bond states [1]. We reformulate a previously used definition based on valance bonds in the wave function as a true ground state expectation value, and find that its scaling for the Heisenberg chain agrees with an exact result. The loop-based entanglement entropy of the two-dimensional Heisenberg model is shown to satisfy the area law (with an additive logarithmic correction), unlike single-bond definitions (which exhibit multiplicative logarithmic corrections).


3:42PM L29.00007 ABSTRACT WITHDRAWN —

3:54PM L29.00008 General relation between energy spectrum and entanglement spectrum. XIAOLIANG QI, Stanford University, HOSHO KATSURA, Gakkushin University, Tokyo, Japan, ANDREAS LUDWIG, University of California, Santa Barbara — We demonstrate that the bipartite density matrix, arising from a spatial bipartitioning of a gapped topological state which possesses gapless edge modes in the form of a conformal field theory (CFT) (when terminated against a topologically trivial state/vacuum), such as e.g. a general quantum Hall state, is the density matrix of the chiral edge state CFT at a finite temperature. We obtain this result by applying a physical instantaneous cut of the gapped system, and by viewing the cutting process as a sudden “quantum quench” into a CFT, using the tools of boundary conformal field theory. In particular, we obtain a general relation between the Hamiltonian spectrum of gapless theories and the entanglement spectrum of the gapped theory obtained from coupling two gapless theories.

4:06PM L29.00009 The entanglement spectrum of perturbed Chern-Simons theories. THOMAS JACKSON, ISRAEL KLIICH, University of Virginia — Topological field theories — theories insensitive to the metric of the space they live on — have been shown to be applicable to a remarkable variety of condensed matter systems. A natural and important question is how perturbations relevant for real systems (interactions, etc.) deform these topological structures. In this work, we consider perturbations of Chern-Simons theory by a small Yang-Mills term, which breaks topological symmetry by introducing local bulk degrees of freedom in the form of massive gluons. We consider the behavior of the entanglement spectrum (the eigenvalues of the reduced density matrix) of this theory under this perturbation. We argue that the act of taking the partial trace may be viewed as adding a chemical potential gradient for the gluons near the boundary of the space, with a length scale determined by the gluon mass — or, colloquially, a “hot edge.”

1Supported by NSF grant DMR 0956053.
4:18PM L29.00010 Entanglement, Dissipation and the Casimir effect, ISRAEL KLICH, University of Virginia — The role of dissipation in the Casimir force between metals or dielectric has been discussed in many works and is an important part of the Casimir theory, where puzzles about the finite temperature corrections to the effect are still being worked out. Here, we study the contribution of dissipation in creating distance dependent entanglement between materials, and on the meaning of the corresponding entropy.

4:30PM L29.00011 Entanglement Entropy Scaling of 2D Critical Wave Functions, MICHAEL ZALETEL, JENS BARDARSON, JOEL MOORE, UC Berkeley — While CFT calculations have revealed a variety of universal predictions for the entanglement spectrum of critical 1+1D field theories, much less is known about higher-dimensional systems. CFT methods can be extended to a class of 2+1D theories characterized by a $\gamma = 2$ critical point, the so-called Rokhsar-Kivelson wave functions. The entanglement entropy of RK-type critical wave functions contains a universal logarithmic contribution $\gamma \log(L)$ for some geometries arising from a trace anomaly in the corresponding CFT. We first re-examine the free boson, where the existence of order-unity contributions that depend on the boson compactification radius has been discussed in several recent papers (Hsu et al., Stéphane et al., Oshikawa). We find analytically and numerically that the logarithmic contribution exists with the coefficient predicted by Fradkin and Moore and is independent of the compactification. However, it appears that their conjecture that general CFTs show the same dependence of $\gamma$ on central charge as the free boson is incorrect. We present arguments and numerical evidence for this conclusion in $c = 1/2$ and $c = 1$ lattice models.

4:42PM L29.00012 Entanglement spectra of Hofstadter and related models, ZHOUSHEN HUANG, DANIEL AROVAS, University of California, San Diego — We compute the bipartite entanglement spectra for the Hofstadter model on various two-dimensional lattices. The behavior of the entanglement eigenstates in the vicinity of a partition boundary is also investigated. We also study the formation of entanglement edge states as one tunes through a topological phase transition in Haldane’s honeycomb lattice model and other related systems.

4:54PM L29.00013 Entanglement Spectrum In Condensed Matter, B. ANDREI BERNEVIG, Princeton University — I will review the information that entanglement spectra give for a wide range of systems in condensed matter physics, such as fractional quantum hall effect, quantum spin chains, topological insulators, and disordered systems. (the results are based on a series of works performed in collaboration with N. Regnault, R. Thomale, A. Chandran, A Sterdyniak, M. Hermanns, Z. Papic, T.L. Hughes, E. Prodan, D.P. Arovas)

5:06PM L29.00014 Simultaneous generation of multiple quadrupartite continuous-variable cluster states in the optical frequency comb of a single optical parametric oscillator, MATTHEW PYSHER, University of Virginia, YOSHICHIKA MIWA, University of Tokyo, REIHANEH SHAHRKHSHAHI, RUSSELL BLOOMER, OLIVIER PFISTER, University of Virginia — We report the experimental generation of multiple, four-mode, continuous-variable cluster states from a single optical parametric oscillator (OPO) operating below threshold. We use a PPKTP crystal phasematching two concurrent nonlinear interactions to entangle the optical frequency comb formed by the OPO cavity. Four independent entanglement witnesses (a.k.a. infinitesimal operators of stabilizers, or “nullifiers”) display squeezing in each cluster state, and we utilize the large phase-matching bandwidth of the nonlinear interactions to display the simultaneous creation of several such cluster states using only a single pump frequency. A slightly more sophisticated version of this experimental method, using a crystal with three nonlinear interactions and 15 pump frequencies, has theoretically shown the ability to produce arbitrarily large square-grid cluster states suitable for universal one-way quantum computing.

5:18PM L29.00015 Multiparticle entanglement in the optical frequency comb of a depleted-pump optical parametric oscillator, REIHANEH SHAHRKHSHAHI, OLIVIER PFISTER — The optical frequency comb (OFC) of a single optical parametric oscillator (OPO) has been shown to be a very interesting candidate for scaling the size of quantum entangled states. In sophisticated OFCs below threshold, square-grid cluster states of very large size can in principle be generated. Here, we study a very simple OPO well above threshold, in the linearized fluctuation approximation, and investigate the effect of pump depletion on multiple, simultaneously resonant, signal-mode pairs. We find that the depleted quantum pump mediates quantum correlations between the signal fields. These correlations lead in turn to inseparability of these fields, as evidenced by the well-known van Loo-Furusawa entanglement criteria. Due to its simplicity and its scalability, this fully inseparable multiparticle entangled state could be used as a resource in quantum information protocols.

Wednesday, March 23, 2011 8:00AM - 10:36AM
Session P27 GQI: Focus Session: Semiconductor Qubits - Spin Readout, Backaction, and Valley Physics in Silicon

8:00AM P27.00001 Development of a Si/SiO₂-based double quantum dot charge qubit with dispersive microwave readout, M.G. HOUSE, University of California, Los Angeles, E. HENRY, A. SCHMIDT, University of California, Berkeley, O. NAAMAN, University of California, Berkeley, I. SIDDIQI, University of California, Berkeley, H. PAN, M. XIAO, H.W. JIANG, University of California, Los Angeles — Coupling of a high-Q microwave resonator to superconducting qubits has been successfully used to prepare, manipulate, and read out the state of a single qubit, and to mediate interactions between qubits. Our work is geared toward implementing this architecture in a semiconductor qubit. We present the design and development of a lateral quantum dot in which a superconducting microwave resonator is capacitively coupled to a double dot charge qubit. The device is a silicon MOSFET structure with a global gate which is used to accumulate electrons at a Si/SiO₂ interface. A set of smaller gates are used to deplete these electrons to define a double quantum dot and adjacent conduction channels. Two of these depletion gates connect directly to the conductors of a 6 GHz co-planar stripline resonator. We present measurements of transport and conventional charge sensing used to characterize the double quantum dot, and demonstrate that it is possible to reach the few-electron regime in this system.

8:12AM P27.00002 Dispersive microwave readout of a double quantum dot charge qubit in silicon, EDWARD HENRY, ANDREW SCHMIDT, QNL, UC Berkeley, MATTHEW HOUSE, UCLA, OFER NAAMAN, H. PAN, MING XIAO, HONG-WEN JIANG, UCLA, IRFAN SIDDIQI, QNL, UC Berkeley, QNL, UC BERKELEY TEAM, JIANG GROUP, UCLA TEAM — Microwave resonators coupled to quantum systems have been used for fast dispersive measurement in many different architectures in solid state and atomic physics. The electronic states of a semiconductor quantum dot represent a promising candidate for quantum information processing. Our work is geared toward developing a fast, non-demolition readout of semiconductor qubit by coupling to a superconducting resonant circuit. We report on microwave measurements of a lateral quantum dot, realized using a silicon MOSFET structure, where the charge degree of freedom is capacitively coupled to a shorted quarter wave 6 GHz resonator. We characterize the sensitivity of this charge detection scheme and its implications for qubit readout fidelity.
8:24AM P27.00003 Radio Frequency Single Electron Transistors on Si/SiGe1, MINGYUN YUAN, ZHEN YANG, A.J. RIMBERG, Department of Physics and Astronomy, Dartmouth College, M.A. ERIKSSON, Department of Physics, University of Wisconsin, D.E. SAVAGE, Material Science Center, University of Wisconsin — Superconducting single electron transistors (S-SETs) are ideal for charge state readout due to their high sensitivity and low back-action. Upon successful formation of quantum dots(QDs) on Si/SiGe, aluminum S-SETs are added in the vicinity of the QDs. Coupling of the S-SET to the QD is confirmed by using the S-SET to perform sensing of the QD charge state at 0.3 K. We have formed a matching network for an SET with an off-chip inductor. The reflection coefficient of the radio frequency(RF) signal is shown to be modulated by the SET resistance. Efforts to develop an on-chip matching network and perform charge sensing with the RF-SETs are in progress. Recent experimental results will be discussed.

3This research was supported by the NSA, LPS and ARO.

8:36AM P27.00004 Two-detector two-qubit correlated continuous measurements and their implications for quantum computing , RUSKO RUSKOV, Laboratory for Physical Sciences,College Park, MD 20740, CHARLES TAHAN, Laboratory for Physical Sciences, College Park, MD 20740 — We calculate the full counting statistics for a system of two interacting qubits which are simultaneously measured by weakly coupled linear detectors. Two approaches are considered based on rate equations for the full system-detectors density matrix and on quantum filtering equations. Implications for the assessment of quantumness in physical devices based on charge qubits are considered. In addition we consider applications of such systems to practical quantum computing in silicon and/or GaAs quantum dots.

8:48AM P27.00005 Backaction due to Resonant Phonon Absorption in Quantum Dots Measured by a Quantum Point Contact , CAROLYN YOUNG, AASHISH CLERK, McGill University — Recent experiments have observed unexplained periodic resonances in the charging diagrams of both double [1] and triple [2] quantum dots (DQDs and TQDs). These resonances correspond to the generation of inelastic transitions, driven by energy transfer from a biased quantum point contact (QPC) charge detector used for measurement. In this talk, we present theoretical results describing how quantum backaction due to hot phonons, generated by the out-of-equilibrium QPC, can lead to excited state occupation under certain “blocking” conditions that result in slow ground state filling. We propose that recent experiments can be understood in terms of resonant phonon absorption in DQDs and TQDs, a process complementary to the backaction of the QPC readout scheme widely used for QD-based quantum computation.


9:00AM P27.00006 Measurement fidelity in the presence of coherent dynamics or dissipation , JIAN-QIANG YOU, Fudan University & RIKEN, S. ASHHAB, FRANÇO NORI, RIKEN & University of Michigan — We analyze the problem of a charge qubit probed by a quantum point contact when the measurement is concurrent with Hamiltonian-induced coherent dynamics or dissipation. This additional dynamics changes the state of the qubit before the measurement is completed. As a result, the measurement fidelity is reduced. We calculate the reduction in measurement fidelity in these cases. References: S. Ashhab, J. Q. You, and F. Nori, New J. Phys. 11, 083017 (2009); Phys. Scr. T137, 014005 (2009).

9:12AM P27.00007 Probing coherent tunneling in semiconductor quantum dots using electromechanical backaction , JAMIE GARDNER, AASHISH CLERK, Department of Physics, McGill University — Self-assembled quantum dots have been studied intensely because of their possible applications to quantum information processing. While such dots are difficult to characterize using direct electrical transport measurements, it has recently been shown both theoretically [1] and experimentally [2] that a capacitively coupled AFM cantilever can serve as a sensitive probe of dot charge dynamics and electronic level structure. This sensitivity is based on the fact that the dot, which is tunnel-coupled to electrons in a reservoir, acts as a dissipative bath for the cantilever. Here, we extend previous theoretical work to describe an AFM cantilever coupled to a double quantum dot. Unlike a single-dot, the double-dot system exhibits both incoherent tunneling to the leads and coherent tunneling between the dots. We find that the cantilever’s motion is affected by both kinds of tunneling and can yield significant information even in regimes where the total double-dot charge does not fluctuate. Cantilever dynamics can also be used to learn about the strength of dephasing processes in the double-dot. After presenting the theoretical approach to this problem, we will discuss the results in the context of current experimental efforts using InAs dots. These effects should also be accessible in a variety of other quantum dot setups. [1] S. D. Bennett, et al., Phys. Rev. Lett. 104, 017203 (2010). [2] L. Cockins, et al., Proc. Nat. Acad. Sci. 107, 9496 (2010).

9:24AM P27.00008 Few-electron states in SiGe double quantum dot structures with non-planar interfaces1, A.A. KISELEV, R.S. ROSS, M.F. GYURE, HRL Laboratories LLC, 3011 Malibu Canyon Road, Malibu CA 90265 — Valley-orbit effects of planar, non-planar, and imperfect heterointerfaces (both on the intra- and inter-dot scale) are directly captured in numerical simulations and analyzed theoretically for electrostatically defined accumulation mode (001) SiGe multi-dot structures. Our modeling is facilitated by explicitly allowing for an arbitrary and spatially inhomogeneous stacking of heterolayers in the active area of the device. Here we focus on results obtained for a double quantum dot (DQD) system, establishing the detailed structure of few-electron states, and, for two electrons, their spin- and valley-selective dynamics when the system is driven by pulse-modulating dot gate potentials. We identify valley-related avoided crossings and evaluate their strength affecting adiabaticity of applied bias sweeps. We system, establishing the detailed structure of few-electron states, and, for two electrons, their spin- and valley-selective dynamics when the system is driven by pulse-modulating dot gate potentials. We identify valley-related avoided crossings and evaluate their strength affecting adiabaticity of applied bias sweeps. We find that the splitting can be enhanced by disorder in the chemical bonds at the interface, in agreement with recent experiments.

1Sponsored by the United States Department of Defense. Approved for Public Release, Distribution Unlimited.

9:36AM P27.00009 Extended interface states enhance valley splitting in Si/SiO21, ANDRE SARAIVA, BELITA KOILLER, U. F. Rio de Janeiro, MARK FRIESEN, U. of Wisconsin — Interface disorder and its effect on valley degeneracy in the conduction band present an important theoretical challenge for operating spin qubit in silicon. Here, we demonstrate and investigate a counterintuitive effect occurring at Si/SiO2 interfaces. By applying tight binding methods, we show that intrinsic interface states can hybridize with conventional valley states to produce an anomalously large ground state energy gap. Such hybridization effects have not previously been explored in detail for valley splitting. We find that the splitting can be enhanced by disorder in the chemical bonds at the interface, in agreement with recent experiments.

1This work was supported in part by ARO and LPS, by NSF and CAPES. BK thanks CNPq, FUJB, INCT on Quantum Information and FAPERJ.
9:48AM P27.00010 Interface-mediated intervalley coupling in Si1. BELITA KOILLER, A.L. SARAIWA, Inst. de Física, UFRJ, Rio de Janeiro, Brazil; M.J. CALDERON, Inst. de Ciencia de Materiales de Madrid (CSIC), Spain; XUEDONG HU, Dep. of Physics, University at Buffalo-SUNY, S. DAS SARMA, Dep. of Physics, Condensed Matter Theory Center, University of Maryland, College Park, Maryland — The conduction band degeneracy in Si is detrimental to spin qubits, for which a nondegenerate ground orbital state is desirable. The Si valley degeneracy is reduced to 2 near an interface with an insulator, and it may be lifted by the spatially abrupt change in the crystal potential. Basic physical mechanisms for Si/barrier mediated valley coupling in different situations are addressed here. Theoretical studies of the interface-induced valley splitting in Si are presented. Abrupt and smooth interface profiles are considered, and the full plane wave expansions of the Bloch functions at the conduction band minima are included. Simple criteria are suggested for optimal fabrication parameters affecting the valley splitting, emphasizing the relevance of different interface-related properties. Refs: A.L.Saraiwa et al, PRB 80, 081305 R (2009); arXiv:1006.3338

1Support: BK and ALS thank CNPq, FUJB, INCT on Quantum Information, and FAPERJ. M.J.C. acknowledges Ministerio de Ciencia e Innovación (Spain). XH amd SDS thank NSA and L PS. S.D.S. also thanks CMT.C.

10:00AM P27.00011 Atomistic simulations of multi-valley silicon double quantum dots in the presence of disorder in the few electron regime1. JACK ROHRS, DAVID DIVINCENZO — The capacitively shunted flux qubit (CSFQ) has recently been shown to have coherence times of 1-2 microseconds repeatedly over many devices at typical qubit operating frequencies. Experiments in our group strongly suggest that losses associated with the shunting capacitor limit the current coherence times. As a result, we propose novel approaches towards decreasing capacitive losses by employing geometric and/or repeated quantum interleaving. We show experimental data and compare these with theoretical predictions.

1This research was supervised by Frederick W. Strauch; it was supported by Williams College and Research Corporation. A paper preprint based on this work is available online: (arXiv: 1008.1806).

10:12AM P27.00012 Engineering anisotropic exchange interactions between quantum dot spin qubits. YUN-PIL SHIM, MARK FRIESEN, Department of Physics, University of Wisconsin-Madison, Madison WI 53706 — We present a method for engineering anisotropic exchange interactions between quantum dot spin qubits using a Heisenberg antiferromagnetic spin chain as a bus spin. An external magnetic field is applied to create XXZ interactions between spin qubits that are weakly connected to a spin bus whose ground state is non-degenerate. We analyze the dependence of the anisotropy of the effective interaction on the external field and on the length of the spin bus. We show that the tunable XXZ interaction mediated by the spin bus can be used to generate multi-qubit entanglement and to efficiently implement universal gates based on encoded qubits. We also show that the operation of the spin bus is qualitatively different when the spin bus is near one of its magnetic field-induced quantum phase transitions. In this case, the qubits interact with a bus pseudo-spin and the resulting entanglement between pairs of qubits is enhanced.

1Supported by DMSE of USDOE, USNSF, and NNSF of China.

10:24AM P27.00013 Asymmetric Quantum Pd Films for Enhanced Hydrogen Separation1. GUANGFEN WU, Southeast U, U of Tennessee-Knoxville, Oak Ridge National Laboratory, WENGUANG ZHU, U of Tennessee-Knoxville, Oak Ridge National Laboratory, JINLAN WANG, Southeast U, ZHENYU ZHANG, Oak Ridge National Laboratory, U of Tennessee-Knoxville, U of Science and Technology of China — Based on density functional theory calculations and numerical simulations, we have investigated the permeation of H2 through ultra-thin Pd quantum films. The H2 flux can be highly increased by the elevation of the chemisorption-well on the permeate side without significantly blocking the subsurface-surface penetration. We find that Cu-coated asymmetric Pd quantum films (with the Cu monolayer on the permeate side) will enhance the capability for H2 separation: the H2 flux can be highly increased by the elevation of the chemisorption-well on the permeate side without significantly blocking the subsurface-surface penetration. We find that Cu-coated asymmetric Pd quantum films (with the Cu monolayer on the permeate side) will enhance the capability for H2 separation: the H2 flux can be highly increased by the elevation of the chemisorption-well on the permeate side without significantly blocking the subsurface-surface penetration. Numerical simulations show enhanced H2 flux by 5 orders of magnitude as an upper-limit for asymmetric Pd films over symmetric ones under similar conditions.

1This research was supervised by Frederick W. Strauch; it was supported by Williams College and Research Corporation. A paper preprint based on this work is available online: (arXiv: 1008.1806).

Wednesday, March 23, 2011 8:00AM - 11:00AM – Session P29 GQI: Focus Session: Superconducting Qubits C148

8:00AM P29.00001 LeRoy Apker Award Talk: Parallel State Transfer and Efficient Quantum Routing on Quantum Networks1. CHRISTOPHER CHUDZICKI, MIT — We study the routing of quantum information in parallel on multi-dimensional networks of tunable qubits and oscillators. These theoretical models are inspired by recent experiments in superconducting circuits using Josephson junctions and resonators. We show that perfect parallel state transfer is possible for certain networks of harmonic oscillator modes. We further extend our model to analyze the distribution of entanglement between every pair of nodes in the network, and find that the routing efficiency of hypercube networks is both optimal and robust in the presence of dissipation and finite bandwidth.

1This research was supervised by Frederick W. Strauch; it was supported by Williams College and Research Corporation. A paper preprint based on this work is available online: (arXiv: 1008.1806).

8:36AM P29.00002 Towards long coherence superconducting qubits. MATTHIAS STEFFEN, IBM, ANTONIO CORCOLES, JERRY CHOW, CHAD RIGETTI, MARK KETCHEN, MARY BETH ROTHWELL, GEORGE KEEFE, JIM ROZEN, MARK BORSTELMANN, JACK ROHRS, DAVID DIVINCENZO — The capacitively shunted flux qubit (CSFQ) has recently been shown to have coherence times of 1-2 microseconds repeatedly over many devices at typical qubit operating frequencies. Experiments in our group strongly suggest that losses associated with the shunting capacitor limit the current coherence times. As a result, we propose novel approaches towards decreasing capacitive losses by employing geometric and/or materials developments. We show experimental data and compare these with theoretical predictions.
An Al interdigitated capacitor with an identical width and gap as the resonator. We will present our experimental progress towards measuring relaxation times of selection rules explains the surprising magnitude of dispersive shifts, at detunings as large as ~8GHz, and also causes peculiarities observed in the fluxonium spectroscopy.

Tunable coupling in circuit quantum electrodynamics with a superconducting V-system. SRIKANTH SRINIVASAN, ANTHONY HOFFMAN, DEVIN UNDERWOOD, Princeton University, JAY GAMBERTA, Institute for Quantum Computing and Department of Applied Mathematics, University of Waterloo. We demonstrate a new superconducting charge qubit that realizes a V-shaped energy level spectrum, enabling tunable coupling between the qubit and a superconducting cavity while retaining all of the advantages, including charge noise insensitivity, common to other charge qubits such as the transmon. Tunable coupling is achieved with quantum interference between the two excited states of the qubit. We report measurements of the vacuum Rabi splitting, showing that the coupling strength can be tuned from greater than 40 MHz to less than 200 kHz using fast flux bias lines. This dynamically tunable coupling is an intrinsic property of the qubit and requires no additional coupling circuit elements. This new qubit design shows great promise for future quantum information processing and quantum optics experiments.

