by energy relaxation, we demonstrate a magnetic field detection sensitivity of high-fidelity quantum measurement, in a way similar to atomic magnetometry. Using an operation mode based on spin-echo manipulation and qubit reset, the magnetic memory—caused by a spatial distribution of trapped vortices—is related to the resonator geometry.

a large range of photon number levels, temperatures, and magnetic fields. The resonators exhibit strong magnetic hysteresis effects in frequency and quality factor. However, under certain circumstances, the presence of trapped vortices can actually lead to an enhancement of the resonator quality factor. In particular we discuss the influence of the spin-spin interactions on the susceptibility noise.

8:24AM A25.00003 Experimental results on decoherence and readout of coupled superconducting flux qubits in a circuit-QED setup1. JEAN-LUC ORGIAZZI, DAVID LAYDEN, Institute for Quantum Computing, University of Waterloo, RYAN MARCHILDON, University of Toronto, MUSTAFA BAL, CHUNQING DENG, FLORIAN ONG, ADRIAN LUPASCU, Institute for Quantum Computing, University of Waterloo—We present the results of experiments with two superconducting flux qubits coupled to a high-quality factor aluminum coplanar waveguide resonator. The flux qubits have a loop area of ~24 μm². The coupling to the resonator is implemented using the inductance of a shared line. The qubits are independently controlled via on-chip fast flux bias lines. Readout is performed by homodyne detection at large resonator driving power. Readout contrast exceeds 70% for each qubit. We observed long relaxation times, approaching 10 microseconds. The coherence time at the symmetry point exceeds 1 microsecond. Away from the symmetry point, decoherence is due to 1/f flux noise, with a measured density of 2.6 × 10⁻⁶ φ₀/√Hz at 1 Hz. We discuss the implementation of a two-qubit controlled-NOT gate using the selective darkening technique [1]. [1] P. C. de Groot, J. Lisenfeld, R. N. Schouten, S. Ashhab, A. Lupascu, C. J. P. M. Harmans, and J. E. Mooij. Nat. Phys., 6(10):763-766, October 2010.

1We acknowledge support from NSERC, Canada Foundation for Innovation, Ontario Ministry of Research and Innovation, and Industry Canada. AL is supported by a Sloan Fellowship. JLO is supported by a WIN scholarship.

9:00AM A25.00006 Effects of vortices trapped in superconducting microwave resonators. IBRAHIM NSANZINEZA, B.L.T. PLOURDE, Syracuse University—The microwave response of superconductors can be influenced by the presence of vortices and the dynamics they exhibit at high frequencies. We present measurements of vortices trapped in coplanar waveguide superconducting resonators fabricated from thin aluminum films, a common material for superconducting qubit circuits. In particular, by adjusting the geometry of our resonators we are able to trap only a few vortices in certain regions of the resonators. We perform field-cooled measurements to study the dependence of the microwave vortex response on magnetic field and frequency for various resonator modes. In most cases, the addition of vortices results in a downward shift in resonant frequency and a reduction in the quality factor. However, under certain circumstances, the presence of trapped vortices can actually lead to an enhancement of the resonator quality factor.

9:12AM A25.00002 Surface spins in superconducting qubits: noise of noise and noise of inducance, ALEXANDER SHNIRMAN, PABLO SCHAD, BORIS NAROZHNY, GERD SCHOEN, Karlsruhe Institute of Technology—in the last several years a growing bulk of experimental evidence has emerged explaining the 1/f magnetic flux noise in superconducting circuits, e.g., qubits, by a very high density of paramagnetic impurities on the surfaces or interfaces of the superconducting metal. A theoretical picture of this phenomenon is still missing. Here we study a model of weakly interacting dissipative spins or spin clusters with the aim to determine their noise properties. In particular we compare the noise of noise (second spectrum) with the noise of the magnetic susceptibility measured as noise of inducance. Both of these were recently studied in experiments. We argue that the noise of inducance is dominated by a simple gaussian background, whereas the noise of susceptibility can provide a hint about the microscopic nature of the spins. In particular we discuss the influence of the spin-spin interactions on the susceptibility noise.