Inductive coupling of superconducting qubits to coplanar waveguide resonators. J.D. STRAND, M.P. DEFFEO, P. BHUPATHI, C. SONG, M. WARE, B. XIAO, B.L.T. PLOURDE, Syracuse University. Superconducting qubits coupled to microwave resonators provide a promising basis for a scalable quantum computing architecture and enable explorations of circuit quantum electrodynamics. One approach for achieving strong coupling between a qubit and resonator involves sharing the kinetic inductance of a narrow superconducting line. We are investigating different designs for inductively coupling qubits, including capacitively shunted flux qubits, to coplanar waveguide resonators. We are working to optimize the coupling while accommodating the space requirements of different qubit types and preserving the performance of the resonator. We present microwave measurements of these structures as well as modeling of the qubit-resonator coupling.

Transmon qubits coupled to compact resonators. S. SHANKAR, K. GEERLINGS, E. EDWARDS, L. FRUNZIO, R.J. SCHOELKOPF, M.H. DEVORET, Applied Physics Dept., Yale University. Compact resonators comprising of a meander inductor and an interdigitated capacitor are desirable building blocks for a multi-qubit processor due to their small size. We present an experiment on a superconducting transmon qubit coupled capacitively to such a compact resonator. We have fabricated low-loss Nb based compact resonators with an area within 1 mm² on a sapphire substrate to operate between 5 and 8 GHz. The resonator geometry was optimized to achieve an intrinsic quality factor above 300,000 at single-photon microwave powers and temperatures below 100 mK. Transmon qubits were made using Al/AIOx/Al Josephson junctions shunted by an Al interdigitated capacitor with an identical width and gap as the resonator. We will present our experimental progress towards measuring relaxation times of these qubits.

Design of a dc SQUID Phase Qubit with Controlled Coupling to the Microwave Signal. R.P. BUDOYO, A.J. PRZYBYSZ, B.K. COOPER, H. KWON, Z. KIM, B. CHENG, A.J. DRAGT, J.R. ANDERSON, C.J. LOBB, F.C. WELSTOOK, University of Maryland, College Park, M. KHALL, S. GLADCHENKO, M. STOUTIMORE, B.S. PALMER, K.D. OSBORN, Laboratory for Physical Sciences — We have designed an Al/AIOx/Al dc SQUID phase qubit on a sapphire substrate with a qubit junction area of 0.3 µm² to minimize loss associated with two-level systems in the junction oxide barrier. The qubit junction is shunted with a 1.5 pF interdigitated capacitor, and is isolated from the bias leads by an LC filter and an inductive isolation network using a larger Josephson junction. A previous device we built with similar parameters had its relaxation time T₁ limited by coupling to the microwave line. To reduce this coupling, we adopted a transmission line design and verified the coupling strength using microwave simulations. The new design will also allow us to measure the coupling to the SQUID by throughput measurements. We will discuss our design, the microwave simulations, our estimates for the overall coherence time due to losses and noise from various sources, and our progress towards testing the device.

Two junction effects in dc SQUID phase qubit. B.K. COOPER, H. KWON, A.J. PRZYBYSZ, R. BUDOYO, J.R. ANDERSON, C.J. LOBB, F.C. WELSTOOK, JQI and CNAM, U. of Maryland — The dc SQUID phase qubit was designed to allow one isolation junction to filter bias current noise from a second junction operating as a single junction phase qubit. As junctions shrink to minimize dielectric loss, the Josephson inductances of each junction approach the coupling loop inductance and this single junction picture appears inadequate. We consider a two-junction model of the dc SQUID phase qubit, where the qubit now corresponds to one of the normal oscillatory modes of the full SQUID. We discuss applications of this model to sweet spots in various control parameters and unusual behavior in the tunneling state measurement.

Two- Dimensional quantum dynamic in a dc SQUID. FLORENT LECOCQ, Institut Neel, CNRS, Grenoble, France, I.M. POP, Z. PENG, I. MATEI, C. NAUD, F.W. HEKKING, W. GUICHARD, O. BUISSON, Institut Neel and LPMMC, CNRS, Grenoble, France, R. DOLATA, A.B. ZORIN, PTB, Braunschweig, Germany — The dynamics of a dc SQUID presents a large variety of quantum effects at very low temperature such as 2D MQT signature, multilevel and phase qubit dynamics. We have shown that along the zero current bias line, the quantum dynamics is protected from current fluctuations. Along this line, the potential is quadratic-quartic and enhanced phase qubit properties have been demonstrated. When the dc SQUID loop inductance is of the order of the Josephson inductance the dynamic becomes two dimensional. As a consequence, in addition to the oscillation mode producing the phase qubit, a second oscillation mode exists, called transverse mode. Here we report spectroscopic evidence and coherence properties of both oscillators as well as coherent oscillations between the quantum states of these two coupled oscillators.

Acknowledgement: DOD, JQI, and CNAM

Funded by DOD, CNAM and JQI

Supported by the EU project EuroSQIP and SOLID, and ANR QUANTJO.

E. Hoskinson et al, Phys. Rev. Lett. 102, 097004 (2009)
Using a pulsing technique in the spin qubit regime, we create a superposition of triple quantum dot states, allow for phase accumulation, and interfere. We demonstrate LZS oscillations in a triple quantum dot environment. Our triple quantum dot design allows us to tune to either the charge or spin qubit regimes.

Recently, Landau-Zener-Stückelberg (LZS) oscillations have been demonstrated in a double quantum dot device [1]. In this talk we couple two S-T states in a single qubit system by driving it into its dark state using microwave fields local to the individual qubits.

Our results indicate that gate fidelities of up to 99.99% are within reach despite the fluctuating nuclear environment. Moreover, the demonstrated ultra long coherence time allows for more than 10^15 nano seconds. Our polarization scheme employs a quantum feedback mechanism that directly conditions the rate at which the qubit polarizes its nuclear environment on a quantum limited measurement of the hyperfine field seen by the same qubit. In addition, the stabilized state of the nuclear environment allows us to perform controlled X rotations and thereby demonstrate full control over the entire Bloch sphere as well as full quantum state tomography. Using dynamic nuclear polarization we are able to suppress fluctuations in the nuclear environment and prolong T2* by nearly an order of magnitude reaching nearly 300 micro seconds. We discuss the fidelity of the Rabi oscillation and the possible way of enhancement of fidelity.


10:48AM P29.00013 Entanglement between the charge and phase degrees of freedom in a superconducting quantum dot system, MUN DAE KIM, Yonsei University — The charge and phase are conjugate variables with each other in superconducting quantum dot systems. Using dynamic nuclear polarization we are able to suppress fluctuations in the nuclear environment and prolong T2* by nearly an order of magnitude reaching nearly 300 micro seconds. Our polarization scheme employs a quantum feedback mechanism that directly conditions the rate at which the qubit polarizes its nuclear environment on a quantum limited measurement of the hyperfine field seen by the same qubit. In addition, the stabilized state of the nuclear environment allows us to perform controlled X rotations and thereby demonstrate full control over the entire Bloch sphere as well as full quantum state tomography. Using dynamic nuclear polarization we are able to suppress fluctuations in the nuclear environment and prolong T2* by nearly an order of magnitude reaching nearly 300 micro seconds. We discuss the fidelity of the Rabi oscillation and the possible way of enhancement of fidelity.

12:15PM Q27.00004 Novel Coherent Spin Oscillations in a Triple Quantum Dot Circuit

ANDREW SACHRAJA, GHISLAIN GRANGER, LOUIS GAUDREAU, ALICIA KAM, SERGEI STUDENIKIN, PIOTR ZAWADZKI, GEOF AERS, National Research Council of Canada, MICHEL PIORO-LADRIERE, Sherbrooke University, ZBIG WASILEWSKI, National Research Council of Canada — We have demonstrated Landau-Zener-Stuckelberg oscillations in a triple quantum dot circuit related to pairs of triple quantum dot states. Different initialization schemes and pulse shapes involving all three dots will be discussed. However, the complexity of a triple quantum dot system suggests that in general coherent behaviour can be expected from interplays between various combinations of states. Here we demonstrate both experimentally and theoretically in a triple quantum circuit containing three spins, a coherent interplay between two coexisting qubits as a function of pulse amplitude and rise time. To further clarify the behaviour within the system we also observe and study coherent oscillations after a fourth spin has been added to the system in one of the relevant dots.

12:27PM Q27.00005 A Single Electron Charge Qubit in the Strong Driving Limit

J. STEHLIK, Y. DOVZHENKO, J. R. PETTA, Department of Physics, Princeton University, H. LU, A. C. GOSSARD, Materials Department, University of California at Santa Barbara — The dynamics of strongly driven two-level systems in the presence of dissipation have been thoroughly studied using theoretical models.[1] We use a model system, a GaAs double quantum dot (DQD) containing a single electron, to experimentally explore the strong-driving regime. We measured the transport through the DQD as a function of detuning and applied microwave power and compare with the Tien-Gordon model. In contrast with previous experiments, we directly access the occupation of the DQD using a quantum point contact charge sensor. In the high frequency regime ($h \omega_{microwave} \gg \Delta$, where $\Delta$ is the tunnel coupling) we observe up to 9-photon transitions and clear Bessel function behavior of the DQD occupation with applied microwave power. We also studied the intermediate frequency regime, observing 18-photon transitions. The data are modeled using the time-dependent Schrodinger equation.[2] By comparing the data with the simulations, we estimate $T_1 \sim 15$ ns and $T_2 \sim 3$ ns.

References:

1 Funded by the Sloan and Packard Foundations, NSF, and DARPA.

12:39PM Q27.00006 Non-adiabatic Quantum Control of a Semiconductor Charge Qubit

YULIYA DOVZHENKO, JIRI STEHLIK, KARL PETERSSON, JASON PETTA, Princeton University, HONG LU, ARTHUR GOSSARD, University of California, Santa Barbara — A GaAs double quantum dot is configured in the single-electron regime and operated as a charge qubit. The two basis states correspond to the electron being in either the left or the right dot. Non-adiabatic voltage pulses are applied to the depletion gates to drive coherent rotations, and the double dot occupation is read out using a nearby quantum point contact charge sensor. In contrast with previous work, where a single non-adiabatic pulse was applied for quantum control, we apply multiple pulses working towards a charge echo.[1,2] Data for $\frac{\pi}{2} - \tau - \frac{\pi}{2}$ and the $\frac{\pi}{2} - \tau_1 - \pi - \tau_2 - \frac{\pi}{2}$ "charge echo" pulse sequences are obtained and compared with numerical simulations of the charge qubit evolution.

References:

1 Funded by the Sloan and Packard Foundations, NSF, and DARPA.

12:51PM Q27.00007 Extended coherence of exchange operations in double quantum dot spin qubits using Hahn echo

MICHAEL SHULMAN, HENDRIK BLUHM, OLIVER DIAL, Harvard University, VLADIMIR UMANSKY, Weizmann Institute of Science, AMIR YACOBY, Harvard University — Exchange interactions are a powerful resource in quantum dots, as it can drive single qubit rotations and inter-qubit entanglement. However, spin qubits driven by exchange become sensitive to charge noise, which in free induction decay experiments has lead to dephasing after a few coherent exchange oscillations. We perform a Hahn echo measurement in two-electron spin qubits in GaAs quantum dots. The $\pi$-pulse is applied by means of a stabilized nuclear gradient in the quantum dots. We find an exponential dephasing with a time constant of up to $10 \mu$s, which is more than an order of magnitude larger than $T_2^*$, and corresponds to 500 coherent exchange operations within $T_2$. This increase in $T_2$ is expected to allow for several cPHASE operations between two charge coupled two-electron qubits within $T_2$.

1:03PM Q27.00008 Two-qubit operations of two-electron spin qubits in GaAs quantum dots

HENDRIK BLUHM, MICHAEL SHULMAN, OLIVER E. DIAL, Harvard University, VLADIMIR UMANSKY, Weizmann Institute, AMIR YACOBY, Harvard University — The realization of two-qubit entangling gates is one of the most important milestones for the development of quantum-dot based electron spin qubits. Our measurements and simulations of the coupling strength and the relevant coherence time indicate very favorable prospects for the realization of such gates using the Coulomb interaction between adjacent spin qubits. This operation can be protected against dephasing due to low frequency electric noise by simultaneously applying a $\pi$-pulse to both qubits, which is essential to achieve the required coherence time. We report the experimental realization of this echo operation in a two-qubit device, conditional evolution of one qubit depending on the charge state of the neighboring double dot, and further progress toward two-qubit entanglement.

1:15PM Q27.00009 Spin Manipulation in InAs Nanowire Double Quantum Dots

M. JUNG, K.D. PETERSSON, C.M. QUINTANA, J.R. PETTA, Princeton University — Recently, much effort has been devoted to the development of physical qubits for integration into quantum computers. Qubits allowing control with electric fields are attractive, as ac magnetic fields are more difficult to generate and localize on the nanoscale. The material properties of InAs allow efficient driving of electron spin resonance via the spin–orbit interaction. Our work has focused on developing quantum dots in InAs nanowires as fully characterized and controllable qubits. We have optimized our nanowire growth to eliminate the presence of planar defects, which impede the predictable formation of quantum dots. Using a bottom-gated architecture [1], we demonstrate tunable InAs nanowire double quantum dots, with the occupation controllable to the last electron. Pauli blockade is observed in the two-electron regime, demonstrating spin-dependent transport. We are able to drive single spin rotations by applying microwaves to one of the local metallic gates; from the electron spin resonance condition we extract a g-factor of $\sim 0$. Finally, we demonstrate full electrical control of the two-electron system and characterize gate fidelities.

References:

1 Funded by the Sloan and Packard Foundations, Army Research Office, and DARPA QuEST.
1:27PM Q27.00010 On-demand single-electron transfer between distant quantum dots with nanosecond pulses of surface acoustic waves. R.P.G. MCNEIL, M. KATAOKA\textsuperscript{1}, C.J.B. FORD, C.H.W. BARNES, J.P. GRIFFITHS, G.A.C. JONES, I. FARRER, D.A. RITCHIE, University of Cambridge — Quantum dots (QDs) provide a useful system for manipulating and storing quantum information. Methods for moving quantum information (spin) between processor and storage, or to a region of holes for conversion to photon qubits, will be required. Tunnelling of electrons over long distances between QDs is not viable. We show controlled long-range transfer of single electrons between QDs through a depleted 1D channel using pulses of surface acoustic waves (SAWs). In our device, two QDs are connected by a 4μm channel with QD occupancy monitored by 1D charge detectors. Electrons may be trapped and raised above the Fermi energy by stepping gate voltages. Having set the first QD to be ‘full’ and the other QD ‘empty’, a short SAW pulse is sent to transfer the electron to the opposite QD. This bi-directional process may be repeated over 100 times with the same electron. SAW power and pulse-width dependences suggest that transfer is achieved during the first few SAW cycles allowing sub-20ns pulses to be used.

\textsuperscript{1}now at NPL Teddington

1:39PM Q27.00011 A proposed all-electrical spin qubit CNOT gate robust against charge noise\textsuperscript{1}, SANKAR DAS SARMA, JASON KESTNER, Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, MD — We shall propose an alternative to the Loss-DiVincenzo implementation of the CNOT gate in a quantum dot spin qubit system. Our all-electrical proposal has the advantage of being robust against uncertainties and fluctuations in the tunnel coupling, barrier gate voltage pulse area, and interwell detuning which typically arise due to charge noise. The core idea is to introduce an auxiliary dot and use an analog to the stimulated Raman adiabatic passage (STIRAP) pulse sequence in three-level atomic systems, often referred to in the context of electron transport in quantum dot systems as CTAP (Coherent Tunneling by Adiabatic Passage). Spin-dependent tunneling opens the possibility of performing entangling two-qubit gates by this method.

\textsuperscript{1}Work supported by IARPA, LPS-CMTC, and CNAM.

1:51PM Q27.00012 Sensitivity to electronics error in coupled double quantum dot qubits. ERIK NIELSEN, RICHARD MULLER, MALCOLM CARROLL, Sandia National Laboratories — Reducing the effects of electronics control error in double quantum dot (DQD) quantum bits (qubit) is a central challenge to the creation of a solid-state quantum computing architecture. We investigate a system of capacitively coupled DQDs which implement a variant of the controlled phase gate when using each DQD as a singlet-triplet qubit. We identify regimes in which the gate action is more robust to sources of noise such as error around the applied bias point due to electronics or charge noise. Energy spectra are found using a configuration interaction (CI) method that accurately captures the (2,0) configuration of the DQD system, which is important for operating in these potentially low-noise regimes. This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin company, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

2:03PM Q27.00013 Gate Capacitance Reproducibility and Modeling in Silicon Double Quantum Dots. TED THORBECK, JQI: NIST & U. of Maryland, AKIRA FUJIVARA, NEIL ZIMMERMAN, NTT — For many applications the ability to design quantum dots with a specific set of gate capacitances and then rely on the reproducibility of those capacitances is crucial. For quantum computing, the ability to design our gate capacitances would help in reaching the few electron regime and in coupling multiple devices. For other applications the ability to design our gate capacitances would enable higher temperature operation. Our double quantum dots are formed by electrostatic gates on a silicon nanowire. We have measured 20 similar devices with 8 different sets of lithographic parameters. We will report on the reproducibility of the gate capacitances. For example, the range of capacitances is typically within 10% of the average. We will also compare our measured capacitances to simulations based on lithographic parameter. This simulation could then be used to design new devices.


Session Q29 GQI: Focus Session: Quantum Information for Quantum Foundations - Experiments and Tests C148

11:15AM Q29.00001 Foundational aspects of energy-time entanglement. JAN-ÅKE LARSSON, Linkoping University — This presentation will discuss whether energy-time entanglement is a properly Quantum Information representation, by considering its relation to Einstein-Podolsky-Rosen (EPR) elements of reality. The interferometric experiment proposed by J. D. Franson in 1989 provides the background, and the main issue here is whether a Local Realist model can give the Quantum-Mechanical predictions for this setup. The Franson interferometer gives the same interference pattern as the usual Bell experiment (modulo postselection). Even so, depending on the precise requirements made on the Local Realist model, this can imply a) no violation, b) smaller violation than usual, or c) full violation of the appropriate statistical bound. The discussion will include the nature of the requirements, the motivation for making them, and their effect. The alternatives include using a) only the measurement outcomes as EPR elements of reality, b) the emission time as EPR element of reality, and c) path realism. These subtle requirements need to be taken into account when designing and setting up future experiments of this kind, intended to test Local Realism, or indeed to do Quantum Information Processing.

11:27AM Q29.00002 Large violation of Bell’s inequalities using both counting and homodyne measurements. VALERIO SCARANI, DANIEL CAVALCANTI, CQT, National University of Singapore, NICOLAS BRUNNER, PAUL SKRZYPZCZYK, University of Bristol, ALEJO SALLES, Bohr Institute, Copenhagen — So far, all the optical demonstrations of violations of Bell’s inequalities have involved discrete degrees of freedom (e.g. polarization, time-bins) and are plagued by the detection-efficiency loophole. Continuous degrees of freedom would be a very interesting alternative because of the efficiency of the homodyne measurement; but the feasible schemes proposed so far reach very weak violations. We show that large violations for easily-prepared states can be achieved if both photon counting and homodyne detections are used. Our simple scheme may lead to the first violation of Bell’s inequalities with continuous variables and pave the way for a loophole-free Bell test.
11:39AM Q29.00003 A non-local quantum eraser: X. MA, J. KOFLER, A. QARRY, N. TETIK, T. SCHEIDL, R. URNS, S. RAMELOW, L. RATSCHBACHER, T. HERBST, A. FEDRIZZI, T. JENNEWEIN, A. ZEILINGER, Univ. of Vienna and OEAW — The complementarity behavior of quantum systems is strikingly illustrated by the quantum eraser, where one can actively choose whether or not to erase which-path information of one particle by performing suitable measurements on another particle entangled with it [1-2]. Quantum mechanics predicts that this choice can be arbitrarily delayed and spatially separated from interference [1-3]. We report the first quantum eraser experiment performed under Einstein locality, i.e. under relativistic space-like separation. We employ the hybrid entanglement between path and polarization of photon pairs and distribute the photons over an optical fibre link of 55 m and, in another experiment, over a free-space link of 1.4 km. A complementarity inequality is measured and well fits the predictions of quantum mechanics. Our experiment represents a conclusive demonstration of the quantum eraser concept.


11:51AM Q29.00004 On the Experimental Violation of Mermin’s High-Spin Bell Inequalities in the Schwinger Representation, RUFIN EVANS, OLIVIER PFISTER, University of Virginia — Since Bell’s original paper in 1964, a wide variety of experimental tests have overwhelmingly supported the completeness of quantum mechanics over local hidden-variable theories. However, relatively little effort has focused on systems of spins larger than $\frac{1}{2}$. Generalizing Bell’s result to higher dimensions is difficult, and the experiments needed to test these high-spin Bell inequalities are exciting. New advances in high efficiency photon-number-resolving detectors suggest that experimental tests of these inequalities should be possible in the Schwinger representation, using the continuous-variable entangled (two-mode squeezed) fields produced by an optical parametric oscillator below threshold. In this paper, we explore the realistic experimental implementation of this proposal to violate Mermin’s high-spin inequalities. We demonstrate that violation for spin values greater than 1 should be attainable under a range of feasible experimental conditions that include finite squeezing and nonideal detection efficiency.

12:03PM Q29.00005 Surface based detection schemes for molecular interferometry experiments - implications and possible applications, THOMAS JUFFMANN, ADRIANA MILIC, MICHAEL MUELLNERITSC, MARKUS ARNDT, Univ. of Vienna - Faculty of Physics — Surface based detection schemes for molecular interferometry experiments [1] might be crucial in the search for the quantum properties of larger and larger objects [2] since they provide single particle sensitivity. Here we report on molecular interferograms of different biomolecules imaged using fluorescence microscopy. Being able to build-up of an interferogram live and in situ reveals the matter-wave behavior of these complex molecules in an unprecedented way. We examine several problems encountered due to van-der-Waals forces between the molecules and the diffraction grating and discuss possible ways to circumvent these. Especially the advent of ultra-thin (1-100 atomic layers) diffraction masks might path the way towards molecular holography. We also discuss other possible applications such as coherent molecular microscopy.


12:15PM Q29.00006 Matter wave interferometry with large and complex molecules, STEFAN GERLICH, SANDRA EIBENBERGER, MATHIAS TOMANDL, University of Vienna, Faculty of Physics, JENS TUXEN, MARCEL MAYOR, University of Basel, Department of Chemistry, MARKUS ARNDT, University of Vienna, Faculty of Physics — Matter wave interferometry with molecules of increasing size, mass and complexity explores the frontiers of quantum mechanics and it is a promising tool for determining molecular properties with high precision. The quantum wave nature of organic molecules is used in a Kapitza-Dirac-Talbot-Lau interferometer to generate a set of high-contrast interference fringes that are highly sensitive to small changes of the matter wave. This is exploited to access thermally activated internal molecular properties, such as optical and static polarizabilities, static and thermally activated electric dipole moments, information about conformational differences and state changes, optical absorption spectra and more. The information about the internal states can be extracted through conservative interactions, i.e. allowing the persistence of full quantum delocalization in position space.

12:27PM Q29.00007 Violation of local realism with freedom of choice, JOHANNES KOFLER, THOMAS SCHEIDL, RUPERT URNS, SVEN RAMELOW, XIAO-SONG MA, Institute for Quantum Optics and Quantum Information (IQOOI), Austrian Academy of Sciences, THOMAS HERBST, Faculty of Physics, University of Vienna, LOThAR RATSCHBACHER, ALESSANDRO FEDRIZZI, NATHAN LANGFORD, THOMAS JENNEWEIN, ANTON ZEILINGER, Institute for Quantum Optics and Quantum Information (IQOOI), Austrian Academy of Sciences — Bell’s theorem shows that local realistic theories place strong restrictions on observable correlations between different systems, giving rise to Bell’s inequality which can be violated in experiments using entangled quantum states. Bell’s theorem is based on the assumptions of realism, locality, and the freedom to choose between measurement settings. In experimental tests, ”loopholes” arise which allow observed violations to still be explained by local realistic theories. Violating Bell’s inequality while simultaneously closing all such loopholes is one of the most significant still open challenges in fundamental physics today. We present an experiment which violates Bell’s inequality while simultaneously closing the locality loophole and addressing the freedom-of-choice loophole, also closing the latter within a reasonable set of assumptions. Reference: T. Scheidl et al., Proc. Natl. Acad. Sci. USA 107, 19708 (2010).

12:39PM Q29.00008 Experimental non-classicality of an indivisible system: RADEK LAPKIEWICZ, PEIZHE LI, CHRISTOPH SCHEAFF, NATHAN LANGFORD, SVEN RAMELOW, MÁRCIN WIESNIAK, ANTON ZEILINGER, University of Vienna, Faculty of Physics, Vienna; Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Vienna — In Quantum Mechanics (QM) not all properties can be simultaneously well defined. An important question is whether a joint probability distribution can describe the outcomes of all possible measurements, allowing a quantum system to be mimicked by classical means. Klyachko et al. [PRL 101, 020403 (2008)] derived an inequality which allowed us to answer this question experimentally. The inequality involves only five measurements and QM predicts its violation for single spin-1 particles. This is the simplest system where such a contradiction is possible. It is also indivisible and as such cannot contain entanglement. In our experiment with single photons distributed among three modes (isomorphic to stationary spin-1 particles) we obtained a value of $-3.893(9)$, which lies more than 90 standard deviations below the “classical” bound of -3.

1Supported by the European Commission program (Q-ESSENCE, ERC Senior Grant QIT4QAD, Marie-Curie RTN EMALI) and the Austrian Science Fund (CoQuS and SFB-FoQuS).
10:00 PM Q29.00009 Testing spontaneous localization with ultra-massive cluster interferometry, STEFAN NIMMRICHER, University of Vienna, KLAUS HORNBERGER, MPIPKS Dresden, MARKUS ARNDT, University of Vienna — Understanding the transition from the microscopic domain of quantum mechanics to the everyday classical world is still an open problem in modern physics. Collapse models are a possible way to resolve this issue by introducing mechanisms which break the quantum superposition principle above a certain mass and time scale. One of the best studied models is the theory of continuous spontaneous localization (CSL) by Ghirardi, Pearle and Rimini [1]. We show that it should be possible to test the predictions of the CSL model in the new matter-wave interferometer for heavy metal clusters that is currently built in Vienna. Extending the original Talbot-Lau setup for biomolecules, the new scheme will operate in the time-domain using three pulsed standing-wave gratings of UV laser light. We argue that this should enable us to see single-particle interference in an unprecedented mass range from $10^5$ up to even $10^9$ atomic mass units. Recent estimates of the strength of the CSL effect by Adler and Bassi [2,3] suggest that a breakdown of the quantum superposition principle would occur in precisely this mass regime.

10:15 PM Q29.00011 Experimental Violation of Two-Party Leggett-Garg Inequalities with Semiweak Measurements, JUSTIN DRESSEL, CURTIS BROADBENT, JOHN HOWELL, ANDREW JORDAN, University of Rochester — We generalize the derivation of Leggett-Garg inequalities to systematically treat a larger class of experimental situations by allowing multi-particle correlations, invasive detection, and ambiguous detection results. Furthermore, we show how many such inequalities may be tested simultaneously with a single setup. As a proof of principle, we violate several such two-particle inequalities with data obtained from a polarization-entangled biphoton state and a semiweak polarization measurement based on Fresnel reflection. We also point out a non-trivial connection between specific two-party Leggett-Garg inequality violations and convex sums of strange weak values.

10:30 PM Q29.00012 Bell’s theorem, and Ontic Definiteness, JOE HENSON, Perimeter Institute — Bell’s theorem shows that the reasonable relativistic causal principle known as “local causality” is not compatible with the predictions of quantum mechanics. It is not possible to maintain a satisfying causal principle of this type while dropping any of the better-known assumptions of Bell’s theorem. However, another assumption of Bell’s theorem is the use of classical logic. One part of this assumption is the principle of ontic definiteness, that is, that it must in principle be possible to assign definite truth values to all propositions treated in the theory. Once the logical setting is clarified somewhat, it can be seen that rejecting this principle does not in any way undermine the type of causal principle used by Bell. Without ontic definiteness, the deterministic causal condition known as Einstein Locality succeeds in banning superluminal influence (including signalling) whilst allowing correlations that violate Bell’s inequalities. Objections to altering logic, and the consequences for operational and realistic viewpoints, are also addressed.

10:45 PM Q29.00013 On dipole anisotropy in spatial distribution of Planck’s constant values, SIMON BERKOVICH, The George Washington University — The work relates to the remarkable fact discovered by John Webb et al. of angular variations of the fine structure constant $\alpha \approx e^2/\hbar c$. We elaborate on this fact using our model of quantum mechanics (see [1] and references within). The peculiarity of quantum behavior stems from interactive holography appearing on top of the cellular automaton mechanism of the Universe. Nonlocality comes naturally from sliced holographic processing. As to the anisotropy of $\alpha$, it is due to variations of $\hbar$ caused by different undulation control patterns in different positions with respect to the source of the holographic reference beam. The angular divergences in $\alpha$ are determined by the eccentric placement of the Solar system with respect to this holographic beam. The eccentricity factor imposes direct holographic on several types of astrophysical observations. So, following [1], small opposite changes in $\hbar$ with respect to the eccentricity displacement of the Solar system could lead to the appearance of the “axis-of-evil” in CMB. Further, the recently discovered anisotropy in high-energy cosmic rays should be also determined by the eccentricity factor, i.e. it should adhere to the same dipole. [1] S. Berkovich, “A Comprehensive Explanation of Quantum Mechanics”, http://www.bestthinking.com/topics/science/physics/ quantum.physics/a-comprehensive-explanation-of-quantum-mechanics

11:00 PM Q29.00014 Scaling of quantum Zeno dynamics in thermodynamic systems, WING CHI YU, LI-GANG WANG, SHI-JIAN GU, Department of Physics, The Chinese University of Hong Kong, Hong Kong — Quantum Zeno effect (QZE) refers to the inhibition of the unitary time evolution of a quantum system by repeated frequent measurements. It has been studied intensively within the content of quantum optics in recent decades. Among those analyses, there are a few under consideration are only of a few. Little attention of QZE in thermodynamic systems has been paid so far. In this presentation, we will investigate the QZE in thermodynamic systems from the viewpoint of condensed matter physics. We take the one-dimensional transverse-field Ising model and the Lipkin-Meshkov-Glick (LMG) model as examples to illustrate analytically the criteria, in terms of the size dependence of the leading term of the survival probability in the short-time limit, for observing the QZE. Our analysis shows that in order to observe the QZE in the Ising model, the frequency of the projective measurement should be comparable order to that of the system sizes. The same criterion also holds in the symmetric broken phase of the LMG model. However, in the polarized phase of the LMG model, the leading term of the survival probability is independent of the system size and the QZE can be easily observed.

11:15 PM Q29.00015 Decoherence Free Neutron Interferometry, DMITRY A. PUSHIN, DAVID G. CORY, IQC, University of Waterloo, MICHAEL G. HUBER, NIST, MOHAMED ABUTALEB, MIT, MUHAMMAD ARIF, NIST, CHARLES W. CLARK, Joint Quantum Institute, NIST and the University of Maryland — A neutron interferometer (NI) is a unique example of the macroscopic quantum coherence and has been used to test fundamental principles of quantum mechanics. In practice, neutron interferometers are not widely used because of their extreme sensitivity to environmental noise which is in part due to the slow velocity (relative to light) of the neutron. We show that a neutron interferometer design can benefit from concepts of quantum information processing. We have machined a Decoherence Free (DF) neutron interferometer designed using a quantum error correction code[1] and have shown it to be much less sensitive to mechanical vibrations than is the standard Mach-Zehnder (MZ) interferometer. Both the MZ and DF geometries are incorporated in one crystal, which allows direct comparisons to be made. We believe that our results and related quantum information approaches, such as "the power of one qubit",[2] will enable a new series of compact neutron interferometers that can be tailored to specific applications in soft condensed matter and spintronics.

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A Theory of entanglement and entanglement-assisted communication, CHARLES H. BENNETT, IBM Research Division — Protocols such as quantum teleportation and measurement-based quantum computation highlight the importance of entanglement as a resource to be quantified and husbanded. Unlike classical shared randomness, entanglement has a profound effect on the capacity of quantum channels: a channel’s entanglement-assisted capacity can be much greater than its unassisted capacity, and in any case is given by much a simpler formula, paralleling Shannon’s original formula for the capacity of a classical channel. We review the differences between entanglement and weaker forms of correlation, and the theory of entanglement distillation and entanglement-assisted communication, including the role of strong forms of entanglement such as entanglement-embezzling states.

2:42PM T5.00003 Less Reality, More Security, ARTUR EKERT, Oxford University and National University of Singapore — Bell’s inequality makes a seemingly insane scenario possible — devices of unknown or dubious provenance, even those that are manufactured by our enemies, can be safely used for secret communication. And this is for real! All that is needed to implement such a bizarre form of cryptography is a loophole-free violation of Bell’s inequalities. It is on the edge of being technologically feasible. I will provide a brief overview of quantum and post-quantum cryptography and describe how studies of entanglement and the foundations of quantum theory influenced the way we may soon protect information.

4:18PM T5.00004 Twenty Seven Years of Quantum Cryptography!, RICHARD HUGHES, Los Alamos National Laboratory — One of the fundamental goals of cryptographic research is to minimize the assumptions underlying the protocols that enable secure communications between pairs or groups of users. In 1984, building on earlier work by Stephen Wiesner, Charles Bennett and Gilles Brassard showed how quantum physics could be harnessed to provide information-theoretic security for protocols such as the distribution of cryptographic keys, which enables two parties to secure their conventional communications. Bennett and Brassard and colleagues performed a proof-of-principle quantum key distribution (QKD) experiment with single-photon quantum state transmission over a 32-cm air path in 1991. This seminal experiment led other researchers to explore QKD in optical fibers and over line-of-sight outdoor atmospheric paths (“free-space”), resulting in dramatic increases in range, bit rate and security. These advances have been enabled by improvements in sources and single-photon detectors. Also in 1991 Artur Ekert showed how the security of QKD could be related to quantum entanglement. This insight led to a deeper understanding and proof of QKD security with practical sources and detectors in the presence of transmission loss and channel noise. Today, QKD has been implemented over ranges much greater than 100km in both fiber and free-space, multi-node network testbeds have been demonstrated, and satellite-based QKD is under study in several countries. “Quantum hacking” researchers have shown the importance of extending security considerations to the classical devices that produce and detect the photon quantum states. New quantum cryptographic protocols such as secure identification have been proposed, and others such as quantum secret splitting have been demonstrated. It is now possible to envision quantum cryptography providing a more secure alternative to present-day cryptographic methods for many secure communications functions. My talk will survey these remarkable developments.

2:42PM T27.00001 Landau-Zener-Stückelberg interference in the presence of quantum noise, YANG YU, LINGJIE DU, MINJIE WANG, National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing 210093, China — We investigated the Landau-Zener-Stückelberg (LZS) interference in strongly driven two-level systems subjected to quantum noise. The transition rate induced by consecutive LZ transitions is obtained, from which LZS interference can be analytically calculated based on rate equation. In the presence of significant frequency dependent noise, the evolving paths of LZS interference is going to be detoured. Therefore, the position of the resonant peaks is shifted and a stationary population inversion in TLS without involving the third qubit state is generated. The LZS interferometry can be used to investigate the noise property hence the decoherence source of the system. In addition, the stationary population inversion may find application in detecting loss and microwave cooling.

This work was supported by the MOST of China (2011CB922104, 2011CBA00205) and the NSFC (10725415, 91021003).

2:42PM T27.00002 Exact master equations for linearly coupled Bosons or Fermions, SHAO-WEN CHEN, REN-BAO LIU, The Chinese University of Hong Kong — Using the coherent-state representation (P-representation), we derived the exact master equation for a quantum system in an environment, which has linear but otherwise arbitrary couplings. This method works for both Boson and Fermion systems, since the coherent states of Bosons and Fermions have the similar algebra structure. The new derivation reproduces the previous works on photon dynamics in coupled cavities or quantum transport through double quantum dots, but it provides a more general theoretical framework for studying quantum dynamics in photonic, mechanical, and photomechanical systems, and quantum transport in nanostructures.

This work was supported by Hong Kong RGC Project CUHK 402208.
high \( Q \) (> temperature (in its spin environment. In this talk we will present our latest results towards these goals.

demonstrate independent quantum control of each of them. This newly gained control opens the door to a number of exciting experiments such as measurement manipulation of the spin bath environment [see De Lange et al., Science 330, 60 (2010)]. Here, we demonstrate a new approach towards decoherence control based on coherent by uncontrolled interactions with their spin environment. High-fidelity single-spin control can be used to prolong the coherence by dynamically decoupling the spin from the environment [see De Lange et al., Science 330, 60 (2010)]. Here, we demonstrate a new approach towards decoherence control based on coherent manipulation of the spin bath environment itself. Our system consists of a single NV center spin in diamond, surrounded by a bath of electronic spins belonging to nitrogen impurities. By driving the bath spins resonantly and using the NV spin as a sensor, we are able to detect all transitions of the bath spins and demonstrate independent quantum control of each of them. This newly gained control opens the door to a number of exciting experiments such as measurement of the spin bath dynamics, manipulation of the spin bath correlation time, decoherence editing, and protection of NV spin coherence by suppressing the dynamics in its spin environment. In this talk we will present our latest results towards these goals.

This work was funded by IARPA.
We show that the decoherence and disentanglement for a pair of interacting qubits can be suppressed by the exchange interaction in the presence of one or more uncorrelated random telegraphic noise sources. The suppression of the dissipative dynamics is more apparent for the maximally entangled Bell states, particularly if the noise is non-Markovian. Hence, the entangled singlet-triplet superposition state of two qubits can be protected by the interaction, while for the triplet-triplet state, it is less effective. This makes the former more suitable for encoding quantum information. Our calculations are done using a recently developed quasi-Hamiltonian formalism that is suitable for describing non-unitary temporal dynamics in an open quantum system subjected to classical stochastic noise processes. Exact and approximate solutions are obtained for a number of cases.

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1 This work is supported by the DARPA/MTO QuEST program through a grant from AFOSR.
2:54PM T29.00003 Surface and Interface Defects in Linear and Nonlinear Superconducting Resonators, STEVEN WEBER, KATER MURCH, UC Berkeley, ALLISON DOVE, University of Illinois Urbana-Champaign, GUSTAF OLSON, gustafolson@gmail.com, ZACK YOSCOVITS, University of Illinois Urbana-Champaign, R. VIJAY, ELI LEVENSON-FALK, UC Berkeley, JAMES ECKSTEIN, University of Illinois Urbana-Champaign, IRFAN SIDDIQI, UC Berkeley — We report on progress to identify and mitigate noise mechanisms in both linear superconducting resonators and devices embedded with Josephson junctions. Defects, either microscopic fluctuators or remnant residue layers associated with nanofabrication, can exist on metal surfaces, at the metal-dielectric interface, within the dielectric, or within the Josephson junctions themselves. We have investigated the quality factor and phase noise of lumped element and distributed element resonators at low temperature and photon number—the operating regime of superconducting qubits. In particular, we compare the performance of poly-crystalline and epitaxial films, silicon and sapphire substrates, and weak link and tunnel type Josephson junctions.

3:06PM T29.00004 Quantum model for superconducting resonator loss via a two-level system, MISHKATUL BHATTACHARYA, K. OSBORN, A. MIZEL, Laboratory for Physical Sciences, University of Maryland, College Park, MD 20740 — Clarifying the mechanisms of dissipation in superconducting resonators is crucial for advancing superconducting quantum computation. The models currently employed to study dielectric loss due to two level charge fluctuators have been based largely on a classical treatment of the problem. In contrast, we carry out a quantum mechanical investigation using a dissipative Jaynes-Cummings model in which the resonator is coupled to a two-level system that is in turn coupled to a bath. We present an analysis of the dynamics of energy decay in the system, comparing its predictions to those of well-known classical models, which agree with our results in the limit of high oscillator excitation.

3:18PM T29.00005 Possible interactions between two-level system defects in SiNx films, SERGII GLADCHENKO, MOE KHAILAL, Physical Laboratory of Physical Sciences, MD, C.J. LOBB, F.C. WELSTOOD, University of Maryland, Department of Physics, KEVIN D. OSBORN, Laboratory for Physical Sciences, MD — Low-temperature properties of PECVD SiNx dielectric films are measured within the capacitor of superconducting LC resonators. Experiments are made at temperatures from 30 to 300 mK, and at storage energies from 1 to 10^10 photons in a resonant cavity. While the power and temperature dependence of the loss agrees with two-level system (TLS) theory above 60 mK, below this temperature we observe significant deviations. In this regime we observe a reduction in loss upon lowering dielectric temperature, in direct contrast with the independent TLS model of defects within our film. This new phenomena may indicate interactions between two-level systems. We can also spectroscopically resolve the loss from dominant defects in our capacitors, which have a volume of ~2000 μm^3.

3:30PM T29.00006 A study of glassy behavior in amorphous dielectrics using GHz frequency superconducting resonators, MOE KHAILAL, M.J.A. STOUTIMORE, University of Maryland and Laboratory for Physical Sciences, AARON HOLDER, CHARLES MUSGRAVE, University of Colorado, C.J. LOBB, F.C. WELSTOOD, University of Maryland, K.D. OSBORN, Laboratory for Physical Sciences — It has been shown that the dielectric constant of certain glassy materials can be changed with a dc electric field bias. Here we extend those studies to higher frequencies where both the real and imaginary part of the dielectric constant can be studied. We have designed a dc electric-field tunable LC resonator built from superconducting thin-film aluminum to test this effect in SiN, at GHz frequencies. We will report progress on measuring these devices down to single photon storage energies at temperatures of approximately 30 mK, where the dynamics are dominated by the tuning of two-level defects.

3:42PM T29.00007 Microwave loss of novel epitaxial superconductor-insulator-superconductor (SIS) trilayers, U. PATEL, Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA, K.H. CHO, Department of Materials Science and Engineering, University of Wisconsin, Madison, Wisconsin 53706, USA, L. MAURER, S. SENDELBACH, D. HOVER, Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA, C.B. EOM, Department of Materials Science and Engineering, University of Wisconsin, Madison, Wisconsin 53706, USA, R. MCDERMOTT, Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA — The performance of superconducting phase qubits is currently limited by spurious coupling of the qubit to two-level state (TLS) defects in the amorphous dielectric materials of the circuits. Thus, it is highly desirable to develop defect free epitaxial dielectric materials for improved junction barriers and capacitor dielectrics. We have characterized the dielectric loss of an in-situ environment without breaking vacuum. The system is also equipped with a reflection high energy electron diffraction (RHEED) which will allow us to perform in-situ characterization of the structure and growth dynamics. We will discuss our strategy of epitaxial growth of various single crystal dielectrics on superconducting thin films in this system and their structural and electrical properties of the heterostructures.

3:54PM T29.00008 Growth of epitaxial superconductor/dielectric heterostructures using a sputtering PLD hybrid system with in-situ RHEED, KWANG HWAN CHO, JACOB PODKAMINER, CHAD FOLKMAN, CHANG-SEON EOM, Department of Materials Science and Engineering, University of Wisconsin-Madison — One of limiting factors in superconducting qubits is decoherence caused by microscopic defects in dielectric layer such as nanocrystalline regions and grain boundaries in a shunted capacitor. We have grown epitaxial Re thin films on a c-plane sapphire substrate using RF magnetron sputtering, then transferred ex-situ to a pulsed laser deposition (PLD) system where dielectrics thin film layer is deposited. One drawback of this fabrication approach is the necessity to expose the sample to air when the sample is transferred to different deposition chambers. In order to avoid these drawbacks, we have employed a hybrid PLD-sputtering deposition that will allow us to grow the oxide dielectric/Re heterostructures in an in-situ environment without breaking vacuum. The system is also equipped with a reflection high energy electron diffraction (RHEED) which will allow us to perform in-situ characterization of the structure and growth dynamics. We will discuss our strategy of epitaxial growth of various single crystal dielectrics on superconducting thin films in this system and their structural and electrical properties of the heterostructures.

4:06PM T29.00009 Barrier defect analysis using Josephson junction resonators, M.J.A. STOUTIMORE, BAHMAN SARABI, MOE KHAILAL, University of Maryland and Laboratory for Physical Sciences, C.J. LOBB, University of Maryland, K.D. OSBORN, Laboratory for Physical Sciences — We have designed Josephson junction (JJ) resonators by adding an Al/AlO_x/Al Josephson junction in parallel with a coplanar sapphire capacitor and an inductor so that the total loss will be dominated by the junction barrier. JJ resonators couple to individual defects in the junction barrier, causing splittings in the spectroscopy of the resonator when it is excited near single-photon energies, similar to phase and other qubits. Measurements are performed in a dilution refrigerator at 30mK with a drive frequency of approximately 7GHz. By applying a dc flux bias, we can tune the resonance frequency by as much as 1GHz. Analysis of the frequency of splittings as a function of junction area and barrier growth process provides a method for determining the source of the defects. We will use this devices to study amorphous aluminum oxide barriers and will report our progress towards studying novel barrier dielectrics.

3 This research was supported by the Intelligence Advanced Research Projects Activity through the U.S. Army Research Office award No. W911NF-09-1-0351.

4:18PM T29.00010 Losses in Josephson junction resonators, MARTIN WEIDES, National Institute for Standards and Technology, Boulder, JIASONG GAO, JEFFREY KLINE, MICHAEL VISSERS, DAVID WISBEY, DAVID PAPPAS — Josephson junctions for superconducting circuits such as SQUIDs and qubits are conventionally based on Al-AlO_x-Al multilayer technology, which was shown to have a low quality factor and two-level-fluctuators in the dielectric AlO_x as limiting decoherence source. By replacing the amorphous Al-rich tunnel oxide with nearly stoichiometric Al_2O_3 we aim to increase the qubit coherence times by reducing the number of dangling bonds in the Josephson tunnel junction. In this talk a test platform for loss determination in high-Q tunnel oxides based on junction resonators will be presented. We will show alternative tunnel junctions based on high temperature grown tunnel oxides.
The number of pulses, $n$, in a Carr-Purcell-Meiborn-Gill (CPMG) dynamical decoupling sequence. In this system, the dominant forms of decoherence are quantum fluctuations of the nuclear spins, $\beta$, and the number of pulses and $1/T_2^\ast$ is the nuclear spin coherence time.

**4:30PM T29.00011 Growth and Properties of Epitaxial Dielectrics/Superconducting Thin Film Heterostructures**, CHANG-BEOM EOM, University of Wisconsin-Madison, KWANG-HWAN CHO, JACOB PODKAMINER, CHAD FOLKMAN — Our objective is to grow epitaxial dielectrics on crystalline superconducting underlayers to improve the performance of superconducting Qubits. A major challenge is heteroepitaxial growth of single crystal dielectric layers with high crystalline quality and atomically sharp interfaces between the dielectric and superconducting electrodes. First, we have grown high quality epitaxial rhenium (Re) thin films on c-plane sapphire substrates by DC magnetron sputtering. The full width at half maximum (FWHM) of Re 0002 rocking curve is less than 0.5 degrees. The RMS surface roughness determined by AFM is less than 1 nm. We have also grown epitaxially various dielectric thin films on top of the single crystal Re bottom electrode by pulsed laser deposition with in situ high pressure reflection high energy electron diffraction (RHEED). In this talk, we will discuss our strategy of epitaxial growth of various single crystal dielectrics on superconducting thin films and their structural and electrical properties of the heterostructures.