9:24AM A25.00005 Magnetic Field Effects on High Quality Factor Superconducting Coplanar Resonators. ANTHONY MTEGRANT, CHARLES NEILL, RAMI BAREND, YU CHEN, BEN CHIARO, JULIAN KELLY, MATTEO MARIANTONI, JOSH MUTUS, PETER O’MALLEY, DANIEL SANK, AMIT VAINSENCHER, JAMES WENER, TRED WHITE, DAVID LOW, SHINOBU OHYA, CHRISTOPHER PALMSTROM, JOHN MARTINIS, ANDREW CLELAND, UC Santa Barbara—Superconducting coplanar waveguide resonators have proven to be invaluable tools in studying some of the same decoherence mechanisms as those found in superconducting qubits. Prior improvements in fabrication led to resonator internal quality factors (Qi’s) in excess of 10 million at high power, enabling us to sensitively probe environmental effects on the resonance frequency and Qi. We have found these resonators to be very susceptible to applied and stray magnetic fields, with measurable changes in the resonator’s Qi and resonance frequency from fields as small as a few milligauss. I will present more recent measurements of resonators in magnetic fields.
9:24AM A25.00008 Flux-dependent loss in aluminum nanobridge SQUID resonators \(^1\). E. M. LEVENSON-FALK, R. VIJAY, I. SIDIQI, QNL, UC Berkeley — Unlike traditional tunnel junctions, nanobridge Josephson junctions have weaker nonlinearity, higher transmissivity, and relatively few conduction channels. These parameters carry with them their own intrinsic loss mechanisms. In particular, quasiparticle trapping has been recently shown \(^1\) to be prevalent in quantum point contact junctions operating in a similar parameter regime. We investigate losses in resonant circuits comprised of nanobridge SQUIDs. We observe an increase in loss and an anomalous frequency shift as the SQUIDs are flux-biased, which we speculate to be the result of quasiparticle tunneling in a phase-biased nanobridge. We present detailed measurements of this effect, and discuss efforts towards eliminating it. \[^1\] Bretheau et al., PRL 106, 257003 (2011)

9:36AM A25.00009 Random frequency modulation of a superconducting qubit \(^1\), MATTI SILVERI, University of Oulu, JIAN LI, KARThIKEYAN SAPMANTH, JUHA-MATTI PIKKALEINEN, ANTTI VEPSÄLÄINEN, WEI-CHENG CHIEN, Aalto University School of Science, JANI TUORILA, University of Oulu, MIKA SILLANPÄÄ, PERTTI HAKonen, Aalto University School of Science, ERKKI THUNEBERG, University of Oulu, GHEORGHE PARAANOU, Aalto University School of Science — Superconducting circuits with Josephson junctions are a promising platform not only for developing quantum technologies, but, importantly, also for the study of effects that typically occur in complex condensed-matter systems. Here, we employ a transmon qubit to conduct an analog simulation of motional averaging, a phenomenon initially observed in nuclear magnetic resonance spectroscopy. To realize this effect, the flux bias of the transmon is modulated by a controllable pseudo-random telegraph noise, which results in stochastic jumping of the energy separation (frequency) between two discrete values. This can also be seen as a simulated fast-fluctuation environment under direct experimental control. Additionally, we discuss the population dynamics using an analytical master equation, and apply the motional averaging analysis on phenomena where the fluctuation of the energy is due to quasiparticles or to photon shot noise.