**4:42PM T29.00012 Microwave Response of Superconducting Resonant Circuits based on 3D Aluminum Nanobridge Josephson Junctions**, ELI LEVENSON-FALK, R. VIJAY, KATER MURCH, IRFAN SIDIQI, QNL, UC Berkeley — Metallic weak links are attractive candidates for low loss superconducting circuits as they offer a route to realize Josephson junctions without the need for an amorphous tunnel barrier—a potential source of both low and high frequency noise. We discuss microwave measurements of high quality factor resonators incorporating both single nanobridges and nanobridge-based SQUIDs. Our results indicate low loss and strong nonlinearity, suggesting the future utility of these devices in qubit and amplifier circuits. Our data are in quantitative agreement with numerically computed nanobridge current-phase relations and dc transport measurements. We show preliminary results on nanobridge-based qubits and parametric amplifiers.

**5:45PM T29.00013 Josephson junctions formed from superconducting nanowires**, B. XIAO, H.Y. CHEN, I. NSANZINEZA, C. SONG, B.L.T. PLOURDE, Syracuse University — We are investigating the feasibility of forming Josephson junctions from thin-film superconducting nanowires. The Josephson coupling through such a constrictor can provide the necessary nonlinearity, for example, for forming a qubit, while avoiding the influence of defects in the amorphous tunnel barriers used in conventional Josephson junctions that can contribute to qubit decoherence. We have developed a fabrication process based on high-resolution electron-beam lithography with a negative-tone resist combined with ion-beam etching to pattern nanowires from 10 nm-thick, sputter-deposited, amorphous MoGe thin films. We have studied nanowires with widths between 20 - 100 nm and lengths between 50 - 200 nm. A Nb wiring layer provides electrical connections to the nanowires. Low-temperature transport measurements allow us to study the nanowire critical current and the influence of microwave irradiation on the current-voltage characteristics.

*Work supported by IARPA*

**5:06PM T29.00014 Via fabrication process for epitaxial superconducting qubits**, JEFFREY KLINE, FABIO DA SILVA, MICHAEL VISSERS, DAVID WISBEY, MARTIN WEIDES, DAVID PAPPAS, NIST — Reducing the density of spurious two level systems (TLS) in the dielectric layers of superconducting qubits has been shown to improve performance. We aim to reduce TLS density in the Josephson junction tunnel barrier through the use of epitaxial materials. The investigation of some new material systems using a trilayer process wherein the base electrode, tunnel barrier, and top electrode are grown and subsequently patterned is problematic due to sidewall damage during the mesa etch. We apply the via fabrication process wherein the base electrode and wiring insulator layers are grown and patterned prior to tunnel barrier growth. The via process is compatible with a different set of electrode materials than the trilayer process and allows us to investigate the suitability of these materials for qubit applications. We present room temperature and low temperature data for Re/AlO$_2$/Re Josephson junctions fabricated using the via process.

**5:18PM T29.00015 Introduction of a DC Bias into a High-Q Superconducting Microwave Cavity**, FEI CHEN, JULIANG LI, M.P. BLENCOWE, A.J. RIMBERG, Dartmouth College, ADAM SIROIS, University of Colorado, Boulder, RAYMOND SIMMONDS, National Institute of Standards and Technology, Boulder — The circuit quantum electrodynamics (QED) architecture has been demonstrated to allow study of cavity QED physics in a high-Q on-chip microwave cavity[1]. Here we develop a technique to apply a DC current or voltage bias to nanostructures embedded in the microwave cavity without significantly degrading the Q at high frequencies. Experimental results show good agreement with theoretical predictions. New highly non-linear fully quantum mechanical devices can be developed by embedding Josephson junction devices such as single electron transistors (SETs) or single electron qubits into the microwave cavity. The interplay between the SET and the microwave cavity offers an interesting system for studying nonlinear quantum dynamics and the quantum-to-classical transition. Recent experimental results will be discussed.


**Thursday, March 24, 2011 8:00AM - 10:48AM — Session V27/GQI: Focus Session: Semiconductor Qubits—Dynamic Decoupling, Dephasing, and Relaxation**

**8:00AM V27.00001 Increasing Quantum Dot Electron Spin Coherence with Persistent Spin Narrowing**, BO SUN, University of Michigan, COLIN CHOW, University of Michigan, ALLAN BRACKER, DANIEL GAMMON, Naval Research Laboratory, LU SHAM, University of California San Diego, DUNCAN STEEL, University of Michigan — We demonstrate reproducible initialization of the Overhauser field in a single InAs self-assembled quantum dot using the hole assisted nuclear feedback mechanism. This fixes the mean the Overhauser field to a value determined by two pump lasers and dramatically reduces the statistical broadening of the electron spin resonance arising from averaging over the nuclear spin ensemble, $1/T_2^\ast$. By initializing for tens of milliseconds, the prepared Overhauser field distribution lasts for well over a second even in the presence of a fluctuating electron spin. Furthermore, we find a mechanism which will initialize the nuclear spins using only a single laser, and that this mechanism involves the evolution of the nuclear spins “in the dark”, that is, absent any optical field. This new method is directly compatible with the CW readout technique used in recent time-domain spin manipulation experiments.

*The authors would like to acknowledge ARO, NSF, AFOSR, and DAPRA for their support*

**8:12AM V27.00002 Effects of Multi-pulse Dynamical Decoupling Schemes on Dephasing in a GaAs Spin Qubit**, JAMES MEDFORD, CHRISTIAN BARTHEL, CHARLES MARCUS, Harvard University, MICAH HANSON, ARTHUR GOSSARD, Materials Department, University of California, Santa Barbara — Coherence time ($T_2^\ast$) of a singlet-triplet qubit in a GaAs double quantum dot is studied as a function of the number of $n$-pulses in a Carr-Purcell-Melburn-Gill (CPMG) dynamical decoupling sequence. In this system, the dominant forms of dephasing are expected to be hyperfine coupling to the nuclei and electrical noise. For $n_B$ ranging from 2 to 32, we find a power law dependence of $T_2^\ast$ by measuring the number of pulses, $T_2 \propto n_B^{\beta}$, where $n_B$ is the number of pulses and $\beta \sim 0.7$ is a fit parameter.

*Support from iARPA, Department of Defense*
8:24AM V27.00003 The central spin problem: electron spin qubit evolution due to coherently evolving nuclear spins. IZHAR NEDER, MARK RUDNER, HENDRIK BLUHM, BERTRAND HALPERIN, AMIR YACOBY, Harvard University — In recent years, electron spin qubits in solid state quantum dots have emerged as promising candidates for the implementation of quantum information processing. We study the dephasing of two electron spins in a double quantum dot system due to the evolution of the underlying nuclear spins, as was measured in a recent spin echo experiments. We develop a semi-classical model for such a system, by treating the Overhauser field induced by the nuclear spins as a classical time-dependent vector. Comparing the outcome of this model to experimental echo signal of the electron qubit allows us to identify MNR-like signatures from the nuclear spin evolution, such as spin diffusion, coherent nuclear Larmor precession and the spread of the Larmor frequencies by various mechanisms.


8:36AM V27.00004 Generating Entanglement and Squeezed States of Nuclear Spins in Quantum Dots, MARK RUDNER, Harvard University, LIJEVEN VANDERSYPEN, TU Delft, VLADAN VULETIC, LEONID LEVITOV, MIT — Entanglement generation and detection are two of the most sought-after goals in the field of quantum control. Besides offering a means to probe some of the most peculiar and fundamental aspects of quantum mechanics, entanglement in many-body systems can be used as a tool to reduce fluctuations below the standard quantum limit. For spins, or spin-like systems, such a reduction of fluctuations can be realized with so-called squeezed states [1]. Here we present a scheme for achieving coherent spin squeezing of nuclear spin states in single electron quantum dots [2]. This work represents a major shift from earlier studies, which have explored classical “narrowing” of the nuclear polarization distribution through feedback involving stochastic spin flips. In contrast, we use the nuclear-polarization-dependence of the electron spin resonance (ESR) line to provide a non-linearity which generates a non-trivial, area-preserving, “twisting” dynamics which squeezes and stretches the nuclear spin Wigner distribution without the need for nuclear spin flips.

8:48AM V27.00005 Dephasing of two-spin qubits due to their charge and nuclear environments1, GUY RAMON, Santa Clara University — We consider dephasing of qubits encoded in the singlet and unpolarized triplet states of pairs of spins localized in biased double quantum dots. The charge environment is modeled by both two-center charge traps in the insulator (where electrons tunnel between the two centers), and single charge traps located near the gate electrodes and QPCs (where electrons charge and empty the trap). The couplings of these trapped charges to the qubits are calculated by considering their charge distributions within a multipole expansion. It is demonstrated that the summation over these random telegraph processes in mesoscopic devices results in non-Markovian and non-Gaussian noise. For the nuclear environment we consider hyperfine-induced electron-spin dephasing in a nuclear spin bath with narrowed distribution. Nuclear state preparation using dynamical polarization cycles was experimentally achieved recently, and it is also essential to enable $X$-rotations for two-spin qubits. Our analysis is performed for both free induction and echo signals. The scaling of these dephasing mechanisms with the number of qubits is also discussed.

1Supported by Research Corporation

9:00AM V27.00006 Noisy (spin) neighbors of a solid state (spin) qubit1, WAYNE WITZEL, MALCOLM CARROLL, Sandia National Laboratories, NM, LUKASZ CYWINSKI, Institute of Physics, Polish Academy of Sciences, SANKAR DAS SARMA, University of Maryland, College Park — Powerful computational methods have been developed in recent years for understanding decoherence induced by environmental spins. Specifically, the cluster correlation expansion [Phys. Rev. B 78, 085315 (2008)] and adaptations [Phys. Rev. Lett. 105, 187602 (2010)] provide successive approximations that approach the solution to the full quantum mechanical problem for small and large spin baths with good efficiency. We present our findings from these computations. These have implications for solid state spin qubit fabrication and materials choices. In silicon where nuclear spins may be eliminated through isotopic enrichment, we consider other sources of bath spins in the bulk and near interfaces. We also investigate the conditions under which we may abstract out an approximate noise model that is independent of operations applied to the qubit.

1Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL850

9:12AM V27.00007 Competing effects of hyperfine and spin-orbit interactions in two-electron spin qubits1, ERNESTO COTA, Centro de Nanociencias y Nanotecnología, UNAM, Ensenada, Mexico, SERGIO ULLO, Ohio University — We analyze the dynamics of a double quantum dot system with two electrons in a uniform magnetic field, taking into account the hyperfine interaction as well as the interdot tunneling-induced Rashba spin-orbit coupling. The former mixes the singlet and triplet (1,1) states while the latter accounts for mixing triplet states and the doubly occupied (0,2) singlet. We focus on the effects on experimental results in GaAs dots [1], involving the generation and control of a nuclear environment. We study the dephasing of two electron spins in a double quantum dot system due to the evolution of the underlying nuclear spins, as was measured in a recent spin echo experiments. We develop a semi-classical model for such a system, by treating the Overhauser field induced by the nuclear spins as a classical time-dependent vector. Comparing the outcome of this model to experimental echo signal of the electron qubit allows us to identify MNR-like signatures from the nuclear spin evolution, such as spin diffusion, coherent nuclear Larmor precession and the spread of the Larmor frequencies by various mechanisms.


9:24AM V27.00008 Two-electron spin relaxation in double quantum dots and P donors1. CHIA-WEI HUANG, Department of Physics, Bar-Ilan University, Ramat Gan, 52900, Israel, MASSOUD BORHANI, XUEDONG HU, Department of Physics, University at Buffalo, SUNY, Buffalo, NY 14260-1500, USA — We study singlet-triplet relaxation of two electrons confined in a double quantum dot or bound to P donors in Silicon. Hyperfine interaction of the electrons with the host/phosphorus nuclei, in combination with the electron-phonon interaction, leads to relaxation of the triplet states. We calculate the triple spin relaxation rates in the presence of an applied magnetic field. This relaxation mechanism affects, for example, the resonance peaks in current Electron Spin Resonance (ESR) experiments on P-dimers. Moreover, the estimated time scales for the spin decay put an upper bound on the gate pulses needed to perform fault-tolerant two-qubit operations in spin-based quantum computers. We have found the optimal regimes, which mitigate this relaxation mechanism, yet permit sufficiently fast two-qubit operations.

1We thank support by NSA/LPS thorough ARO.
We have obtained a generic form for the spin Hamiltonian for two electrons confined in (elliptic) harmonic potentials in doubles dots and in the presence of an arbitrary applied magnetic field. Our focus is on the interdot bias regime where singlet-triplet splitting is small, in contrast to the spin-blockade regime. Our results clarify the spin-orbit mediated two-spin relaxation in lateral/nanowire quantum dots, particularly when the confining potentials are different in each dot.

We thank support by NSA/LPS thorough ARO.


The work was supported by the Research Grant Council of Hong Kong.

1. Work (EB) supported by LPS-CMTC and CNAM
8:12AM V29.00002 Exact, Floquet-based, Single Qubit Control1. ANDREW SORNBORGER, University of Georgia, EMILY PRITCHETT, Institute for Quantum Computing — Single-qubit gate design using oscillatory controls is related to the Rabi problem of rotating a spin. In the classical solution one drives the spin with an oscillatory electromagnetic field orthogonal to a background field. Here, we introduce a new, general method for constructing continuous, oscillatory quantum controls based on Floquet’s theorem. We then derive a family of exact, analytical solutions to the generalized Rabi problem of completely controlling a single-qubit in a fixed background field.

1 NSF 1029764, NSF 0939853

8:24AM V29.00003 Protection of quantum systems by nested Uhrig dynamical decoupling1. ZHEN-YU WANG, REN-BAO LIU, Department of Physics, The Chinese University of Hong Kong — Based on a theorem we establish on dynamical decoupling of multi-dependent systems, we present a scheme of nested Uhrig dynamical decoupling (NUDD) to protect multi-qubit systems in generic quantum baths to arbitrary decoupling orders. This scheme uses only single-qubit operations. Higher order decoupling is achieved at the cost of a polynomial increase in pulse number. For general multi-level systems, this scheme protects a set of unitary Hermitian system operators which mutually either commute or anti-commute, and hence all operators in the Lie algebra generated from this set of operators, generating an effective symmetry group for the system up to a given order of precision. We also show how to implement NUDD with pulses of finite amplitude, up to an error in the second order of the pulse durations.

1 This work was supported by Hong Kong GRF CUHK402209.

8:36AM V29.00004 Quantum noise of an electromagnetically controlled two level system. CHING-KIT CHAN, L.J. SHAM, Department of Physics, University of California San Diego — A coherent control of a spin is limited by both the decoherence due to coupling with the environment and noise coming from the quantized control. A quantum noise study is particularly important in fault tolerant quantum computation where a very high fidelity is demanded. Here, we present a time evolution study of a two level system interacting with a laser pulse and the electromagnetic vacuum based on the multimode Jaynes- Cummings model. We develop a diagrammatic formalism in which one can easily identify the coherent Rabi oscillation of the TLS and its relaxation from corresponding diagrams. In the small time limit (T ≪ t), where the noise level is small but still an issue to fault tolerant quantum computing, this method gives a quantitative evaluation of the quantum noise of the TLS under an optical control with an arbitrary pulse shape. Furthermore, this approach can be naturally extended from the Markovian to the non-Markovian regime, resulting in dynamics different from that obtained in the optical Bloch analysis. All these calculations are done without any stochastic assumption.

8:48AM V29.00005 Optimal control of an ensemble of atoms in an optical lattice1. BOTAN KHANI, SETH MERKEL, JAY GAMBETTA, FELIX MOTZOI, FRANK K. WILHELM, University of Waterloo, QUANTUM DEVICE THEORY GROUP TEAM — Controlling quantum systems in a manner that is robust to experimental errors and inhomogeneities is vital for practical realization of quantum gates. We demonstrate numerically the control of motional degrees of freedom of an ensemble of neutral atoms in an optical lattice of shallow trapping potential. Taking into account the range of quasi-momenta across different Brillouin zones results in an ensemble whose members effectively have inhomogeneous control fields as well as spectrally distinct control Hamiltonians. We present a modified optimal control technique that yields high fidelity control pulses, irrespective of quasi-momentum, with average fidelities above 90%. The resultant controls show a broadband spectrum with gate times in the order of several Rabi oscillations.

1 Work supported by NSERC discovery grants, quantumworks, SHARCNET, and IARPA-MQCO. Jay Gambetta was supported by CIFAR, MRI, MITACS, NSERC, and DARPA.

9:00AM V29.00006 High Fidelity State Transfer Over an Unmodulated Linear XY Spin Chain. C. ALLEN, BISHOP, Department of Physics, Southern Illinois University Carbondale, YONG-CHENG OU, Department of Physics, Texas Tech University, ZHAO-MING WANG, Department of Physics, Ocean University of China, MARK BYRD, Department of Physics, Southern Illinois University Carbondale — We provide a class of initial encodings that can be sent with a high fidelity over an unmodulated, linear, XY spin chain. As an example, an average fidelity of 96% can be obtained using an 11-spin encoding to transmit a state over a chain containing 10,000 spins. An analysis of the magnetic-field dependence is given, and conditions for field optimization are provided.

9:12AM V29.00007 Geometric Phase Gates via Adiabatic Control Using Electron Spin Resonance. HUA WU, ERIK GAUGER, Department of Materials, Oxford University, Oxford OX1 3PH, UK, RICHARD GEORGE, Clarendon Laboratory, Department of Physics, Oxford University, Oxford OX1 3PU, UK, JOHN MORTON, Department of Materials, Oxford University, Oxford OX1 3PH, UK, MIKKO MÖTTÖNEN, 1)Department of Applied Physics/COMP, Aalto University, FI-00076 AALTO, Finland 2)Low Temperature Laboratory, Aalto University, FI-00076 AALTO Finland — High fidelity operations are essential elements of quantum information processing. In contrast with the dynamic pulses that are routinely used in electron spin resonance for spin qubit manipulation, geometric phase gates achieved via adiabatic control are less sensitive to certain kinds of noise and field inhomogeneities. Here, we employ theoretical and numerical tools to show that these geometric operations can be realized in electron spin systems with greater fidelities than composite dynamic pulses for large inhomogeneities in the microwave field. We further show that the adiabatic geometric phase is robust against fast fluctuations in the static magnetic field. Finally, we investigate adiabatic geometric phase operations experimentally, showing that we are able to apply such robust phase gates to the electron spin on the microseconds timescale.

9:24AM V29.00008 Nanoscale control of individual proximal NV spins via a scanning magnetic field-gradient. MICHAEL GRINDOLS, PATRICK MALETINSKY, SUNKUN HONG, MIKHAIL LUKIN, RONALD WALSWORTH, AMIR YACOBY, Harvard University — Nanoscale ensembles of nitrogen-vacancy (NV) spins have been proposed for implementing quantum information protocols as well as performing sensitive nanoscale magnetometry. However, it has proven experimentally difficult to control individual NV spins without affecting the state of other, proximal spins, as spins are read-out optically and are often collectively driven by applied radio-frequency fields. We demonstrate that single-spin control in NV-spin ensembles can be achieved via a scanning magnetic field-gradient, which locally splits the electron spin resonances of proximal NVs. With this method, we achieve 9 nm spatial resolutions in imaging, characterization, and simultaneous manipulation of individual NVs, roughly two orders of magnitude better than the optical diffraction limit. We discuss applications of this individual control such as creating entangled spin-states and performing sensitive magnetometry.
9:36AM V29.00009 Nested Uhrig Dynamical Decoupling with Non-uniform Error Suppression
GREGORY QUIROZ, DANIEL LIDAR, University of Southern California — Here the performance of Nested Uhrig Dynamical Decoupling (NUDD) for qubit systems is analyzed when error suppression is non-uniform. The error suppression provided by NUDD is controlled by the sequence order of each nested sequence. The properties of the error suppression are characterized with respect to varying sequence order to verify the expected error suppression scaling of UDD, order $N = 1$. Error suppression with respect to the total time of evolution for an $N$th order sequence. The system operators present in the system-environment evolution are isolated and used to quantify the order of error suppression associated with each system error operator. Using this as a measurement, error suppression is examined with respect to the strength of system-environment interaction, as well as the pure bath strength. In the case of single-qubit NUDD, known as Quadratic Dynamical Decoupling (QDD), the results show that the error suppression provided by the inner sequence scales exactly with that of UDD, while the outer sequence dynamics leads to error suppression greater than or equal to that expected from UDD. These results can be extended to multi-qubit systems where the error suppression scaling for the inner sequence applied to each qubit follows that of UDD and the outer sequence applied to each qubit gives an error suppression greater than or equal to $N + 1$. 

9:48AM V29.00010 Pulsed Quantum Optomechanics
MICHAEL R. VANNER, University of Vienna, IGOR PIKOVSKI, GARRETT D. COLE, MYUNGSHIK KIM, CASLAV BRUKNER, KLEMMENS HAMMERER, GERALD J. MILBURN, MARKUS ASPELMeyer — By combining quantum optics with mechanical resonators an avenue is opened to extend investigations of quantum behavior into unprecedented mass regimes. The field resulting from this combination - “cavity quantum optomechanics” - is receiving a surge of interest for its potential to contribute to quantum measurement and control, studies of decoherence and non-classical state preparation of macroscopic objects. However, quantum state preparation and especially quantum state reconstruction of mechanical oscillators is currently a significant challenge. We are pursuing a scheme that employs short optical pulses to realize quantum state tomography, squeezing via measurement and state purification of a mechanical resonator. The pulsed scheme has considerable resilience to initial thermal occupation, provides a promising means to explore the quantum nature of massive oscillators and can be applied to other systems such as trapped ions. Our theoretical proposal and experimental results will be discussed.

10:00AM V29.00011 Quantum measurement with Mach-Zehnder Interferometer
YUNJIN CHOI, JUSTIN DRESSEL, ANDREW JORDAN, University of Rochester — We use an electronic Mach-Zehnder Interferometer (MZI) as a measurement device. We perform a measurement on a system by coupling with MZI using a phase shift induced by Coulombic coupling. By reading current and noise cross-correlations, strange conditioned averages can be constructed using the contextual values technique.

10:12AM V29.00012 Continuous phase amplification with a Sagnac interferometer
NATHAN WILLIAMS, DAVID STARLING, BEN DIXON, ANDREW JORDAN, JOHN HOWELL, University of Rochester — We describe a weak value inspired phase amplification technique in a Sagnac interferometer. We monitor the relative phase between two paths of a slightly misaligned interferometer by measuring the average position of a split-Gaussian mode in the dark port. Although we monitor only the dark port, we show that the signal varies linearly with phase and that we can obtain similar sensitivity to balanced homodyne detection. We derive the source of the amplification both with classical wave optics and as an inverse weak value.