9:48AM A25.00010 Driven Dynamics and Rotary Echo of a Qubit Tunably Coupled to a Harmonic Oscillator \(^1\). WILLIAM OLIVER, MIT Lincoln Laboratory, Lexington, Massachusetts, SIMON GUSTAVSON, JONAS BYLANDER, FEI YAN, POL FORN-DIAZ, Massachusetts Institute of Technology, Cambridge, Massachusetts, VLAD BOLKHOVSKY, DANIELLE BRAJE, GEORGE FITCH, MIT Lincoln Laboratory, Lexington, Massachusetts, KHALIL HARRABI, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama, Japan, DONNA LENNON, JOVI MILOSHI, PETER MURPHY, RICK SLATTERY, STEVEN SPECTOR, BEN TUREK, TERRY WEIR, PAUL WELANDER, MIT Lincoln Laboratory, Lexington, Massachusetts, FUMIKI YOSHIIHARA, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama, Japan, DAVID CORY, Institute for Quantum Computing and Department of Chemistry, University of Waterloo, Ontario, Canada, YASUNOBU NAKAMURA, The University of Tokyo, Komaba, Meguro-ku, Tokyo, Japan, TERRY ORLANDO, Massachusetts Institute of Technology, Cambridge, Massachusetts — We have investigated the driven dynamics of a superconducting flux qubit that is tunably coupled to a microwave resonator. We find that the qubit experiences an oscillating field mediated by off-resonant driving of the resonator, leading to strong modifications of the qubit Rabi frequency. This opens an additional noise channel, and we find that low-frequency noise in the coupling parameter causes a reduction of the coherence time during driven evolution. The noise can be mitigated with the rotary-echo pulse sequence, which, for driven systems, is analogous to the Hahn-echo sequence.

10:00AM A25.00011 Effect of environmental coupling on tunneling of quasiparticles in Josephson junctions \(^1\). MOHAMMAD ANSARI, University of Waterloo, FRANK WILHELM, Saarland University, URBASI SINHA, Raman Research Institute, ANINDA SINHA, Indian Institute of Science — We study quasiparticle tunneling in Josephson tunnel junctions embedded in an electromagnetic environment. We identify tunneling processes that transfer electrical charge and couple to the environment in a way similar to that of normal electrons, and processes that mix electrons and holes and are thus creating charge superpositions. The latter are sensitive for the phase difference between the superconductor and are thus limited by phase diffusion even at zero temperature. We show that this term is suppressed in many environments, thus leading to lower quasiparticle decay rates and thus better qubit coherence than previously expected.

\[^1\] supported by NSERC, ODNI, IARPA

10:12AM A25.00012 Real-time measurement of quasiparticle tunneling in a single-junction transmon qubit using feedback \(^1\). DIEGO RISTÈ, NIELS BULTINK, MARUN TIEGELMAN, RAYMOND SCHOUTEN, Kavli Institute of Nanoscience, Delft University of Technology, KONRAD LEHNERT, JILA, NIST and the University of Colorado, Boulder, LEONARDO DICARLO, Kavli Institute of Nanoscience, Delft University of Technology — Consistent high coherence of superconducting qubits now exceeding 100 µs, the contribution of quasiparticle (QP) tunneling to qubit relaxation and dephasing becomes potentially relevant. We report the real-time measurement of QP tunneling across the single junction of a 3D transmon qubit. We integrate recent developments in projective qubit readout with 99% fidelity and feedback-based reset to transform the qubit into a charge-parity detector with 6 µs resolution. We detect a symmetric random telegraph signal matching a QP tunneling time of 0.8 ms. By measuring the correlation function of charge parity conditioned on specific initial and final qubit states, we determine that most QP tunneling does not induce qubit transitions, in contradiction with recent theory \(^1\). We extract a QP-induced qubit relaxation time \(T_1^{\text{QP}} \sim 3\) ms, decidedly not limiting the measured \(T_1 = 0.14\) ms.


\[^2\] Research supported by NWO, FOM, and EU Project SOLID.

10:24AM A25.00013 Interfacing Superconducting Quibts and Resonator Qudits. FREDERICK STRAUCH, Williams College, XIAOTING WANG, KURT JACOBS, University of Massachusetts at Boston — We consider methods to transfer multi-qubit states into the higher-dimensional state space of a superconducting resonator, acting as a qudit. Several methods are proposed, using different combinations of resonant, dispersive, and auxiliary interactions. The complexity of such schemes are explored using analytical and numerically optimized control sequences. Extension to resonator measurement and qubit logic will be also be described.