10:24AM V29.00013 Conservation of Vacuum in an Interferometer
DOMINIC BERRY, University of Waterloo, ALEXANDER LOVSKY, University of Calgary — Source efficiency and photon loss are major problems in optical metrology and quantum information. To understand how to address these, we need to explore these questions through interferometry. In this work, we describe a technique to measure correlation functions in a simple interferometer. We have developed a theory for the behavior of loss under LO processing, resolving many long-standing questions from previous work [1,2]. In particular, we have shown that, provided the efficiency of the sources is appropriately quantified, the efficiency of the state in any single mode cannot be increased beyond that of the highest-efficiency mode available at the input [1]. It is also not possible to increase efficiency in a catalytic way, using some high-efficiency modes to increase the efficiency of other modes [2]. The results provide a powerful unifying framework for quantifying efficiency by the incoherent vacuum contribution to optical states, even when entangled over multiple modes. The amount of vacuum is invariant under interferometers, and can only be increased by measurement.

10:36AM V29.00014 Dynamics of entanglement in two-dimensional spin system
QING XU, SABRE KAIS, Purdue University, GEHAD SADIEK, King Saud University and Ain Shams University — We consider the time evolution of entanglement in a finite two dimensional transverse Ising model. The model consists of a set of $N$ localized spin-$1/2$ particles in a two dimensional triangular lattice coupled through exchange interaction $J$ in presence of an external time dependent magnetic field $H(t)$. The magnetic field is presented in various function forms. We find that the magnetic field with sudden change does not provide a way to control or tuning the entanglement. While for the smoothly changing field, when its the character frequency is small, entanglement tends to follow the change of external magnetic field; when it gets larger, entanglement gradually loses pace with the field. It is also shown that the mixing of even a few excited states by small thermal fluctuation is devastating to the entanglement of the ground state.


10:48AM V29.00015 Probing Majorana edge states with a qubit
CHANG-YU HOU, FABIAN HASSLER, Institute Lorentz, Leiden University, JOHAN NILSSON, Department of Physics, University of Gothenburg, ANTON AKHMEROV, Institute Lorentz, Leiden University — A pair of counter-propagating Majorana edge modes can be described by an Ising conformal field theory. These modes appear in a chiral $p$-wave superconductor or in some superconducting system belonging to the same universality class. We show how a superconducting flux qubit attached to a such system couples to the two chiral edge modes via the disorder field of the Ising model. Thus, measuring the back-action of the edge states on the qubit allows to probe the properties of Majorana edge modes.

Thursday, March 24, 2011 11:15AM - 2:15PM —
Session W27 GQI: Focus Session: Semiconductor Qubits- Optical Control, Donors, and Hybrid Systems
C155

11:15AM W27.00001 Ultrafast optical entanglement control between two quantum dot spins
SAM CARTER, DANNY KIM, ALEX GRELICH, ALLAN BRACKER, DANIEL GAMMON, Naval Research Laboratory — A single electron spin in an InAs quantum dot is very attractive as a qubit since this system is potentially scalable and allows complete quantum control on an ultrafast timescale using optical pulses. While great progress has been achieved with single spin qubits, it is essential for quantum information applications to move toward entangled multi-qubit systems. Two-qubit systems have been studied in electrostatically-defined quantum dots, but their optical functionality remains unexplored. Here we demonstrate ultrafast optical control of two interacting qubits consisting of two electron spins in separate InAs dots. We initialize the system into a spin singlet state using a cw laser. We then manipulate the entangled state of the two spins with single qubit gates (acting only on one spin) by using pulses faster than the exchange interaction. This allows us to generate all four Bell states. Two-qubit gates are obtained either by the natural exchange precession or by using a longer laser pulse that induces a phase shift in the precession. The two-qubit exchange rate (30 GHz) here gives SWAP gate times of 16 ps, the fastest of any candidate for quantum information processing.
11:27AM W27.00002 Complete ultrafast optical coherence control and spin echo of single InAs quantum dot spins . KRISTIAAN DE GREVE, PETER MCMAHON, DAVID PRESS, Ginzt Lab, Stanford University, THADDEUS LADD1, Ginzt Labs, Stanford University and National Institute of Informatics (NII), Tokyo, CHRISTIAN SCHNEIDER, DIRK BISPING, MARTIN KAMP, Lukas WORSCHECH, Sven Hoefling, Alfred Forchel, Technische Physik, Physikalisches Institut, Wilhelm Conrad Röntgen Research Center for Complex Material Systems, Universität Würzburg, Yoshihisa Yamamoto, Ginzt Labs, Stanford University and National Institute of Informatics (NII), Tokyo — We report on recent progress on the complete ultrafast optical coherence control of individual InAs quantum dot spin qubits. We demonstrate Rabi-oscillations and Ramsey-fringes, and implement a spin echo to overcome time-averaged dephasing. We probe the hyperfine interaction of a single spin using optical pulse control. Interesting non-Markovian dynamics could be observed in the single electron spin free-induction decay, resulting from feedback between the strong electron spin Overhauser shift and spin dependent nuclear relaxation. 2

1 currently at HRL Laboratories, LLC, Malibu, CA 90265

11:39AM W27.00003 Control of quantum dot relaxation channels in quantum dot molecules , KUSHAL C. WIESUNDARA, JUAN E. ROLON, SERGIO E. ULLAOA, ERIC A. STINAFF, Department of Physics and Astronomy, and Nanoscience and Quantum Phenomena Institute, Ohio University, Athens, OH 45701, USA, ALLAN BRACKER, DAN GAMMON, Naval Research Laboratory, Washington, DC 20375, USA — We observe modulation in radiative lifetimes and intensities of the spatially indirect exciton as the InAs/GaAs coupled quantum dot system is tuned between molecular and atomic-like states. With standard time-resolved single photon counting techniques the measured lifetimes were found to vary between 0.3 and 2.0 ns which resulted in modulations of the observed photoluminescence intensity of the indirect exciton. These modulations can be attributed to phonon-mediated relaxations and carrier tunneling processes in good agreement with the modeled results. We clearly see the structure of the acoustic phonon distribution as shown in recent theoretical predictions. Tuning the relative energy levels in coupled quantum dots results in controllable modulation of exciton relaxation channels that may provide new directions in engineering decoherence in these systems.

11:51AM W27.00004 Charge dynamics and phonon induced oscillatory relaxation rates of indirect excitons in quantum dot molecules1, J.E. ROLON, K.C. WIESUNDARA, E.A. STINAFF, S.E. ULLOAO, Ohio University — Optoelectronic control of quantum dot is a thriving area of research with impact on fundamental physics and quantum information devices. Time-resolved photoluminescence experiments, carried out in charge-tunable coupled quantum dots, have demonstrated non-Markovian behavior of neutral indirect exciton lifetimes over a wide range of applied electric fields [1]. We present a model for neutral indirect exciton lifetimes in electric field tunable quantum dot molecules. Our model includes field-dependent oscillatory phonon-induced relaxation rates [2], carrier tunneling rates, and carrier relaxation into nearby charged exciton states. To this end we have used a multi-excitonic Hamiltonian, and calculated the exciton population dynamics using a master equation with electric field dependent rates. We find that lifetime suppression is dominated by scattering with LA phonons at low fields, and that the maximum lifetime gain information on the effective dimension of the molecule. In contrast, at high fields the lifetime suppression is dominated by the interplay of carrier population exchange with nearby charged excitons. This prompts for ways of controlling exciton lifetimes and possible decoherence in quantum dots. [1] K. C. Wijesundara et al., (unpublished), [2] J. I. Clemente et al., Phys. Rev. B 74, 035313 (2006).

1Supported by CONACYT and NSF PIRE and MWN/CIAM.

12:03PM W27.00005 Ultralong Coherence of Phosphorus Donors in High-Purity 28Si Silicon . S.A. LYON, A.M. TYRSHSKIN, Princeton University, S. TOJO, K.M. ITOH, Keio University, J.J.L. MORTON, Oxford University, T. SCHENKEL, Lawrence Berkeley National Laboratory, M.L.W. THEWALT, Simon Fraser University, H. RIEMANN, N.V. ABROSIMOY, Institute for Crystal Growth, IKZ, P. BECKER, PTB Braunschweig, H.-J. POHL, VITCON Projectconsult GmbH — We report on electron spin coherence measurements for phosphorus donors in high purity, highly-enriched 28Si, with residual 29Si of less than 50 ppm. At this low 29Si density, spectral diffusion processes by nuclear spin flip-flops are suppressed, and therefore other relaxation processes become prominent. By examining a series of 28Si crystals with a donor concentration of 1×10^14 to 3×10^15/cm^3, we identified three decoherence mechanisms, all related to dipole interactions between donors: (1) instantaneous diffusion, caused by flips of donor spins induced by the applied microwave pulse; (2) spectral diffusion caused by T1- induced flips of neighboring donors; (3) spectral diffusion caused by donor spin flip-flips. We demonstrate how all three mechanisms can be suppressed, leading to measured coherence times extrapolating to T2~10 sec. The work was funded by DOE and LPS.

12:15PM W27.00006 Electrical Control of the high spin system Mn2+ in ZnO , RICHARD GEORGE, JOHN MORTON, ARZHANG ARDAVAN, University of Oxford, JAMES EDWARDS, University of Cambridge — We examine the high spin impurity Mn2+ in single crystal ZnO (5=5/2, l=5/2), and report a strong linear coupling (K = 52.3 rad/V/m) of the manganese electrical and magnetic moments that preserves quantum coherence. We combine pulsed EPR and electric field techniques to manipulate the Mn states and study electron spin lifetimes, finding interesting non-Markovian dynamics could be observed in the single electron spin free-induction decay, resulting from feedback between the strong electron spin Overhauser shift and spin dependent nuclear relaxation. We report on recent progress on the complete ultrafast optical coherence control of individual InAs quantum dot spin qubits. We demonstrate Rabi-oscillations and Ramsey-fringes, and implement a spin echo to overcome time-averaged dephasing. We probe the hyperfine interaction of a single spin using optical pulse control. Interesting non-Markovian dynamics could be observed in the single electron spin free-induction decay, resulting from feedback between the strong electron spin Overhauser shift and spin dependent nuclear relaxation.

12:27PM W27.00007 Electron spin coherence and electron nuclear double resonance of Bi donors in natural Si , JOHN MORTON, STEPHANIE SIMMONS, RICHARD GEORGE, Oxford University, WAYNE WITZEL, Sandia National Labs, H. RIEMANN, NIKOLAI ABROSIMOY, N. NOTZEL, Institute for Crystal Growth, Berlin, MIKE THEWALT, Simon Fraser University — We have shown that the electron spin coherence times of Si:Bi donors in natural silicon are limited by the same mechanism of spectral diffusion as seen in Si:P, though the smaller Bohr radius of the Bi donor leads to ~30% shorter T2* times (up to 0.8 ms). We have mapped out the 3 ENDOR transitions observable at X-band arising from the I = 9/2 nuclear spin of 209Bi, going up to 1.3 GHz. We also demonstrate the transfer of electron spin coherence to and from the 209Bi nuclear spin with a fidelity of ~ 60%. Using pulsed ESR at W-band (100 GHz), we observe optically-induced dynamic nuclear polarization, consistent with the mechanism of exciton capture proposed in by T. Sekiguchi et al. Finally, we explore the zero-field splitting of 7.5 GHz in this system, within the context of coupling to superconducting resonators.

12:39PM W27.00008 Neutral donors interacting with a two-dimensional electron gas measured by electrically detected magnetic resonance up to 94GHz . C.C. LO, J. BOKOR, University of California, Berkeley, V. LANG, R.E. GEORGE, J.J.L. MORTON, University of Oxford, A.M. TYRSHSKIN, S.A. LYON, Princeton University, T. SCHENKEL, Lawrence Berkeley National Laboratory — Electrically detected magnetic resonance of a silicon field-effect transistor with channel-implanted donors is measured in a W-band (94 GHz, 3.36 T) resonant microwave cavity. It is found that the two-dimensional electron gas (2DEG) resonance signal intensity increases by two orders of magnitude compared with conventional low-field X-band (9.7 GHz, 0.35 T) measurements. On the other hand, the neutral donor resonance signals increase by over one order of magnitude. We interpret the results in terms of direct spin-dependent scattering and a polarization transfer from the donors to the 2DEG spin system.
12:51PM W27.00009 Electrical Manipulation of Spin Qubits in Li-doped Si. ANDRE PETUKHOV, LUKE PENDO, ERIN HANDBERG, South Dakota School of Mines, VADIM SMELYANSKY, NASA Ames Research Center — We propose a complete quantum computing scheme based on Li donors in Si under external biaxial stress. The qubits are encoded on the ground state Zeeman doublets and coupled via long-range spin-spin interaction mediated by acoustic phonons. This interaction is unique for Li donors in Si due to their inverted electronic structure. Our scheme takes advantage of the fact that the energy level spacing in a Li donor manifold is comparable with the magnitude of the spin-orbit interaction. As a result the Li spin qubits can be placed 100 nm apart and manipulated by a combination of external electric field and microwave field impulses. We present a specially-designed sequence of the electric field impulses which allows for a typical time of a two-qubit gate $\sim 1 \mu$s and a quality factor $\sim 10^{-6}$. These estimates are derived from detailed microscopic calculations of the quadratic Stark effect and electron-phonon decoherence times.

1:03PM W27.00010 Entanglement in a Solid State Spin Ensemble. STEPHANIE SIMMONS, RICHARD BROWN, Oxford University, HELGE RIEMMAN, NIKOLAI ABROSIMOV, Leibniz Institut, PETER BECKER, PTB Braunschweig, HANS-JOACHIM POHL, VITCON Projectconsult GmbH, MIKE THEWALT, Simon Fraser University, KOHEI ITOH, Keio University, JOHN MORTON, Oxford University — Entanglement is a both a fascinating phenomenon and a critical ingredient in most emerging quantum technologies. Spin ensembles manipulated using magnetic resonance have demonstrated the most advanced quantum algorithms to date, however in an effort to describe no entanglement. We present candidate structures for lateral charge control of image potential surface electrons over negative electron affinity diamond are examined. Image potential surface electron states, located spatially outside the semiconductor heterostructure. The region containing the drain is p-doped. The configuration of the intrinsic region is designed to trap a single pair of electron and hole; this is due to Pauli Exclusion Principle and Coulomb blockage. This is achieved by applying a reverse voltage to neutralize the intrinsic electric field to its ground state and the observed homodyne tomography of the emitted photon can yield information about the qubit state of the emitter. Though the characteristic lifetime of photon emission is traditionally modeled via the Weisskopf-Wigner approximation, we seek to model the fully quantized spontaneous emission, including near field effects, of a photon from the excited state of a quantum dot beyond the Markovian limit. We further investigate subsequent interactions between the emitted photon and adjacent quantum dots in an effort to describe multipartite entanglement. We propose the use of discretized central-difference approximations of space and time partial derivatives, similar to finite-difference time domain models, to describe single photon states via single photon operators. Additionally, within the future scope of this model, we seek results in the Purcell and Rabi regimes for spontaneous emission events from quantum dots embedded in micro-cavities.

1:15PM W27.00011 Optimized Electron-spin-cavity coupling in a double quantum dot1. XUEDONG HU, University at Buffalo, SUNY, YU-XI LIU, Tsinghua University, China, FRANCO NORI, RIKEN, Japan — We search for the optimal regime to couple an electron spin in a semiconductor double quantum dot to a superconducting stripline resonator via the electrically driven spin resonance technique. In particular, we calculate the spin relaxation rate in the regime when spin-photon coupling is strong, so that we can identify system parameters that allow the electron spin to reach the strong coupling limit.

1:27PM W27.00012 Near Field Photon Emission and Revival in Quantum Dot Qubits1. S. TAFUR, M.N. LEUENBERGER, Dept of Physics, University of Central Florida — Modeling the spontaneous emission of photons coupled to the electronic states of quantum dots is important for understanding quantum interactions and entanglement in condensed matter as applied to proposed solid-state quantum computers, quantum networks, single photon emitters, and single photon detectors. A quantum dot in an excited state can be experimentally observed to decay to its ground state and the observed homodyne tomography of the emitted photon can yield information about the qubit state of the emitter. Through the characteristic lifetime of photon emission is traditionally modeled via the Weisskopf-Wigner approximation, we seek to model the fully quantized spontaneous emission, including near field effects, of a photon from the excited state of a quantum dot beyond the Markovian limit. We further investigate subsequent interactions between the emitted photon and adjacent quantum dots in an effort to describe multipartite entanglement. We propose the use of discretized central-difference approximations of space and time partial derivatives, similar to finite-difference time domain models, to describe single photon states via single photon operators. Additionally, within the future scope of this model, we seek results in the Purcell and Rabi regimes for spontaneous emission events from quantum dots embedded in micro-cavities.

1:39PM W27.00013 A Theoretical Model of Single Photon Source at Room Temperature. AHMED ELHALAWANY, MICHAEL LEUENBERGER, University of Central Florida — In this work we present a theoretical model for an electrically injected single photon source at room temperature. The source is made of three regions. The region containing the source is n-doped, the middle region is an intrinsic semiconductor heterostructure. The region containing the drain is p-doped. The configuration of the intrinsic region is designed to trap a single pair of electron and hole; this is due to Pauli Exclusion Principle and Coulomb blockage. This is achieved by applying a reverse voltage to neutralize the intrinsic electric field between the n- and p-doped regions. Based on the calculated tunneling time of the electron/hole, the reverse voltage will be switched on. For the kinetics at the room temperature operation is calculated by means of the Master equations. For this we use an effective Hamiltonian in the tight-binding approximation. The results show that a single electron and a single hole are trapped simultaneously for an adequate period of time until they recombine.

1:51PM W27.00014 Phonons and solid-state qubits for quantum technology. Ö.Ö. SOYKAL, RUSKOV, University of Maryland, College Park, MD 20742, CHARLES TAHAN, Laboratory for Physical Sciences, College Park, MD 20740 — Phonons in the context of quantum information processing are traditionally negatives. They induce relaxation or decoherence of or between qubit states. Learning to control phonons for positive purposes, both as supporting technology for quantum information processing, and for other quantum devices is of great possible interest. Already, acoustic waves are used as a supporting technology in microelectronics and optoelectronics (e.g. their slow speed can be useful in certain contexts). Here we consider some methods for making phonons useful and describe the physics of such systems in several potential solid-state systems including silicon. Our results may also be of interest to the optomechanics community.

2:03PM W27.00015 Towards electrons floating over diamond1. M.P. RAY, J.W. BALDWIN, M.K. ZALALUTDINOV, J.L. SHAW, J.E. BUTLER, B.B. PATE, Naval Research Laboratory, T.I. FEYGELESON, SAIC Inc. — The opportunities for development of a 2D electron system of image potential surface electrons over negative affinity diamond are examined. Image potential surface electron states, located spatially outside the solid, are well established on a variety of surfaces (metals, semiconductors and dielectrics). In particular, laterally confined electrons above liquid helium have been demonstrated and proposed for advanced computing applications [1,2]. Unlike the surface of liquid helium, the electron affinity of the diamond surface can be varied [3], providing the ability to lithographically pattern surface electron ‘pools’ and ‘wires’. We present candidate structures for lateral charge control that make use of buried and surface features patterned in and on diamond. Electronic properties and spectroscopy of electrons over diamond in our fabricated structures are discussed.


1Work supported by the Office of Naval Research.
11:15AM W29.00001 Pairwise complementary observables and their mutually unbiased bases.

BERGE ENGLERT, National University of Singapore — Pairs of complementary observables (PCO) characterize all quantum degrees of freedom and are central to a technical formulation of Bohr’s principle of complementarity. A defining property of such pairs are their mutually unbiased bases (MUB) of eigenstates. MUB have found many applications for tasks in quantum information processing. Maximal sets of PCO and MUB are known, by explicit construction, for degrees of freedom that live in finite-dimensional Hilbert space whose dimension is a power of a prime; continuous sets of MUB are also known for most continuous degrees of freedom. I will review the situation and mention a couple of open problems.

11:51AM W29.00002 Quantum States as Probabilities from Symmetric Informationally Complete Measurements1, ASA ERICSSON, Institute Mittag-Leffler — If you pick d2 symmetrically spread vectors in a d-dimensional Hilbert space, you get a symmetric informationally complete set of quantum states (or SIC for short). SICs have applications within quantum information science, such as to quantum state tomography and quantum cryptography, and are also of interest for foundational studies of quantum mechanics. In this talk I will review the representation of quantum states as probability distributions over the outcomes of a SIC measurement. Not all probability distributions correspond to quantum states, thus quantum state space is a restricted subset of all potentially available probabilities. We will explore how this restriction can be characterized. A recent publication (Fuchs and Schack, arXiv:0906.2187) advocates the SIC-representation and suggests that the Born rule rewritten in this language can be taken as a postulate for quantum mechanics. This motivates the introduction of so-called maximally consistent sets (Appleby, Ericsson, and Fuchs, arXiv:0910.2750); one such set is quantum state space.

1This work was supported in part by the U.S. Office of Naval Research (Grant No. N00014-09-1-0247).

12:27PM W29.00003 The Lie Algebraic Significance of Symmetric Informationally Complete Measurements, STEVEN FLAMMIA, Caltech — Examples of symmetric informationally complete positive operator valued measures (SIC-POVMs) have been constructed in every dimension less than 68. However, it remains an open question whether they exist in all finite dimensions. A SIC-POVM is usually thought of as a highly symmetric structure in quantum state space. However, its elements can equally well be regarded as a basis for the Lie algebra g(d,C). We examine the resulting structure constants, which are calculated from the traces of the triple products of the SIC-POVM elements and which, it turns out, characterize the SIC-POVM up to unitary equivalence. We show that the structure constants have numerous remarkable properties. In particular we show that the existence of a SIC-POVM in dimension d is equivalent to the existence of a certain structure in the adjoint representation of g(d,C). We hope that transforming the problem in this way, from a question about quantum state space to a question about Lie algebras, may help to make the existence problem tractable. This is joint work with M. Appleby and C. Fuchs.

1:03PM W29.00004 Experimental access to higher-dimensional discrete quantum systems, towards realizing SIC-POVM and MUB measurements, using integrated optics1, CHRISTOPH SCHAEFF, IQOQI — The aim of our work is to access and explore higher-dimensional photonic quantum systems. In terms of stability and complexity, normal bulk-optic setups greatly limit the capabilities of reaching higher-dimensional systems. However, the recent development in integrated photonic circuits has opened new possibilities [1]. Our approach is to use integrated photonic circuits on-chip, as well as in fiber, to reach photonic states of higher dimension. We are working toward a fully integrated realization of a multiport [2], a device which can apply any unitary transformation based on tunable internal parameters. Our first step is to realize a multiport in dimension four, implementing any unitary transformation on Qubits, Qutrits and Ququarts. Furthermore, we have built an integrated source using purely in-fiber components for creating higher-dimensional entangled photons. The combination of this source with the multipport yields a very general system applicable to a variety of experiments in higher dimensional Hilbert spaces. It is possible to realize different experimental setups by setting the device for different incoming entangled states, and subsequently applying unitary transformations. For example, this opens the possibility to observe new types of higher-order perfect correlations [3], or to realize full SIC-POVM measurements in higher dimensions.


1The research has been supported by ERC Advanced Grant QIT4QAD and FWF SFB-grant F4007.

1:39PM W29.00005 Isotropic States in Discrete Phase Space, WILLIAM WOOTTERS, Williams College — An energy eigenstate of a harmonic oscillator is isotropic in phase space, in the sense that the state looks the same along any ray emanating from the origin. It is energy eigenstate of a harmonic oscillator is isotropic in phase space, in the sense that the state looks the same along any ray emanating from the origin. It is possible to extend this notion of "isotropy" to quantum systems with finite-dimensional state spaces—the rays are then rays in discrete phase space. In this talk I present examples of discrete isotropic states and discuss their properties. One can show that every isotropic state minimizes a specific information-theoretic measure of uncertainty with respect to a complete set of mutually unbiased bases. Numerical results on a certain class of isotropic state vectors suggest that their components, in any of those same mutually unbiased bases, exhibit a semicircular distribution when the dimension of the state space is large.

Thursday, March 24, 2011 11:15AM - 2:15PM –
Session W29 GQI: Symmetric Discrete Structures for Finite Dimensional Quantum Systems C148

Thursday, March 24, 2011 2:30PM - 5:30PM –
Session X27 GQI: Quantum Computing and Simulation II C155

2:30PM X27.00001 Analysis of quantum Monte Carlo dynamics for quantum adiabatic evolution in infinite-range spin systems1, JUN-ICHI INOUE, Hokkaido University — We analytically derive deterministic equations of order parameters such as spontaneous magnetization in infinite-range quantum spin systems obeying quantum Monte Carlo dynamics. By means of the Trotter decomposition, we consider the transition probability of Glauber-type dynamics of microscopic states for the corresponding classical system. Under the static approximation, differential equations with respect to macroscopic order parameters are explicitly obtained from the master equation that describes the microscopic-law. We discuss several possible applications of our approach to disordered spin systems for statistical-mechanical informatics. Especially, we argue the ground state searching for infinite-range random spin systems via quantum adiabatic evolution.

1We were financially supported by Grant-in-Aid for Scientific Research (C) of Japan Society for the Promotion of Science, No. 22500195.
An Open-System Quantum Simulator with Trapped Ions.

JULIO T. BARREIRO, MARKUS MUELLER, PHILIPP SCHINDLER, DANIEL NIGG, THOMAS MONZ, MICHAEL CHWALLA, MARKUS HENNRICH, CHRISTIAN F. ROOS, PETER ZOLLER, Universitaet Innsbruck, RAINER BLATT — The control of quantum systems is of fundamental scientific interest and promises powerful applications and technologies. Improper progress has been achieved in isolating the systems from the environment and coherently controlling their dynamics, as demonstrated by the creation and manipulation of entanglement in various physical systems. However, for open quantum systems, engineering the dynamics of many particles by a controlled coupling to an environment remains largely unexplored. Here we report the first realization of a toolbox for simulating an open quantum system with up to five qubits. Using a quantum computing architecture with trapped ions, we combine multi-qubit gates with optical pumping to implement coherent spin interactions and the quantum non-demolition measurement of multi-qubit observables. By adding controlled dissipation to coherent operations, this work offers novel prospects for open-system quantum simulation and computation.

This work was supported in part by ARO and DOD (W911NF-09-1-0439). J.K.G. acknowledges support from the NSF.
We study the dynamics of quantum systems using discrete quantum walks on binary trees. These walks allow us to explore the effects of decoherence in quantum simulations by observing the evolution of the system when the Quantum Information Processor is coupled to the environment. We simulate the noise as the interactions between the particles of the processor itself and observe the effects of varying the strength of the couplings. We perform these calculations for different quantum systems and compare the results of those that interact with the environment to the same system when it's completely isolated from it to observe the effects of the noise on the simulation and investigate ways to prevent the adverse effects of the noise.

References:
1. NAGENDRA DHAKAL, MICHAEL LEUENBERGER, University of Central Florida — We developed new codes for simulating the Schrödinger equation and the Master equation.
2. We acknowledge support from NSF Grant No. ECCS-0901784 and AFSR Grant No. FA9550-09-1-0450.
3. 06:00PM X27.00014 Experimental photonic quantum simulation of frustrated Heisenberg spins

**4:06PM X27.00009 Discrete quantum walk on a binary tree**, ZLATKO DIMCOVIC, IAN MILLIGAN, DAN ROCKWELL, ROBERT M. BURTON, THINH NGUYEN, YEVGENIY KOVCHEGOV, Oregon State University — We recently constructed a framework for quantum walks, based on classical walks with memory. This framework reproduces known walks, while it can be used to build walks in systems that are difficult for current approaches. As our first example of its utility, we study a symmetric discrete quantum walk on the infinite binary tree. For a walk starting from a pure state at a given level in the tree, we compute the amplitude at the root, as a function of time and starting level. The result is strikingly different from the classical case, as its amplitude spans an order of magnitude, with a power law tail, while the classical one decays exponentially. (For example, for a delayed walk this property yields a polynomial vs. exponential speed up over the classical walk, in delay time.) The breadth of the probability peak indicates that any restriction of the extent of the tree, such as a matching tree, sinks or boundaries, would likely yield algorithms superior to classical. The calculation utilizes a variety of analytical techniques (memorized stochastic processes, combinatorics and path counting, transforms, steepest descent, orthogonal polynomials). This study also brings up interesting general questions about quantum processes on such structures.

References:
1. KENNETH RUDINGER, JOHN KING GAMBLE, MARK WELLONS, MARK FRIESEN, DONG ZHOU, ERIC BACH, ROBERT JOYNT, S.N. COPPERSMITH, University of Wisconsin-Madison — We investigate the quantum dynamics of particles on graphs ("quantum walks"), with the aim of developing quantum algorithms for determining if two graphs are isomorphic and show that there are fundamental differences between the distinguishing power of two-particle and three-particle non-interacting quantum walks. We investigate quantum walks on strongly regular graphs (SRGs), a class of graphs with high symmetry. We show analytically that the two-particle walk always fails to distinguish non-isomorphic members of the same SRG family. We show numerically that the three-boson walk is able to distinguish 99.6% of 70,712 SRG comparisons made and that this distinguishing power comes from different multiplicities of certain graph substructures in non-isomorphic graphs. We identify certain distinguishing substructures and examine ones that appear in the four-boson walk, discovering they are able to distinguish almost all of the graphs that the three-boson walk failed on. This indicates a positive correlation between the number of bosons in the walk and distinguishing power.

References:
1. This work was supported by ARO and DOD (W911NF-09-1-0439) and NSF (CCF-0635355). J.K.G. acknowledges support from the NSF.

**4:18PM X27.00010 Quantum Random Walks of Non-Interacting Bosons on Strongly Regular Graphs**, KENNETH RUDINGER, JOHN KING GAMBLE, MARK WELLONS, MARK FRIESEN, DONG ZHOU, ERIC BACH, ROBERT JOYNT, S.N. COPPERSMITH, University of Wisconsin-Madison — We investigate the quantum dynamics of particles on graphs ("quantum walks"), with the aim of developing quantum algorithms for determining if two graphs are isomorphic and show that there are fundamental differences between the distinguishing power of two-particle and three-particle non-interacting quantum walks. We investigate quantum walks on strongly regular graphs (SRGs), a class of graphs with high symmetry. We show analytically that the two-particle walk always fails to distinguish non-isomorphic members of the same SRG family. We show numerically that the three-boson walk is able to distinguish 99.6% of 70,712 SRG comparisons made and that this distinguishing power comes from different multiplicities of certain graph substructures in non-isomorphic graphs. We identify certain distinguishing substructures and examine ones that appear in the four-boson walk, discovering they are able to distinguish almost all of the graphs that the three-boson walk failed on. This indicates a positive correlation between the number of bosons in the walk and distinguishing power.

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1. KENNETH RUDINGER, JOHN KING GAMBLE, MARK WELLONS, MARK FRIESEN, DONG ZHOU, ERIC BACH, ROBERT JOYNT, S.N. COPPERSMITH, University of Wisconsin-Madison — We investigate the quantum dynamics of particles on graphs ("quantum walks"), with the aim of developing quantum algorithms for determining if two graphs are isomorphic and show that there are fundamental differences between the distinguishing power of two-particle and three-particle non-interacting quantum walks. We investigate quantum walks on strongly regular graphs (SRGs), a class of graphs with high symmetry. We show analytically that the two-particle walk always fails to distinguish non-isomorphic members of the same SRG family. We show numerically that the three-boson walk is able to distinguish 99.6% of 70,712 SRG comparisons made and that this distinguishing power comes from different multiplicities of certain graph substructures in non-isomorphic graphs. We identify certain distinguishing substructures and examine ones that appear in the four-boson walk, discovering they are able to distinguish almost all of the graphs that the three-boson walk failed on. This indicates a positive correlation between the number of bosons in the walk and distinguishing power.

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1. KENNETH RUDINGER, JOHN KING GAMBLE, MARK WELLONS, MARK FRIESEN, DONG ZHOU, ERIC BACH, ROBERT JOYNT, S.N. COPPERSMITH, University of Wisconsin-Madison — We investigate the quantum dynamics of particles on graphs ("quantum walks"), with the aim of developing quantum algorithms for determining if two graphs are isomorphic and show that there are fundamental differences between the distinguishing power of two-particle and three-particle non-interacting quantum walks. We investigate quantum walks on strongly regular graphs (SRGs), a class of graphs with high symmetry. We show analytically that the two-particle walk always fails to distinguish non-isomorphic members of the same SRG family. We show numerically that the three-boson walk is able to distinguish 99.6% of 70,712 SRG comparisons made and that this distinguishing power comes from different multiplicities of certain graph substructures in non-isomorphic graphs. We identify certain distinguishing substructures and examine ones that appear in the four-boson walk, discovering they are able to distinguish almost all of the graphs that the three-boson walk failed on. This indicates a positive correlation between the number of bosons in the walk and distinguishing power.
5:18PM X27.00015 A realistic topological quantum computation platform using hole-doped semiconductor nanowires and s-wave superconductors, MING GONG, LI MAO, Department of Physics and Astronomy, Washington State University, Pullman, Washington, 99164 USA, SJUMANTA TEWARI, Department of Physics and Astronomy, Clemson University, Clemson, South Carolina, 29634, USA, CHUANWEI ZHANG, Department of Physics and Astronomy, Washington State University, Pullman, Washington, 99164 USA, ZHANG TEAM, TEWARI TEAM — We show that two majorana fermions exist at the two ends of a hole-doped semiconductor nanowire that is in proximity contact with an s-wave superconductor. The required experimental parameters (carrier density, g-factor, spin-orbit coupling effect, magnetic field, etc.) for the observation of the Majorana fermions are within the experimentally reachable regime of InSb and InAs nanowires and the mini gap that provides the topological protection for the Majorana zero energy states is of the order of the s-wave superconducting gap. The Majorana zero energy states can be observed through the zero bias peak in the STM signal. The Josephson effects between two nanowire are studied. The proposed model provides a realistic experimental platform for observing non-Abelian statistics and performing topological quantum computation. This work is supported by DARP-MTO (FA955-10-1-0497), and DARPA-YFA (N66001-10-1-4025).

Thursday, March 24, 2011 2:30PM - 5:18PM –

Session X29 GQI: Focus Session: Quantum Information for Quantum Foundations - Information Measures, Entanglement, and Entropies C148

2:30PM X29.00001 ABSTRACT WITHDRAWN –

2:42PM X29.00002 Uncertainty Relation for Smooth Entropies, MARCO TOMAMICHEL, RENATO RENNER, ETH Zurich — Uncertainty relations give upper bounds on the accuracy by which the outcomes of two incompatible measurements can be predicted. While the established uncertainty relations apply to cases where the predictions are based on purely classical data (e.g., a description of the system’s state before the measurement), an extended relation which remains valid in the presence of quantum information has been proposed recently [Berta et al., Nature Physics 6, 659 (2010)]. Here we generalize this uncertainty relation to one formulated in terms of smooth entropies. Since these entropy measures are related to operational quantities, our uncertainty relation has various applications. As an example, we show that it directly implies security of quantum key distribution protocols.

2:54PM X29.00003 Inadequacy of von Neumann entropy for characterising extractable work, OSCAR DAHLSTEN, Singapore Centre for Quantum Technology, National University of Singapore, and Clarendon Laboratory, University of Oxford, RENATO RENNER, ETH Zurich, ELISABETH RIEPER, Singapore Centre for Quantum Technology, National University of Singapore, VLATKO VEDRAL, Singapore Centre for Quantum Technology, National University of Singapore, and Clarendon Laboratory, University of Oxford — The lack of knowledge an observer has about a system limits the amount of work it can extract. This lack of knowledge is normally quantified using the Shannon/von Neumann entropy. We show that this standard approach is, surprisingly, only correct in very specific circumstances. In general one should use the recently developed smooth entropy approach. For many common physical situations, including large but internally correlated systems, the resulting values for the extractable work can deviate arbitrarily from those suggested by the standard approach. (For details see arXiv:0908.0424)

3:06PM X29.00004 Interpreting quantum discord through quantum state merging1, VAIBHAV MADHOK, University of New Mexico, ANIMESH DATTA, Clarendon Laboratory, University of Oxford — We present an operational interpretation of quantum discord based on the quantum state merging protocol. Quantum discord is the markup in the cost of quantum communication in the process of quantum state merging, if one discards relevant prior information. Our interpretation has an intuitive explanation based on the strong subadditivity of von Neumann entropy. We use our result to provide operational interpretations of other quantities like the local purity and quantum deficit. Finally, we discuss in brief some instances where our interpretation is valid in the single copy scenario.

3:18PM X29.00005 The thermodynamic meaning of negative entropy1, LIDIA DEL RIO, RENATO RENNER, JOHAN AABERG, ETH Zurich, OSCAR DAHLSTEN, VLATKO VEDRAL, entre for Quantum Technologies, National University of Singapore — Landauer’s erasure principle states that all irreversible operations, like the erasure of data stored in a system, have an inherent work cost. This work cost depends on our knowledge of the system: the less we know about its state, the more it costs to erase it. Here, we analyse erasure in a general setting, where our information about a system can be quantum mechanical. We show that the work cost of erasure is bounded by the entropy of the system conditioned on that quantum information. For many common physical situations, including large but internally correlated systems, the resulting values for the extractable work can deviate arbitrarily from those suggested by the standard approach. (For details see arXiv:0908.0424)

3:30PM X29.00006 Operational interpretations of quantum discord1, MARCO PIANI, University of Waterloo, DANIEL CAVALCANTI, National University of Singapore, LEANDRO AOLIDTA, ICFO-Institut de Ciencies Fotoniques, SERGIO BOIXO, California Institute of Technology, KAVAN MODI, National University of Singapore, ANDREAS WINTER, University of Bristol — Quantum discord quantifies non-classical correlations going beyond the standard classification of quantum states into entangled and unentangled ones. Although it has received considerable attention, it still lacks any precise interpretation in terms of some protocol in which quantum features are relevant. Here we give quantum discord its first information-theoretic operational meaning in terms of entanglement consumption in an extended quantum state merging protocol. We further relate the asymmetry of quantum discord with the performance imbalance in quantum state merging and dense coding.

3:42PM X29.00007 Measures of non classical correlations, MATTHIAS LANG, Center for Quantum Information and Control, University of New Mexico, ANIL SHAJI, School of Physics, Indian Institute of Science Education and Research, CARLTON CAVES, Center for Quantum Information and Control, University of New Mexico — To quantify non classical correlations in a quantum state, much effort has been put into the investigation of entanglement and its properties. It is known, however, that entanglement does not capture all quantum correlations. Several entropic measures of non-classical correlations beyond entanglement have been proposed, quantum discord being the most popular amongst them. We have developed an entropic framework for formulating such measures. We discuss new measures that emerge from this framework, and relations among the various measures, and we present numerical results for the measures for two-qubit states.
Quantum Darwinism provides an information-theoretic framework for the emergence of the classical world from the quantum substrate. It recognizes that we - the observers - acquire our information about the “systems of interest” indirectly from their imprints on the environment. Objectivity, a key property of the classical world, arises via the proliferation of redundant information into the environment where many observers can then intercept it and independently determine the state of the system. While causing a system to decohere, environments that remain nearly invariant under the Hamiltonian dynamics, such as very mixed states, have a diminished ability to transmit information about the system, yet can still acquire redundant information about the system [1,2]. Our results show that Quantum Darwinism is robust with respect to non-ideal initial states of the environment.


This research is supported by the U.S. Department of Energy through the LANL/LDRD Program.

http://mike.zwolak.org

Quantum Darwinism in an Everyday Environment: Huge Redundancy in Scattered Photons\[3\] ., CHARLES RIEDEL, University of California, Santa Barbara, WOJCIECH ZUREK, Los Alamos National Laboratory — We study quantum Darwinism—the redundant recording of information about the preferred states of a decohering system by its environment—for an object illuminated by a blackbody. In the cases of point-source, small disk, and isotropic illumination, we calculate the quantum mutual information between the object and its photon environment. We demonstrate that this realistic model exhibits fast and extensive proliferation of information about the object into the environment and results in redundancies orders of magnitude larger than the exactly solvable models considered to date. We also demonstrate a reduced ability to create records as initial environmental mixedness increases, in agreement with previous studies.

This research is supported by the U.S. Department of Energy through the LANL/LDRD program and, in part, by the Foundational Questions Institute (FQXi).

Quantum networks reveal quantum nonlocality. DANIEL CAVALCANTI, CQT-Centre for Quantum Technologies, MAFALDA ALMEIDA, VALERIO SCARANI, ANTONIO ACIN, CQT-ICFO COLLABORATION — The results of local measurements on some composite quantum systems cannot be represented classically. This impossibility, known as quantum nonlocality, represents a milestone in the foundations of quantum theory. Quantum nonlocality is also a valuable resource for information processing tasks, e.g. quantum communication, quantum key distribution, quantum state estimation or randomness extraction. Still, deciding if a quantum state is nonlocal remains a challenging problem. Here we introduce a novel approach to this question: we study the nonlocal properties of quantum states when distributed and measured in networks. Using our framework, we show how any one-way entanglement distillable state leads to nonlocal correlations. Then, we prove that nonlocality is a non-additive resource, which can be activated. There exist states, local at the single-copy level, that become nonlocal when taking several copies of it. Our results imply that the nonlocality of quantum states strongly depends on the measurement context.

Quantum systems as embarrassed colleagues: what do tax evasion and state tomography have in common? ., CHRIS FERRIE, Institute for Quantum Computing, University of Waterloo, ROBIN BLUME-KOHOUT, Theoretical Division, Los Alamos National Laboratory — Quantum state estimation (a.k.a. “tomography”) plays a key role in designing quantum information processors. As a problem, it resembles probability estimation – e.g. for classical coins or dice – but with some subtle and important discrepancies. We demonstrate an improved classical analogue that captures many of these differences: the “noisy coin.” Observations on noisy coins are unreliable – much like soliciting sensitive information such as one’s tax preparation habits. So, like a quantum system, it cannot be sampled directly. Unlike standard coins or dice, whose worst-case estimation risk scales as 1/N for all states, noisy coins (and quantum states) have a worst-case risk that scales as 1/√N and is overwhelmingly dominated by nearly-pure states. The resulting optimal estimation strategies for noisy coins are surprising and counterintuitive. We demonstrate some important consequences for quantum state estimation – in particular, that adaptive tomography can recover the 1/N risk scaling of classical probability estimation.

Quantum Theory for a Total System with One Internal Measuring Apparatus ., WEN-GE WANG, Univ of Sci & Tech of China — We propose a quantum theory for a total system including one internal measuring apparatus. The theory is based on three basic assumptions and a principle termed the principle of compatible description (PCD). The assumptions are: (i) Physical states of the total system can be associated with vectors in the Hilbert space. (ii) Dynamical evolution of a state vector obeys Schrödinger equation. (iii) For a physical state of the total system described by a pure vector, in which a subsystem may play the role of an internal measuring apparatus, when certain stable condition is satisfied, the pure-vector description may be given a Born-type ensemble interpretation. The PCD states that different descriptions for the same state of the total system must give consistent predictions for results of measurements performed by the internal measuring apparatus. The proposed theory lies at a meeting point of Copenhagen, Everett’s relative-state, and consistent-histories interpretations of quantum mechanics. While, it provides something new: For example, the PCD imposes a restriction to vectors that can be associated with physical states, which may effectively break the time-reversal symmetry of Schrödinger equation. As an application of the theory, we derive a condition under which a two-level quantum system may have definite properties, such that it may play the essential role of a measuring apparatus.
new path forward in topological quantum computation that benefits from physical transparency and experimental realism. We propose experimental setups that enable braiding of Majorana fermions and that they exhibit non-Abelian statistics like vortices in a p+ip superconductor. We show that some signatures of the Majorana mode remain but the Majorana mode is not localized and hence not suitable for quantum computation. Therefore we propose an 1D periodic heterostructure which can support localized Majorana modes at the end of the wire without gating on the superconductor.

8:12AM Y27.00002 Majorana fermions in nanowires without gating superconductors1, CHIEN-HUNG LIN, HOI YIN HUI, JAY SAU, SANKAR DAS SARMA, Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA — Majorana fermions have been proposed to be realizable at the end of the semiconductor nanowire on top of an s-wave superconductor [1,2]. These proposals require gating the nanowire directly in contact with a superconductor which may be difficult in experiments. We analyze [1,2] in configurations where the wire is only gated away from the superconductor. We show that some signatures of the Majorana mode remain but the Majorana mode is not localized and hence not suitable for quantum computation. Therefore we propose an 1D periodic heterostructure which can support localized Majorana modes at the end of the wire without gating on the superconductor.

8:24AM Y27.00003 Effects of Interactions on a Topological Phase Exhibiting Majorana Fermions in Quantum Wires, MILES STOUDENMIER, JASON ALICEA, UC Irvine — The ability to create and manipulate Majorana fermions in condensed matter systems is not only of fundamental interest for understanding topological phases but also provides a realistic route toward quantum computation. Recently, a series of devices have been proposed that could realize exotic Majorana physics in relatively conventional settings; among the most promising is a superconducting wire system with strong spin-orbit coupling. Because superconductivity is induced in this system by proximity effect, the system remains superconducting even in the presence of strong interactions. This effects such interactions on this system have until now remained unexplored. Using the Density Matrix Renormalization Group method, we explore the fate of the topological phase in the presence of interactions. Obtaining a matrix product state representation of the degenerate ground states is especially helpful as it allows us to determine detailed properties of the Majorana edge states. Furthermore, we find that interactions significantly expand the topological region of the phase diagram, a result which strengthens proposals to realize Majorana fermions in such wire systems experimentally.

8:36AM Y27.00004 The exchange statistics of Majorana fermions in quasi-one-dimensional networks, DAVID J. CLARKE, University of California, Riverside, JAY D. SAU, University of Maryland, College Park, SUMANTA TEWARI, Clemson University — Under appropriate external conditions a semiconductor with strong spin-orbit coupling in proximity to an s−wave superconductor can be in a topological superconducting (TS) phase in which the time-reversal invariant charge gap and the paired zero energy excitations are Majorana bound states. A network of such wires allows the pairwise exchange of the Majorana bound states. Alicea et al. have shown that these bound states obey non-Abelian exchange statistics, and have proposed [1] such a system as a platform for topological quantum computation (TQC). Here we show that the particular realization of non-Abelian statistics produced in a Majorana wire network is highly dependent on the local properties of individual wire junctions. For a simply connected network, the possible realizations can be characterized by the chirality of individual junctions. We demonstrate how this chirality may be calculated for a particular junction. There is in general no requirement for junction chiralities to remain consistent across a wire network. Careful control of the junction chirality is required for TQC applications of Majorana wire networks. [1] J. Alicea et al., arXiv:1006.4395.

8:48AM Y27.00005 Interferometry and topological quantum computation using Majorana Fermions at semiconductor/superconductor interfaces1, JAY SAU, CMTC, Dept of Physics, University of Maryland, College Park, SUMANTA TEWARI, Dept of Physics, Clemson University, South Carolina, SANKAR DAS SARMA, CMTC, Dept of Physics, University of Maryland, College Park — Majorana Fermions are hitherto unobserved exotic Fermionic excitations, which are their own anti-particles. Recently, a lot of excitement has been generated by proposals to realize Majorana fermions in topological superconductors in a rather general class of topological superconductors, some of which may be as simple as the interface 1D or 2D InAs and Al in the appropriate parameter regime might have exotic topological properties and Majorana Fermions [1]. In my talk, I will discuss recent proposals for performing interferometry in 2D and 1D versions of such systems [2] together with ideas for performing Quantum Computation [3] using such robust Majorana fermion based qubits.