10:36AM A25.00014 Frequency multiplexed dispersive readout of transmon qubits with the UCSB paramp \(^1\). DANIEL SANK, UCSB, R. BARENDTS, J. BOCHMANN, B. CAMPBELL, Y. CHEN, B. CHIARO, E. JEFFREY, J. KELLY, M. MARIANTONIO, A. MEGRANT, J. MUTUS, C. NEILL, P. O’MALLEY, S. OHYA, P. ROUSHAN, A. VAINSENCHER, J. WENNER, T. WHITE, A.N. CLELAND, J.M. MARTINIS, UC Santa Barbara — Our new Xmon qubit shows good coherence, controllability and simplified coupling to other circuit elements, making it a good candidate for a large scale quantum computer. Like all qubits, it requires high fidelity readout. To this end we have developed a new parametric amplifier circuit. Simplified input coupling of the amplifier allows straightforward interfacing with our frequency multiplexed dispersive readout circuitry. The amplifier features five different modes of pump power delivery, some of which allow us to reduce the microwave component count in our readout chain. We characterize our readout system using each of these modes of operation, as well as multi qubit readout.
10:48AM A25.00015 Engineering and control of coupled superconducting qubits arrays for quantum simulation1, E. HENRY, A. SCHMIDT, QNL, UC Berkeley, O. VIEHMANN, Ludwig-Maximilians-Universität, I. SIDDIQI, QNL, UC Berkeley — Superconducting qubit technology allows for engineering experimentally accessible, macroscopic quantum systems to arbitrary specifications within a large parameter space. By coupling multiple superconducting qubits in a periodic array, it is possible to fabricate physical objects which mimic the properties of naturally occurring systems not readily accessible to measurement or parameter variation, or theoretical systems not occurring in nature. We discuss design, fabrication, and measurement of a physical realization of the quantum Ising model in zero and one dimension. This is accomplished using a chain of identical transmon qubits acting as artificial spins whose interaction is dominated by nearest neighbor coupling. Control and readout of the system is accomplished by coupling only one of the artificial spins to a microwave resonator in a circuit QED architecture.

---

**Monday, March 18, 2013 8:00AM - 11:00AM**

**Session A26 GQI: Focus Session: Semiconductor Qubits - Optical Hybridization**

---

8:00AM A26.00001 Observation of quantum dot spin-photon entanglement, ATAC IMAMOGLU, ETH Zurich — Entanglement plays a central role in the burgeoning field of quantum information processing. A possible route towards a scalable architecture is provided by the concept of distributed quantum computation, based on small-scale few-qubit quantum processor nodes interconnected by single photon pulses. Generation of quantum correlated spin-photon pairs is a key step in such an approach. In this talk, we report the observation of quantum entanglement between a semiconductor quantum dot spin and the color of a propagating optical photon. The demonstration of entanglement relies on the use of fast single-photon detection which allows us to project the photon into a superposition of its two frequency components. Our results extend the previous demonstrations of single-spin photon entanglement in trapped ions, neutral atoms and nitrogen vacancy centers to the domain of artificial atoms in semiconductor nano-structures that allow for on-chip integration of electronic and photonic elements.

8:36AM A26.00002 Entanglement between a single quantum spin and a photon through ultra-fast frequency downconversion to telecom wavelengths, KRISTIAAN DE GREVE, Stanford University (currently at Harvard University), LEO YU, PETER MCMAHON, Stanford University, JASON PELC, Stanford University (currently at HP Labs, Palo Alto), CHANDRA NATARAJAN, NA YOUNG KIM, Stanford University, EISUKE ABE, Stanford University and NII, Tokyo, Japan, SEBASTIAN MAIER, CHRISTIAN SCHNEIDER, MARTIN KAMP, Universitaet Wuerzburg, SVEN HOEFLING, Stanford University and Universitaet Wuerzburg, ROBERT HADFIELD, Heriot-Watt University, ALFRED FORCHEL, Universitaet Wuerzburg, MARTIN FEJER, Stanford University, YOSHIHISA YAMAMOTO, Stanford University and NII, Tokyo, Japan — We demonstrate high-fidelity entanglement between a single InAs quantum dot electron spin, and the polarization of a spontaneously emitted single photon. With a magnetic field in Voigt geometry, the quantum dot’s excited (trion) states are connected to the spin states in a lambda-configuration. We use these lambda-systems for all-optical spin manipulation, and spontaneous emission from one of the trion states gives rise to entanglement between both the polarization and color of the photon, as well as the spin state. Leakage of which-path information through e.g. the color of the photon obscures the spin-photon-polarization entanglement, which we overcome by a quantum erasure procedure. By time-resolved frequency conversion to a low-fiber-loss wavelength (1560 nm), we measure the photon arrival time with sub-10 ps resolution. Such ultrafast detection is inherently broadband, and incapable of distinguishing between the respective colors of the decay paths, providing the necessary quantum erasure. The conversion to 1560 nm also provides a means to extend the distance over which spin-photon entanglement can be maintained.

8:48AM A26.00003 Tomography of a high-fidelity spin-photon entangled state, PETER MCMAHON, KRISTIAAN DE GREVE, LEO YU, JASON PELC, CHANDRA NATARAJAN, NA YOUNG KIM, EISUKE ABE, Stanford University, SEBASTIAN MAIER, CHRISTIAN SCHNEIDER, MARTIN KAMP, SVEN HOEFLING, Universitaet Wuerzburg, ROBERT HADFIELD, Heriot-Watt University, ALFRED FORCHEL, Universitaet Wuerzburg, M.M. FEJER, YOSHIHISA YAMAMOTO, Stanford University — The generation of entanglement between a quantum memory and a flying qubit is an important step towards building a quantum repeater node. Entanglement between a photon and a matter qubit has been demonstrated in several systems, including neutral atoms, trapped ions, NV centers and quantum dots. Quantum dots have a natural advantage that their radiative lifetimes are short, and therefore the rate of entanglement generation can be much faster than in other systems. We have recently demonstrated entanglement between an electron spin in a quantum dot, and the polarization of an emitted photon. In addition, the photon is converted to the low-loss 1550 nm band, which is important for implementing long-distance quantum communication systems. In this talk, I will present the reconstruction of the full density matrix of the entangled spin-photon state that we produce. We calculate the fidelity of the state from the density matrix, and conclude that it is > 90%.

---

1This work was supported by the JSPS through its FIRST programme, NICT, NSF CCR-08 29694, NIST 60NANB9D9170, Special Coordination Funds for Promoting Science and Technology, and the State of Bavaria.