9:00AM Y27.00006 Topological Phases in Dissipative Quantum Transport, MARK RUDNER, Harvard, MICHAEL LEVIN, Maryland, LEONID LEVITOV, MIT — Recently, a new type of topological quantization was discovered in dissipative quantum transport on a one dimensional bipartite lattice with decay [1]. The transition between distinct topological phases is accompanied by a discontinuous change in the expected displacement covered by a particle before it decays. Here we show that this behavior extends to a much wider family of models, and provide a prescription for computing the topological invariant which distinguishes all of the phases which arise in the general case. When the underlying hopping problem without decay possesses time reversal symmetry, we show that the expected displacement, averaged with respect to all initial states, is quantized. The topological nature of this phenomenon, which is unique to systems with decay, places it on a similar footing as other robust topological phenomena such as the quantization of the Hall conductance [2], or of the adiabatically-pumped charge in periodically-driven 1D systems [3]. Correspondingly, here we find that quantization is robust against a range of perturbations and certain types of decoherence. Similarities and differences with the phases of one-dimensional topological insulators will be discussed. [1] M. S. Rudner and L. S. Levitov, Phys. Rev. Lett. 102, 065703 (2009). [2] D. J. Thouless, M. Kohmoto, M. P. Nightingale, and M. den Nijs, Phys. Rev. Lett. 49, 405 (1982). [3] D. J. Thouless, Phys. Rev. B 27, 6083 (1983).
9:12 AM Y27.00007 Counting Majorana zero modes in superconductors, LUZ SANTOS, Harvard University, YUSUKE NISHIDA, MIT, CLAUDIO CHAMON, Boston University, CHRISTOPHER MUDRY, PSI, Switzerland — We present a counting formula for computing the number of (Majorana) zero modes bound to topological point defects. The counting formula is evaluated in a gradient expansion for systems with charge-conjugation symmetry. We will consider examples that include Dirac fermions and the chiral $p$-wave superconductor in two-dimensional space. In all cases, we explicitly relate the counting of zero modes to Chern numbers.

9:24 AM Y27.00008 Non-Abelian order in $s$-wave superconductors: Phases and quantum transitions, SUMANTA TEWARI, Physics & Astronomy, Clemson University, Clemson, SC, TUDOR STANESCU, Department of Physics, West Virginia University, Morgantown, WV, JAY SAU, Condensed Matter Theory Center, Dept. of Physics, University of Maryland, College Park, MD, PARAG GHOSH, Dept. of Physics and Astronomy, George Mason University, Fairfax, VA, SANKAR DAS SARMA, Condensed Matter Theory Center, Dept. of Physics, University of Maryland, College Park, MD — Non-Abelian topological superconductivity has been predicted to occur in $s$-wave superconductors with a sizable spin-orbit (SO) coupling. As is now well known, such a system can be used for topological quantum computation. When an external Zeeman splitting crosses a critical value, the system passes from a regular, non-topological, superconducting phase to a topological one. On the other hand, in the absence of SO coupling this critical value corresponds to the Zeeman splitting above which the system loses its $s$-wave superconductivity. We are thus led to the paradoxical conclusion that the topological superconducting phase appears in a parameter regime at which the system actually is non-superconducting in the absence of SO coupling. In this work we resolve this paradox.

1 Work supported by DARPA-MTO Grant No: FA 9550-10-1-0497, DARPA QuEST, and JQI-NSF-PFC.

9:36 AM Y27.00009 Induced Chiral $f$-wave Superconducting Pairing and Majorana Fermions in a Hole-doped Semiconductor, CHUANWEI ZHANG, LI MAO, Department of Physics and Astronomy, Washington State University, Pullman, Washington, 99164 USA, JUNREN SHI, International Center for Quantum Materials, Peking University, Beijing 100871, China, QIAN NII, Department of Physics, The University of Texas, Austin, Texas 78712 USA — We show that a chiral $f$-wave superconducting pairing may be induced in the lowest heavy hole band of a hole-doped semiconductor thin film by proximity contact with an $s$-wave superconductor. The chirality of the pairing originates from the $3\pi$ Berry phase accumulated for a heavy hole moving along a close path on the Fermi surface. There exist three chiral gapless Majorana edge states, in consistence with the chiral $f$-wave pairing. We show the existence of zero energy Majorana fermions in vortices in the semiconductor-superconductor heterostructure by solving the Bogoliubov-de-Gennes equations numerically as well as analytically in the strong confinement limit. The proposed semiconductor/superconductor heterostructure can be used as a platform for observing non-Abelian statistics and performing TQC.

1 This work is supported by DARPA-YFA, DARPA-MTO, ARO, 973 program, NSF, DoE, and the Welch Foundation.

9:48 AM Y27.00010 Anyonic entanglement renormalization, ROBERT KOEING, ERSEN BILGIN, Institute for Quantum Information, Caltech — We introduce a family of variational ansatz states for chains of anyons which optimally exploits the structure of the anyonic Hilbert space. This ansatz is the natural analog of the multi-scale entanglement renormalization ansatz for spin chains. In particular, it has the same interpretation as a coarse-graining procedure and is expected to accurately describe critical systems with algebraically decaying correlations. We numerically investigate the validity of this ansatz using the anyonic golden chain and its relatives as a testbed. This demonstrates the power of entanglement renormalization in a setting with non-Abelian exchange statistics, extending previous work on qudits, bosons and fermions in two dimensions.

10:00 AM Y27.00011 Protected phase gates for superconducting qubits, PETER BROOKS, JOHN PRESKILL, California Institute of Technology — Quantum systems with inherent error-correcting properties offer a powerful tool for building quantum computers to be insensitive to the effects of errors. Kitaev [arXiv:cond-mat/0609441] has proposed an intrinsically fault-tolerant qubit design based on superconducting systems. The phase gate $\Lambda(i)$ in this system is performed by coupling the qubit to a quantum LC oscillator for a period of time. The evolution of the oscillator can be understood as being protected by a family of continuous variable quantum codes at every point in its evolution, providing natural robustness against random variations in the duration and strength of the coupling. We present the results of numerical simulations of this system which investigate the fidelity of the phase gate operation as a function of the duration mistiming. We discuss the robustness of the gate under the effect of anharmonic perturbations to the oscillator and oscillator coupling, and addiablity requirements for this scheme to properly function.

10:12 AM Y27.00012 Resilience of Topological Codes to Depolarization, RUBEN S. ANDRIST, Department of Physics, ETH Zurich, HECTOR BOMBIN, Perimeter Institute for Theoretical Physics, MIGUEL ANGEL MARTIN-DELGADO, Departamento de Fisica, Universidad Complutense, HELMUT G. KATZGRABER, Department of Physics, Texas A&M University & ETH Zurich — Standard error correction is based on redundant storage of quantum information. However, in topological quantum error correction decoherence effects are prevented by encoding logical qubits in nonlocal degrees of freedom, while actively correcting for errors that occur locally in the system. Previous studies have shown that the two hallmark topological codes— the toric code and color codes—are stable against bit-flip/phase-flip and measurement errors. In this work we study the effects of the depolarizing channel to both the toric code and topological color codes. By mapping the quantum problem onto a disordered statistical-mechanical 8-vertex model we compute the error tolerance of these systems using large-scale Monte Carlo simulations. Our results show that the error threshold increases significantly for both the toric code and color codes.

10:24 AM Y27.00013 Local equivalence of topological order: Kitaev’s code and color codes, GUILLAUME DUCLOS-CIANCI, Université de Sherbrooke, HECTOR BOMBIN, Perimeter Institute for Theoretical Physics, DAVID POULIN, Université de Sherbrooke — We demonstrate that distinct topological codes can be mapped onto each other by local transformations. The existence of such a local mapping can be interpreted as saying that these codes belong to the same topological phase. When used as quantum error correcting codes, the local mapping also enables us to use any decoding algorithm suitable for one of these codes to decode other codes in the same topological phase. We illustrate this idea with the topological color code and the topological subsystem color code that are found to be locally equivalent to two copies of Kitaev’s toric code. We are therefore able to decode these two codes that had no previously known efficient decoding algorithm, and find error thresholds comparable to previously estimated optimal values. These local mappings could have additional use for fault-tolerant quantum computation. In particular, one could in principle take advantage of the features (transversal gates, topological gates, etc.) of all the codes that are locally equivalent by switching between them during the computation in a fault-tolerant fashion.

10:36 AM Y27.00014 Exactly solvable 3D quantum model with finite temperature topological order, ISAAC KIM, Institute of Quantum Information — We present a family of exactly solvable spin-$\frac{1}{2}$ quantum hamiltonians on a 3D lattice. The degenerate ground state of the system is characterized by a quantum error correcting code whose number of encoded qubits is equal to the second Betti number of the manifold. These models 1) have solely local interactions 2) admit a strong-weak duality relation with an Ising model on a dual lattice 3) have topological order in the ground state, some of which survive at finite temperature. The associated quantum error correcting codes are all non-CSS stabilizer codes.
Universal Behavior of Entanglement in 2D Quantum Critical Dimer Models, BENJAMIN HSU, EDUARDO FRADKIN, UIUC — We examine the scaling behavior of the entanglement entropy for the 2D quantum dimer model (QDM) at criticality and derive the universal finite size subleading correction $\gamma_{\text{QCP}}$. We compute the value of $\gamma_{\text{QCP}}$ without approximation working directly with the wave function of a generalized 2D QDM at the Kosterlitz-Thouless QCP in the continuum limit. Using the replica approach, we construct the conformal boundary state corresponding to the cyclic identification of $n$-copies along the boundary of the observed region. We find that the universal finite size term is $\gamma_{\text{QCP}} = \ln R - 1/2$ where $R$ is the compactification radius of the boson field theory quantum Lifshitz model, the effective field theory of the 2D QDM at quantum criticality. We also demonstrated that the entanglement spectrum of the critical wave function on a large but finite region is described by the characters of the underlying conformal field theory. It is shown that this is formally related to the problems of quantum Brownian motion on $n$-dimensional lattices or equivalently a system of strings interacting with a brane containing a background electromagnetic field and can be written as an expectation value of a vertex operator.

Friday, March 25, 2011 8:00AM - 11:00AM —
8:00AM Y29.00001 Investigating decoherence in the transmon qubit using a 3D resonator1. HANHEE PAIK, D.I. SCHUSTER2, L. BISHOP3, A.P. SEARS, G. KIRCHMAIR, L. FRUNZIO, M.H. DEVORET, R.J. SCHOELKOPF, Yale University — We studied the coherence times of transmon qubits using three-dimensional resonators. The three-dimensional (3D) superconducting resonant cavity is machined with aluminum alloy, whose quality factor is higher than 5 million at 10 mK inside a magnetic shield. The transmons are fabricated on sapphire substrates whose internal Q was not lower than 2 million when evaluated in the 3D resonator. We measured the relaxation and dephasing times of the qubits and were able to draw a lower bound on these numbers.

8:12AM Y29.00002 Decoherence in Improved Transmon Qubits. ADAM SEARS, HANHEE PAIK, DAVID SCHUSTER, LEV BISHOP, GERHARD KIRCHMAIR, LUIGI FRUNZIO, MICHEL DEVORET, ROB SCHOELKOPF, Yale University — The transmon is a simple superconducting qubit which has less dependence on the usual sources of $1/f$ noise, and has coherence which is mostly limited by a source of anomalous dissipation. The quality factors of transmon qubits on sapphire are observed to be $\sim$ 50,000, similar to that of transmission line resonators made with the same geometry. It is likely that both these devices may be limited by surface dielectric losses. We will report on the design and characterization of transmon qubits which are fabricated with reduced dielectric losses to possibly increase coherence times.

8:24AM Y29.00003 Measurements of quasiparticle tunneling rate in a superconducting transmon qubit, LUYAN SUN, Departments of Physics and Applied Physics, Yale University, LEONARDO DICARLO, MATTHEW REED, LEV BISHOP, TERRI YU, GIANLUIGI CATELANI, LEONID GLAZMAN, LUIGI FRUNZIO, MICHEL DEVORET, ROBERT SCHOELKOPF, Departments of Physics and Applied Physics, Yale University — A practical quantum computer requires qubits with long coherence times in order to perform many quantum gates. For a superconducting qubit, non-equilibrium quasiparticle tunneling is one possible source of decoherence. Spectroscopy measurements of a superconducting transmon qubit can be used to set a bound on the quasiparticle tunneling rate. When operated in the low $E_J/E_C$ regime, the transmon qubit transition frequency switches between two well-resolved branches due to quasiparticle tunneling. A selective $\pi$ pulse applied to one of these two branches can excite the qubit only if the qubit is at that frequency. Thus by repeatedly applying $\pi$ pulses to interrogate the qubit state, the quasiparticle dynamics can be studied. We will present our results on the quasiparticle tunneling rate in a transmon qubit.

8:36AM Y29.00004 Dynamical decoupling and noise spectroscopy with a superconducting flux qubit, JONAS BYLANDER, SIMON GUSTAVSSON, FEI YAN, Massachusetts Institute of Technology, FUMIKI YOSHIHARA, KHALIL HARRABI, Institute of Physical and Chemical Research RIKEN, DAVID CORY, MIT and University of Waterloo, YASUNOBU NAKAMURA, JAW-SHEN TSAI, RIKEN and NEC Corporation, WILLIAM D. OLIVER, MIT Lincoln Laboratory — We demonstrate dynamical decoupling in a superconducting flux qubit with a long energy-relaxation time, $T_1=12\,\mu$s. Low-frequency noise acts to dephase the qubit, reducing its transverse coherence time $T_2$. At the noise-optimal bias point we observe a free-induction decay time $T_2^* = 2.5\,\mu$s and $T_1$-limited spin-echo decay, $T_2 = 2T_1$. Biased away from this point, the increased sensitivity to flux noise leads to increased echo and free-induction decay rates. We moderate the dephasing effects of this noise by applying dynamical-decoupling sequences with up to 200 $\pi$-pulses. Using the CPMG sequence, we achieve a more than 50-fold enhanced decay time over $T_2^*$ and Gaussian pure-dephasing times $T_2 > 100\,\mu$s.

We use the filtering property of this pulse sequence to facilitate spectroscopy of the environmental noise and reconstruct its $1/f$ power spectral density, which we independently confirm by a Rabi-spectroscopy approach. We characterize the noise sources coupling to the energy-bias and tunnel-coupling terms of the Hamiltonian.

8:48AM Y29.00005 Multi-mode circuit quantum electrodynamics, JEROME BOURASSA, Universite de Sherbrooke, JAY M. GAMBETTA, IQC and University of Waterloo, ALEXANDRE BLAIS, Universite de Sherbrooke — In circuit QED experiments with low anharmonicity superconducting qubits, like the transmon, it has been shown how the many-level structure of the qubits can give rise to non-trivial effects. Examples are the straddling regime [1] and high-power qubit readout induced by qubit nonlinearities [2]. In the same spirit, there are also clear experimental evidences to the effect that higher resonator modes play an important role in setting the size of the qubit-qubit flip-flop interaction mediated by virtual resonator photons [3] and the qubit decay rate due to the Purcell effect [4]. In this talk we explore how these higher modes can be taken into account in a theoretical description of the system, and how they affect the flip-flop and Purcell decay rates.

9:00AM Y29.00006 Dissipation in the ultra-strong coupling regime. FELIX BEAUDOIN, Universite de Sherbrooke, JAY GAMBETTA, Institute for Quantum Computing, University of Waterloo, ALEXANDRE BLAIS, Universite de Sherbrooke — It has recently been shown that the ultra-strong coupling regime, in which the rotating-wave approximation breaks down, can be obtained using a flux qubit coupled to a transmission line [1]. This regime has been observed experimentally in [2, 3]. We will show the usual quantum optics master equation fails in this context and give a more accurate one. We will also explain how non-trivial properties of the ground state could be experimentally studied.


9:12AM Y29.00007 Strong frequency dependence of coupling of a Cooper- pair box qubit to Quantum Noise. B. SURI, Dept.of Phys., Univ.of MD., Z. KIM, Dept.of Phys., Univ. of MD., V. ZARETSKEY, S. NOVIKOV, Dept. of Phys., Univ. of Maryland, B. S. PALMER, Lab. For Physical Sciences, B. S. PALMER, Lab. for Physical Sciences, F. C. WELLSTOOD, Dept. of Phys., Univ. of MD., QJI, CNAM — Our system consists of an Al/AIOx/Al Cooper-pair box (CPB) charge qubit coupled to a lumped element resonator, which in turn is coupled to a transmission line. From the measured Rabi frequency, for a given microwave frequency \( f \) and amplitude in the transmission line, we can extract the coupling of the qubit to the transmission line. We observe an order of magnitude variation in this coupling over the range of \( f = 4 \) to 8GHz which is in agreement with the variation of our measured lifetimes. Assuming that our qubit is coupled directly to a 50Ω impedance with the measured coupling, we find that for \( f = 6 \) to 7 GHz the lifetime of 30µs measured at the charge sweet spot can be well explained by quantum noise. At \( f = 4 \)GHz, we observe an order of magnitude weaker coupling and a \( T1 \) of 200µs .

9:24AM Y29.00008 Dephasing Measurements of a Cooper-pair box. VITALEY ZARETSKEY, Dept. of Physics, Univ. of Maryland, S. NOVIKOV, B. SURI, Z. KIM, Dept. Of Physics, Univ. Of Maryland, F. C. WELLSTOOD, QJI, CNAM, Dept. Of Physics, Univ. Of Maryland, B. S. PALMER, Lab. For Physical Sciences — We present data on the dephasing properties of our Al/AIOx/Al Cooper-pair box (CPB) qubit. The CPB had a charging energy \( E_C/h = 6.25 \) GHz and a maximum \( E_J/h = 19 \) GHz which was decreased by an external magnetic field to an effective \( E_J/h = 6.1 \) GHz. The qubit was capacitively coupled to a lumped element microwave resonator (\( f_0 = 5.446 \) GHz, \( Q_\ell = 1.8 \times 10^4 \)) which was in turn coupled to a transmission line. To manipulate the qubit, a microwave pulse at 6.1 GHz was sent to the transmission line. The state of the qubit was then measured by sending a second microwave pulse at \( f_0 \) and measuring the amplitude and phase of the transmitted power. We observed Rabi oscillations with Rabi frequencies from 1.94 to 5.32 MHz decay with time constants in the range \( \tau' = 0.5 - 1.6 \) µs. We measured an inhomogeneous dephasing time (\( T2^* \)) of 322 ns by performing a Ramsey fringe experiment. Assuming 1/f charge noise is the dominant dephasing mechanism we extracted a 1/f charge noise amplitude of \( 1.6 \times 10^{-3} \sqrt{ \text{Hz} } \) at 1 Hz.

9:36AM Y29.00009 Improved T2 in Josephson Phase Qubits. DANIEL SANK, RAMI BARENDTS, RADOSŁAW BIALCZAK, YU CHEN, JULIAN KELLY, MICHAEL LENANDER, ERIK LUCERO, MATTEO MARIANTONI, MATTHEW NEELEY, AARON O’CONNELL, PETER O’MALLEY, AMIT VAINSCHERCH, HOAHOA WANG, MARTIN WEIDES, JAMES WENNER, THEODORE WHITE, YI YIN, JIAN ZHAO, ANDREW CLELAND, JOHN MINTELS, UCSD — Phase qubit gate fidelities are limited by individual device dephasing times (\( T2 \)). Reduction of dephasing is therefore an important immediate goal for phase qubit experiments. A simple way to reduce dephasing is to increase the device loop inductance in order to lower the noise currents driven by magnetic flux noise. \( T2 \) should scale linearly with loop inductance. Surface spin models for flux noise also predict that wider loop traces should reduce the noise. We present data on \( T2 \) for phase qubits with varied loop inductance and trace width. We present data from experiments in which we find that doubling the loop inductance increases \( T2 \) by 25%.

9:48AM Y29.00010 Evidence for coherent quantum phase slips from dephasing of fluxonium qubit. ARCHANA KAMAL, NICHOLAS MASLUK, Yale University, VLADIMIR MANUCHARYAN, Harvard University, JENS KOCH, Northwestern University, LEONID GLAZMAN, MICHEL DEVORET, Yale University — Phase slips are events in which the phase across a superconducting wire changes by \( 2\pi \). The thermally activated phase slips at high temperatures are well understood but the coherent phase slips caused by quantum fluctuations well below the critical temperature have, so far, eluded observation. We report new decoherence data for the fluxonium qubit [1] that provide evidence for coherent quantum phase slips across the qubit inductance, implemented with a long array of Josephson tunnel junctions. Coherent quantum phase slips result in broadening of the qubit transition frequency due to Aharonov-Casher interference of multiple phase slip paths (or flux tunneling through different junctions) encircling random offset charges on array islands [2].


Work supported by IARPA, ARO and NSF.

10:00AM Y29.00011 Relaxation mechanisms of the fluxonium qubit. NICHOLAS MASLUK, ARCHANA KAMAL, Yale University, VLADIMIR MANUCHARYAN, Yale University, Harvard University, JENS KOCH, Northwestern University, LEONID GLAZMAN, MICHEL DEVORET, Yale University — Fluxonium is a highly anharmonic artificial atom, which utilizes an inductance formed by an array of large Josephson junctions to shunt the junction of a Cooper-pair box. The first excited state transition frequency is widely tunable with flux, yet can be read out over the entire five octave range due to interactions of the 2nd excited state with the readout cavity, enabling a dispersive readout. We present \( T1 \) times of several fluxonium samples over the full range of flux dependent transition energies. By mapping out the qubit lifetimes we are able to distinguish between the contributions due to the Purcell effect and quantify dissipation internal to the qubit. With this understanding, we can design a qubit with minimized contribution from internal losses, which should push lifetimes further into the tens of microseconds. [1] V. E. Manucharyan et al., Science 326, 113 (2009).

Work supported by IARPA, ARO and NSF.

10:12AM Y29.00012 1/f noise and susceptibility-magnetization correlation in disordered ferromagnets. KOSTYANTYN KECHEDZHI, Rutgers, The State University of New Jersey — We consider a strongly disordered ferromagnet modeled by Ising spins placed at random in 2D with ferromagnetic interactions decaying exponentially with inter-site distance. Ferromagnetic phase in this model arises due to formation of infinite percolation cluster of strongly interacting spins. Fractal nature of the percolation cluster manifests itself in the dynamics of the system in the vicinity of the percolation transition. Simulating the dynamics with single spin flip Monte Carlo algorithm we observe 1/f power spectra of magnetization noise in a wide temperature range near the transition. Subjected to external AC magnetic field the system shows significant cross-correlation between susceptibility and magnetization in the ferromagnetic phase. This results suggest a possible explanation of the inductance-flux cross-correlation recently observed in SQUIDs [1].

3This work is done in collaboration with Lara Faoro and Lev B. Ioffe.
10:24AM Y29.00013 Are “pinholes” the cause of excess current in superconducting tunnel junctions? A study of Andreev decay in highly resistive junctions. MARKKU STENBERG, TINE GREIBE, CHRISTOPHER WILSON, THILO BAUCH, VITALY SHUMEIKO, PER DELSING, Chalmers University of Technology — In highly resistive superconductor—insulator—superconductor (SIS) and superconductor—insulator—normal-metal (SIN) junctions, “excess” subgap current is usually observed. We have studied subgap conductance in Al/AIOₓ/Al and Al/AIOₓ/Cu tunnel junctions. In the former, we observed a huge (two orders of magnitude) decrease in subgap conductance upon the transition from the SIS to the SIN regime. In the latter, we observed several signatures of coherent diffusive two-particle transport. We use the quasiclassical Keldysh-Green function theory to quantify the contributions of the single- and two-particle processes on subgap conductance. Our observations indicate insignificance of highly transparent microscopic defects (“pinholes”) in the tunneling barrier, and we therefore argue that the common “pinhole” scenario is not the explanation for the observed excess subgap current in SIS tunnel junctions.