9:00AM A26.00004 Ultrafast downconversion quantum interface for a single quantum dot spin and 1550-nm single-photon channel, L. YU, J.S. PELC, K. DE GREVE, P.L. MCMAHON, M.M. FEJER, E. L. Ginzton Laboratory, Stanford University, Y. YAMAMOTO, E. L. Ginzton Laboratory, Stanford University and National Institute of Informatics, Tokyo, S. MAIER, C. SCHNEIDER, M. KAMP, S. HOEFLING, Technische Physik, Physikalisches Institut, Wilhelm Conrad Rontgen Research Center for Complex Material Systems, Universitat Wurzburg; C.M. NATARAJAN, R.H. HADFIELD, Scottish Universities Physics Alliance and School of Engineering and Physical Sciences, Heriot-Watt University — Long-distance quantum communication networks require appropriate interfaces between matter qubit-based nodes and low-loss photonic quantum channels. Quantum frequency conversion (QFC), whereby a photonic qubit’s carrier frequency is translated while maintaining its quantum state, is well-suited to the task. Quantum dots have been studied extensively as potential quantum network nodes, but they do not emit indistinguishable single photons at telecom wavelengths. We report an ultrafast, low-noise downconversion quantum interface, in which 910-nm single photons from a quantum dot are downconverted to the 1.5-µm lowest-loss telecom band, showing near-perfect preservation of antibunched photon statistics. Moreover, the resulting time resolution could also improve photon indistinguishability. Together with the III-V semiconductor quantum dot spin system, this ultrafast downconversion quantum interface provides new possibilities to realize long-distance quantum communication networks.
9:12AM A26.00005 Observation of quantum entanglement between a photon and a single electron spin confined to an InAs quantum dot. JOHN Schaibley, Alex Burgers, Greg McCracken, Luming Duan, Paul Bernman, Duncan Steel, University of Michigan, Allan Bracker, Daniel Gammon, Naval Research Lab, Lui Sham, University of California, San Diego — A single electron spin confined to a single InAs quantum dot (QD) can serve as a qubit for quantum information processing. By utilizing the QD’s optically excited trion states in the presence of an externally applied magnetic field, the QD spin can be rapidly initialized, manipulated, and read out. A key resource for quantum information is the ability to entangle distinct QD spins. One approach relies on intermediate spin-photon entanglement to mediate the entanglement between distant QD spin qubits. We report a demonstration of quantum entanglement between a photon’s polarization state and the spin state of a single electron confined to a single QD. Here, the photon is spontaneously emitted from one of the QD’s trion states. The emitted photon’s polarization along the detection axis is entangled with the resulting spin state of the QD. By performing projective measurements on the photon’s polarization state and correlating these measurements with the state of the QD spin in two different bases, we obtain a lower bound on the entanglement fidelity of 0.59 (after background correction). The fidelity bound is limited almost entirely by the timing resolution of our single photon detector. The spin-photon entanglement generation rate is $3 \times 10^3$ s$^{-1}$.

1Supported by: NSF, MURI, AFOSR, DARPA, ARO.

2Currently at Stanford University

9:24AM A26.00006 A Spin Qubit Coupled to a Photonic Crystal Cavity. Timothy Sweeney, NRC postdoc at the Naval Research Lab, Washington, DC 20375, Samuel Carter, NRL, Mujin Kim, Sotera Defense Solutions, Annapolis, MD 20701, Chul Soo Kim, NRL, Dmitry Solenov, NRL postdoc at NRL, Sophia Economou, Thomas Reineke, NRL, Lily Yang, NRC postdoc at NRL, Allan Bracker, Daniel Gammon, NRL — The development of a scalable light-matter quantum interface is an important goal of quantum information research. Photonic crystal (PC) membranes provide an architecture in which the interaction of photons with an optically active matter qubit can be controlled through the introduction of optical cavities and waveguides. Charge neutral quantum dots are commonly integrated into PC architectures and are useful for sources and switches, but do not demonstrate long-lived coherences. A charged quantum dot in a PC environment could lead to a spin-photon quantum interface, where it is the long-lived spin of the electron, not the exciton that serves as a qubit. We demonstrate optical spin initialization and coherent control of an electron in a quantum dot that is embedded in and coupled to a 2D PC membrane cavity. The PC membrane is incorporated into an asymmetric NIP diode that allows for charging of an InAs quantum dot via an applied bias. Resonant laser spectroscopy performed in a transverse magnetic field enables the optical measurement and initialization of the electron spin. Furthermore, with the introduction of detuned control pulses, we perform coherent rotations of the electron spin state. These studies demonstrate several essential accomplishments toward a spin-photon interface.

9:36AM A26.00007 Quantum Dots in H1 Photonic Crystal Microcavities for Quantum Information. Jenna Hagemeier, Physics Department, University of California Santa Barbara, USA, Cristian Bonato, Huygens Laboratory, Leiden University, The Netherlands, Pierre Petroff, ECE Department, University of California Santa Barbara, USA, Dirk Bouwmeester, Physics Department, University of California Santa Barbara, USA, Huygens Laboratory, Leiden University, The Netherlands — Coupling semiconductor quantum dots to optical microcavities is a promising technique for implementing quantum information processing protocols in the solid-state. By placing one or more emitters in a cavity, it is possible to create an efficient source of single photons or to explore collective interactions of few-emitter systems. Our devices consist of two layers of quantum dots, embedded in the cavity region of H1 photonic crystal microcavities. One of the quantum dot layers can be frequency-tuned deterministically, allowing two resonant quantum dots to be coupled to a single cavity mode. Because good mode-matching between the cavity mode and the input/output channel is necessary for many applications, we optimize the far-field profiles of our H1 cavities and demonstrate strong enhancement of the external mode matching properties. We will discuss our far-field optimization results as well as our ongoing work to study interactions of multiple emitters in a cavity.

9:48AM A26.00008 Dynamical effects of Stark-shifted quantum dots strongly coupled to photonic crystal cavities. Kaushik Roy Choudhury, Ranojoy Bose, Edo Waks, Department of Electrical and Computer Engineering, IREAP, University of Maryland, College Park, Maryland 20742, USA — Single semiconductor quantum dots (QDs) strongly coupled to photonic crystal cavities are a strong candidate for single photon generation, ultra-fast all optical switching and quantum information processing. A single quantum dot can be used to generate ultra-fast indistinguishable single photons using rapid Stark tuning of the quantum dot. Theoretical limit for the speed is shown to be faster than adiabatic rapid passage technique used for microwave photon generation in circuit QED. A systematic study of role of device parameters such as pulse shape, dot-cavity coupling and incoherent losses on the efficiency and speed of single photon generation is also presented for possible experimental realization.

10:00AM A26.00009 Optical tuning of single quantum dots coupled to photonic crystal molecules using the optical Stark effect. Ranojoy Bose, University of Maryland, College Park, Kaushik Roy, Tao Cai, University of Maryland, College Park, Glenn S. Solomon, NIST-Gaithersburg, and Joint Quantum Institute, University of Maryland, College Park, Edo Waks, University of Maryland, College Park — The interaction of semiconductor quantum dots (QD) with photonic crystal resonator systems provides a highly integrated, solid-state platform for studies in ultra-low energy nonlinear optics and quantum optical phenomena. Here, we present a method to tune a semiconductor quantum dot (QD) all-optically into resonance with a cavity mode using the non-resonant optical Stark effect. We use a system comprised of two evanescently coupled photonic crystal cavities containing a single QD in one of the cavities. One mode of the coupled cavity system is used to generate a cavity-enhanced optical Stark shift, enabling the QD to be resonantly tuned to the other cavity mode. We show that the optical tuning of the QD results in a large radiative enhancement of the QD photon emission via the Purcell effect. We will further discuss dynamic experiments in the system using a Stark laser that has a time-duration on the order of the system decay rates. We will show that under this scenario, the cavity-QD spectrum provides a rich array of information on the system dynamics. The experiments are promising for a variety of applications in highly-efficient single photon generation, cavity quantum electrodynamics, ultra-fast optical switching, and classical and quantum information processing.
10:12AM A26.00010 Controlling interactions between coupled photonic crystal cavities using photochromic tuning. TAO CAI, RANOJOY BOSE, Department of Electrical Engineering, University of Maryland, College Park, GLENN SOLOMON, Joint Quantum Institute, University of Maryland and National Institute of Standards and Technology, National Institute of Standards and Technology, EDO WAKS, Department of Electrical Engineering, University of Maryland, College Park — Strongly coupled photonic crystal (PhC) resonator systems provide a promising platform for studying cavity quantum electrodynamics (QED) using semiconductor quantum dots (QDs). These device structures enable important applications such as photon blockade, quantum simulation, quantum-optical Josephson interferometer, and quantum phase transition of light. Many of these applications require the ability to accurately tune the resonant frequencies of individual cavities in the array, which provides a method to control their coupling interactions. This tuning method must be sufficiently local to address individual cavities spaced by less than 1 micron spatial separation. Here, we present a method for controlling the coupling interaction of photonic crystal cavity arrays by using a local and reversible photochromic tuning technique. By locally altering the refractive index of the photochromic material all-optically, the coupling interaction between two cavity modes could be modified over a tuning range as large as 700 GHz. By using this technique, we demonstrate the ability to couple photonic crystal cavities with a normal mode splitting of only 31.50 GHz. We further demonstrate that this tuning method can be extended to control the coupling interaction in larger cavity arrays.