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

10:36AM Y29.00014 Critical current noise and junction resonators in Josephson junction from interacting trap states. MOHAMMAD H. ANSARI, Institute for Quantum Computing, IQC and University of Waterloo, FRANK K. WILHELM-MAUCH, Institute for Quantum Computing, IQC and University of Waterloo — We analyze the impact of trap states in the oxide layer of superconducting tunnel junctions on the fluctuation of the Josephson current. These are known to inhibit the coherent operation of superconducting qubits. These have a twofold effect: Occupying trap states blocks out parts of the critical current of the Josephson junction. Electrons can also cross the junction via hopping across a trap. We are extending previous studies of noninteracting traps to the case where the traps have on-site electron repulsion. We use second order perturbation theory which allows to obtain analytical results but limited to small and intermediate repulsion. Remarkably, it still reproduces the main features of the model as identified from the Numerical Renormalization group. We present analytical formulations for the subgap bound state energies, the singlet-doublet phase transition, and the spectral weights, which are in agreement with recent Numerical Renormalization Group analysis. We show that interactions can reverse the supercurrent across the trap. We finally work out the resonance noise spectrum in the presence of on-site repulsive electrons and suggest a criteria for the fabrication of parameters that may help to suppress low frequency noise from superconducting quantum computation devices.

10:48AM Y29.00015 Energy relaxation mechanisms in capacitively shunted flux qubits. ANTONIO CORCOLES, JIM ROZEN, MARY BETH ROTHWELL, GEORGE KEEFE, DAVID DI VINCENTO, MARK KETCHEN, JERRY CHOW, CHAD RIGETTI, JACK ROHRS, MARK BORSTELMANN, MATTHIAS STEFFEN, IBM, IBM QUANTUM COMPUTING GROUP TEAM — Energy losses in superconducting qubits remain a major object of study in the road towards scalable, highly coherent qubit devices. The current understanding of the loss mechanisms in these devices is far from being complete and it is sometimes difficult to experimentally separate the different contributions to decoherence. Here we compare a traditional three Josephson-junction flux qubit to the recently implemented capacitively shunted flux qubit [1], whose energy decay is thought to be limited by dielectric losses arising from native oxides in the shunting capacitor. Keeping all parameters identical except for the shunting capacitance, we obtain energy relaxation times that are comparable for both types of qubit. This suggests that the energy relaxation time is not limited by junction losses in capacitively shunted flux qubits. We discuss some other possible loss mechanisms present in these devices.


Friday, March 25, 2011 11:15AM - 1:51PM — Session Z27 GQI: Focus Session: Semiconductor Qubits - Theory and Experiment C155

11:15AM Z27.00001 Quantum dot charge stability diagram from a generalized Hubbard model. XIN WANG, SHUO YANG, SANKAR DAS SARMA, Condensed Matter Theory Center, Department of Physics, University of Maryland — We develop a theory for the charge stability diagram in solid state quantum dot spin qubits using a general form of the Hubbard model. We argue that the extended Hubbard model (with both on-site and inter-site Coulomb repulsion) is the minimal model to describe the system. The appropriate parameters of the Hubbard model can be read off by comparing our theoretically derived results with the experimental charge stability plots. We make predictions on how the charge stability diagram depends on various parameters of the Hubbard model, especially the spin-exchange and hopping energies.

This work is supported by IARPA, LPS-CMTC, and CNAM.

11:27AM Z27.00002 Microscopic theory for the charge stability diagram of coupled quantum dot systems. SHUO YANG, XIN WANG, SANKAR DAS SARMA, Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, MD 20742 — We present a quantitative microscopic theory for the charge stability diagram of coupled quantum dot systems. Using the configuration interaction method we obtain a generalized Hubbard model, from which the charge stability diagram is calculated and compared with experiments. We establish an exact connection between experimental measurements and the microscopic theory, and predict some experimentally observable quantum effects. We also map the classical capacitance model to the extended Hubbard model, and argue that the effect of spin-exchange and various hopping terms cannot be expressed in the capacitance model.

This work is supported by LPS-CMTC, IARPA, and CNAM.

11:39AM Z27.00003 Formation and electrical characterization of directed self-assembled Ge/Si quantum dot. DONGYUE YANG, U. Pittsburgh, CHRIS PETZ, U. Virginia, JEREMY LEVY, U. Pittsburgh, JERROLD FLORO, U. Virginia — Directed self-assembly of sub-10 nm Ge islands is a candidate for producing laterally coupled quantum dot molecules with geometrically-defined spin exchange couplings. The islands are created by the nucleation of Ge islands on nanoscale SiC templates defined by direct-write electron-beam lithography. Ge islands are coupled through ohmic contacts to the Si capping layer, and geometries can be defined that are suitable for either vertical or lateral transport. We describe low-temperature magneto-transport measurements on individual and small arrays of Ge islands grown on semi-insulating silicon substrates.

This work is supported by DOE DE-FG02-07ER46421.

11:51AM Z27.00004 The Kondo Effect in a Double Quantum Dot. SAMI AMASHA, ILEANA RAU, ANDREW KELLER, Stanford University, JORDAN KATINE, Hitachi Global Storage Technologies, HADAS SHTRIKMAN, Weizmann Institute, DAVID GOLDHABER-GORDON, Stanford University — A quantum dot consists of a confined droplet of electrons connected to electron reservoirs by tunnel barriers. When the dot has an odd number of electrons it has a net spin. The electrons in the reservoir can screen this spin via the Kondo effect, which corresponds to a many-body, highly correlated electron state. We study a lateral GaAs/AlGaAs double quantum dot, where one or both of the dots can be in the Kondo regime. The dots are also coupled to each other, and this inter-dot interaction can compete with the Kondo effect. We report transport measurements in this system at low electron temperatures and for a variety of inter-dot couplings.

12:03PM Z27.00005 Exhibition of tunnel coupling of negatively charged dangling bonds on Si Surface Using Scanning Tunneling Microscope. M. Baseer Haider, Dept of Physics, King Fahad University of Petroleum & Minerals, Saudi Arabia, L. Livadaru, Dept of Physics, University of Alberta, Canada, J. Pitters, National Institute for Nanotechnology, National Research Council of Canada, Canada, R. Wolkow, Dept of Physics, University of Alberta, Canada — We have performed Scanning tunneling microscopy study of hydrogen terminated Si (100). We will show that single Si atoms in a solid state environment can be served as quantum dots. These negatively charged quantum dots can be tunnel coupled to the nearby Si quantum dots. We will demonstrate that this tunnel coupling can be controlled by adjusting the separation between the two Si atomic quantum dots. Moreover electron occupation in the tunnel coupled Si quantum dots can be controlled. We have used this tunnel coupling effect of Si atomic quantum dots to fabricate Quantum Cellular Automata Cells. Quantum Cellular Automata are used to transmit binary information through electrostatic interaction between adjacent cells without the transfer of charge from one cell to the next. Devices based on Quantum Cellular Automata will consume much less power compared to the conventional transistor based devices. Moreover, since there is no transfer of charge so power dissipation during its operation is minimal compared to conventional semiconductor devices. This Si based Quantum Cellular Automat Cell works at room temperature.

12:15PM Z27.00006 The RKKY Interaction and the Nature of the Ground State of Double Dots in Parallel. Manas Kulkarni, Stony Brook University and Brookhaven National Laboratory, Robert Konik, Brookhaven National Laboratory — We argue through a combination of slave boson mean field theory and the Bethe ansatz that the ground state of closely spaced double quantum dots in parallel are antiferromagnetically coupled. We do so by studying the dots conductance, impurity entropy and spin correlation. In particular we find that the zero temperature conductance is characterized by the Friedel sum rule, a hallmark of Fermi liquid physics, and the impurity entropy vanishes in the limit of zero temperature, indicating the ground state is a singlet. This conclusion is in contradistinction to a number of numerical renormalization group studies. We suggest a possible reason for the discrepancy. Our findings are also consistent with a 1/N diagrammatic approach to the same setup.

12:27PM Z27.00007 Frequency-dependent Fano factor of multilevel systems with inelastic decay processes. Farzad Qassemi, Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Ontario, Canada, Bill Coish, Department of Physics and Astronomy, McGill University, Montreal, Canada, Joakim Bergli, Department of Physics, University of Oslo, Norway, Frank K. Wilhelm, Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Ontario, Canada — We study the frequency-dependent noise of electrons passing through a multilevel quantum dot or molecule accounting for “dark” states through which current is prohibited and inelastic transitions between the levels. Our theory results in simple closed-form expressions directly relating the frequency-dependent noise to inelastic decay rates in the limit where the rates are widely separated. To demonstrate the method, we apply it to evaluate the shot noise for electrons passing through single and double quantum dots in the presence of multiple spin decay mechanisms.

3 Thanks to our sponsors Quantumworks, NSERC, CIFAR and Waterloo Inst for Nanotechnology.

12:39PM Z27.00008 Quantum Point Contacts. Abhijit C. Mehta, Duke University, Cyrus J. Umrigar, Cornell University, A. Devrim Guclu, National Research Council of Canada, Harold U. Baranger, Duke University — We use Quantum Monte Carlo (QMC) techniques to investigate the behavior of electrons in an inhomogeneous quasi-one-dimensional wire as a model of quantum point contact geometries. Previous QMC work by Guclu et al. demonstrated that electrons can be strongly localized in quantum point contacts, and this result was reproduced by Welander et al. using LSDA calculations. We model a quantum point contact as a constriction in a quantum ring, and we use variational and diffusion Monte Carlo to investigate the effects of different point contact lengths and geometries on the electronic properties of the QPC. A key issue is how robust the previous results are to the length of the constriction, the depth and steepness of the confining potential, and to increasing the density of the electrons in the high-density lead region.

12:51PM Z27.00009 Electron pair tunneling resonance in a double-dot interferometry. Jinhong PARK, H.-S. SIM, KAIST — It is difficult to experimentally detect an electron pair tunneling resonance in a quantum dot with repulsive Coulomb interactions, since it is usually masked by lower-order single-electron tunneling processes. We propose to use an Aharonov-Bohm interferometry consisting of two quantum dots for the detection. We find that in the second harmonics of the interference current, pair tunneling processes give a leading non-monotonous contribution around the bias voltages at which pair tunneling resonances appear. The second-harmonics differential conductance shows the signal of a pair tunneling resonance as well as the destructive interference of two pair tunneling resonances.

1:03PM Z27.00010 Giant current fluctuations in an overheated single-electron transistor. Matti Laakso, Tero Heikkila, Low Temperature Laboratory, Aalto University, Yuli Nazarov, Kavli Institute of Nanoscience, Delft University of Technology — Interplay of cotunneling and single-electron tunneling in a thermally isolated single-electron transistor leads to peculiar overheating effects. In particular, there is an interesting crossover interval where the competition between cotunneling and single-electron tunneling changes to the dominance of the latter. In this interval, the current exhibits anomalous sensitivity to the effective electron temperature of the transistor island and its fluctuations. We present a new theoretical method for the study of the temperature fluctuations and induced fluctuations of other quantities, e.g., current, based on the Fokker-Planck equation. We apply this method to the study of the current and temperature fluctuations in an overheated SET over the crossover interval.

1:15PM Z27.00011 Electron exchange between quantum dot and ring by jumping in magnetic field. Igor Filikhin, Sergei Matinyan, James Nimmo, Branislav Vlahovic, North Carolina Central University — Semiconductor heterostructures as quantum dots (QD) or quantum rings (QR) demonstrate atom-like energy level configuration. In the presented work we show that in the weak coupled Double Concentric Quantum Ring (DCQR) electron position jumping can exist due to the energy level crossing. We study DCQR composed of GaAs in an $A_{0.70}Ga_{0.30}$As substrate under influence of magnetic field. In our model the DCQR is considered in three dimensional space within single sub-band effective mass approach [1]. Magnetic field is applied in z direction, perpendicular to the DCQR plane. The electron position in DCQR is defined by effective radius which is radius of most probable localization of a single electron. The study of the structure of DCQR located at the center of QR. The electron position jumping between QR and QD is considered. Discuss will be possibility of experimental implementations of the jumping effect for composite object of QD and QR.


Minerals, Saudi Arabia, L. Livadaru, Dept of Physics, University of Alberta, Canada, R. Wolkow, Dept of Physics, University of Alberta, Canada — We have performed Scanning tunneling microscopy study of hydrogen terminated Si (100). We will show that single Si atoms in a solid state environment can be served as quantum dots. These negatively charged quantum dots can be tunnel coupled to the nearby Si quantum dots. We will demonstrate that this tunnel coupling can be controlled by adjusting the separation between the two Si atomic quantum dots. Moreover electron occupation in the tunnel coupled Si quantum dots can be controlled. We have used this tunnel coupling effect of Si atomic quantum dots to fabricate Quantum Cellular Automata Cells. Quantum Cellular Automata are used to transmit binary information through electrostatic interaction between adjacent cells without the transfer of charge from one cell to the next. Devices based on Quantum Cellular Automata will consume much less power compared to the conventional transistor based devices. Moreover, since there is no transfer of charge so power dissipation during its operation is minimal compared to conventional semiconductor devices. This Si based Quantum Cellular Automat Cell works at room temperature.
1:27PM Z27.00012 Quantum phase transition of light as a control of the entanglement between interacting quantum dots, ANGELA BARRAGAN, Instituto de Fisica, Universidad de Antioquia, Medellin, Colombia; Instituto de Ciencias Nucleares, Universidad Nacional Autonoma de Mexico, Mexico, CARLOS VERA-CIRO, Instituto de Fisica, Universidad de Antioquia, Medellin, Colombia; Kapteyn Institute, University of Groningen, Groningen, The Netherlands, IAN MONDRAGON-SHEM, Instituto de Fisica, Universidad de Antioquia, Medellin, Colombia; Department of Physics, Cornell University, Ithaca, NY, USA — We study coupled quantum dots arranged in a photonic crystal, interacting with light which undergoes a quantum phase transition. At the mean-field level for the infinite lattice, we compute the concurrence of the quantum dots as a measure of their entanglement. We find that this quantity smoothly changes in the vicinity of the phase transition, and in a step-like fashion in the Mott-insulator phase. This behavior can be externally monitored through the second-order correlation function for the light in each lattice site. For the finite case, we discuss boundary induced effects using a mean-field ansatz, as well as the impact of having finite temperatures on the entanglement of the quantum dots.

1:39PM Z27.00013 First-principles study of the energy and spin structure of excited states of NV−center in diamond and its corresponding Hubbard model parameters, SANGKOOK CHOI, MANISH JAIN, STEVEN G. LOUIE, University of California, Berkeley and Lawrence Berkeley National Laboratory — A negatively charged nitrogen-vacancy pair defect (NV) in diamond is one of the promising candidates to embody a qubit for quantum computation in solid states. It is an individually addressable quantum system that may be initialized, manipulated, and measured with high fidelity at room temperature due to a long coherence time of the spin in the ground states and long-life time of the excited states. The knowledge of the electronic and spin structures of the NV center in the ground as well as excited state is crucial in understanding them. Here, we evaluate the energies and spin structures of its excited states employing the first-principles GW-BSE methods. We further obtain the Hubbard model parameters for this defect system by comparing the excited-state energies from our ab-initio GW-BSE calculation with those from the model Hamiltonian. This work was supported by NSF Grant No. DMR10-1006184, the U.S. DOE under Contract No. DE-AC02-05CH11231. Computational resources have been provided by DOE at LBNL’s NERSC facility.

Friday, March 25, 2011 11:15AM - 12:39PM –
Session Z29 GQI: Focus Session: Superconducting Qubits - Coherence and Materials III C148

11:15AM Z29.00001 Improving the Quality Factor of Microwave Compact Resonators, K. GEERLINGS, S. SHANKAR, E. EDWARDS, L. FRUNZIO, R.J. SCHÖELKÖPF, M.H. DEVORET, Applied Physics Dept., Yale University — Superconducting microwave resonators are now widely used for coupling to superconducting qubit systems. Compact resonators [1] consisting of an interdigitated capacitance and a meander inductance take up much less space than a typical coplanar waveguide resonator. Since the design of compact resonators and qubits share common features, qubit decoherence mechanisms can be studied through the measurement of resonator loss. We measured order 100 resonators and have achieved internal quality factors in excess of 300,000. Results indicate loss appears to be due to spurious two level systems. Loss increases when the participation of surfaces in the energy density is increased. Thus a large separation of electrodes is preferred, in agreement with the findings of other groups. Work in progress involves the combination of these resonators with transmon qubits. Work supported by IARPA, ARO and the NSF.


11:27AM Z29.00002 Radiative Losses in Superconducting Coplanar Resonators, JAMES WENNER, R. BARENDS, R.C. BIALCZAK, Y. CHEN, J. KELLY, M. LENANDER, E. LUCERO, M. MARIANTONI, M. NEELEY, A.D. O’CONNELL, P. O’MALLEY, D. SANK, A. VAINSENCHER, H. WANG, M. WEIDES, T. WHITE, Y. YIN, J. ZHAO, A.N. CLELAND, JOHN M. MARTINIS, UC Santa Barbara — Radiation is a potential loss mechanism in superconducting qubits. Radiation loss was studied in superconducting coplanar resonators, which are important both in coupling superconducting qubits and because they provide a simple system to quantitatively measure the resulting effects. We fabricated 8 GHz resonators and measured the resulting reduction of the high-power Q. We found it was necessary to design the resonators carefully to reduce stray coupling between the resonators so that losses would be dominated by radiation. The radiation loss is measured to be 30 times greater than predicted by a simple theoretical model, but was predicted accurately by simulation data. We attribute this to the effects of the device mount and the finite substrate height on the radiation pattern. We conclude that radiation is an unlikely decoherence mechanism for the present generation of qubits and resonators.

11:39AM Z29.00003 Minimal resonator loss for circuit quantum electrodynamics, RAMI BARENDS, UC Santa Barbara, N. VERCUYSSSEN, A. ENDO, P.J. DE VISSE, T. ZULSTRA, T.M. KLÄPIWJK, Delft University of Technology, P. DIENER, S.J.C. YATES, J.J.A. BASELMANS, SRON Netherlands Institute for Space Research, H. WANG, M. HOFHEINZ, J. WENNER, M. ANSMANN, R.C. BIALCZAK, M. LENANDER, E. LUCERO, M. NEELEY, A.D. O’CONNELL, D. SANK, M. WEIDES, A.N. CLELAND, J.M. MARTINIS, UC Santa Barbara — In Josephson quantum information processing superconducting coplanar waveguides are used as memory elements and coupling buses. Quality factors of these resonators reach up to a million at high excitation powers, but decrease down to below 100x10^3 at the single photon level in the presently used materials, such as Al and Nb. We report quality factors of up to 500x10^3 by using NbTiN or Re and removing the dielectric from regions with high electric fields. Using a model-analysis and by a comparison with Ta, the crucial sources of intensity-dependent loss are dielectrics on the surface of the metal and substrate. Our approach shows that using non-oxidizing superconductors such as Re and NbTiN and removing dielectrics is a straightforward route to high quality factors in the single photon regime.

11:51AM Z29.00004 Low-loss superconducting microwave resonators with NbN films, C. SONG, B. XIAO, M. WARE, B.L.T. PLOURDE, Syracuse University — The native oxide that forms on the surface of most superconducting thin films contains a distribution of two-level system (TLS) defects that results in a significant microwave loss channel at low temperatures and powers. One of the key limitations in the quality factor of microwave devices in this regime for superconducting quantum information processing schemes is due to this surface loss mechanism. Thus, nitride superconducting materials are promising candidates due to their lack of a significant surface oxide. We have fabricated coplanar waveguide microresonators from reactively sputtered NbN films on sapphire and Si substrates. We characterize the resonators with measurements of the center frequency and quality factor as a function of temperature and power. In the low-temperature and low-power limit, we have observed quality factors for NbN resonators in excess of 200,000.

1Supported by IARPA
Low Loss Superconducting Titanium Nitride Coplanar Waveguide Resonators

Michael Vissers, David Wisbe, Jianson Gao, Jeffrey Kline, Martin Weides, David Pappas, NIST-Boulder — The introduction of new, low loss superconducting materials will be necessary for the improvement of superconducting qubits. To fulfill this aim, thin films of titanium nitride (TiN) were sputter-deposited onto intrinsic Si and c-plane sapphire wafers with and without SiN buffer layers. The films were then fabricated into RF coplanar waveguide resonators, and internal quality factor measurements were taken at millikelvin temperatures in both the high and low power limits, i.e., many and single photon regimes, respectively. At high power, internal quality factors (Qi’s) higher than 10^7 were measured for multiple TiN films with a predominantly (200) orientation. Films that showed significant (111) texture invariably had much lower Qi’s in this regime, on the order of 10^5. Our studies show that the (200) TiN is favored for growth at high temperature on either bare Si or substrates with SiN buffer layers. However, growth on bare sapphire or Si (100) at low temperature resulted in primarily a (111) orientation. Ellipsometry and Auger measurements indicate that the (200) TiN growth on the bare Si substrates is correlated with the formation of a thin, ~2nm, layer of SiN during the pre-deposition procedure. We found that TiN grown on these surfaces also showed significant increases of Qi in the low power limit, while thicker SiN buffer layers resulted in reduced Qi’s.

Dielectric loss measurements using an embedded transmission line resonator

Bahman Sarabi, M.J.A. Stoutimore, Moe Khalil, Sergiy Gladchenko, University of Maryland and Laboratory for Physical Sciences, Alexander Kozon, Gary Rubloff, F.C. Wellstood, J.C. Lobb, University of Maryland, K.D. Osborn, Laboratory for Physical Sciences — Lossy dielectrics are a major source of decoherence in superconducting qubits. Superconducting linear resonators have proven to be ideally suited for measuring loss in different dielectrics due to their versatility and relative simplicity in design, fabrication, and measurement. We will present data from samples where the low-loss coplanar resonators are fabricated on top of AlOx dielectric films grown using atomic layer deposition (ALD). Although the low-power loss can be extracted from this geometry, embedding the dielectric under study between metal films has advantages that we will discuss. In addition, ALD films can be grown conformally and without pinholes to small thicknesses in comparison to conventional PECVD films. This allows us to make lumped-element resonators with a relatively small footprint, which can easily be embedded within the transmission line.

Design and Fabrication of High Q Titanium Nitride Resonators

David Wisbe, Jianson Gao, Michael Vissers, Jeffrey Kline, Martin Weides, David Pappas, National Institute of Standards and Technology — Titanium nitride (TiN) is a new material that shows promise in quantum information circuits as a low loss material for resonators, and as a multiplexed kinetic inductance photon detector. We have measured lumped element LC resonators and coplanar waveguides resonators. For the lumped element resonator we report internal quality factor (Qi) of over 300,000 at low power, in the single photon regime, and 4 million at high power, and for a half wave coplanar waveguide we report low power Qi of 800,000 and high power Qi of 5 million. We found that overetch in single layer devices can shift the resonance frequency and affect the internal quality factor Qi, and that as the trench depth grew, both the resonance frequency and internal quality factor increased. When designing resonators it is important to know quantities such as the kinetic inductance, superconducting transition temperature (Tc), penetration depth, and amount of overetch so the resonator can be accurately simulated.