10:24AM A26.00011 A qubit-photon controlled-NOT gate using a quantum dot strongly coupled to a cavity. HYOCHUL KIM, RANOJOY BOSE, THOMAS SHEN, University of Maryland, GLENN SOLOMON, Joint Quantum Institute, NIST, EDO WAKS, University of Maryland — Strong interactions between matter quantum bits (qubits) and photons play an essential role in quantum information. Quantum dots (QDs) provide a promising implementation of a matter qubit that can be strongly coupled to optical nanocavities, providing a direct light-matter interface. We use this light-matter interface to demonstrate a picosecond timescale controlled NOT logic gate between a QD and a photon, which is a fundamental building block for complex quantum logic. Coherent control of the QD qubit state by optical pulses results in a modification of cavity reflectivity, enabling a conditional bit-flip on the polarization state of a photon incident on the cavity.

10:36AM A26.00012 All-optical, arbitrary-basis initialization and readout of a diamond spin qubit. C. G. YALE*, B. B. Buckley*, D. J. Christle, G. Burkard, F. J. Heremans, L. C. Bassett, D. D. Awschalom, Center for Spintronics and Quantum Computation, University of California, Santa Barbara, California 93106, G. BURKARD, Department of Physics, University of Konstanz, D-78457 Konstanz, Germany — The nitrogen-vacancy (NV) center in diamond is a promising spin qubit candidate, in large part due to its optical addressability via a spin-selective intersystem crossing. Here we demonstrate a general all-optical technique to initialize and readout the NV spin state along an arbitrarily-chosen basis using coherent light fields below 10 K, which negates the need for this special addressability. By tuning the NV center’s excited-state structure to a lambda (Λ) configuration with a magnetic field, we use coherent population trapping (CPT) to initialize its spin into any desired superposition. We investigate the CPT time dynamics and use quantum state tomography to characterize the resultant state. We also demonstrate spin-state readout along an arbitrarily-chosen basis by measuring photoluminescence emitted during the transient period of the CPT interaction. Since these techniques do not rely on the intersystem crossing, they provide a pathway for all-optical control of other potential defect spin qubits, which may lack the pathway’s unique structure.

1This work is funded by AFOSR, ARO, and DARPA.


Monday, March 18, 2013 8:00AM - 11:00AM — Session A27 GQI: Focus Session: Adiabatic Quantum Computing I

8:00AM A27.00001 Adiabatic Quantum Computation with Neutral Atoms. GRANT BIEDERMANN, Sandia National Laboratories — We are implementing a new platform for adiabatic quantum computation (AQC) based on trapped neutral atoms whose coupling is mediated by the dipole-dipole interactions of Rydberg states. Ground state cesium atoms are dressed by laser fields in a manner conditional on the Rydberg blockade mechanism, thereby providing the requisite entangling interactions. As a benchmark we study a Quadratic Unconstrained Binary Optimization (QUBO) problem whose solution is found in the ground state spin configuration of an Ising-like model. In collaboration with Lambert Parazzoli, Sandia National Laboratories; Aaron Hankin, Center for Quantum Information and Control (CQuIC), University of New Mexico; James Chin-Wen Chou, Yuan-Yu Jau, Peter Schwindt, Cort Johnson, and George Burns, Sandia National Laboratories; Tyler Keating, Krittika Goyal, and Ivan Deutsch, Center for Quantum Information and Control (CQuIC), University of New Mexico; and Andrew Landahl, Sandia National Laboratories.

3This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories.


8:36AM A27.00002 On scalable, universal adiabatic quantum computation. ARI MIZEL, Laboratory for Physical Sciences — We investigate scalable, universal adiabatic quantum computation. We exhibit a specific Hamiltonian of local one- and two-body interactions for which the ground state (a) yields the correct answer with high probability and (b) is provably fault-tolerant against local excitations. The effects of finite temperature are discussed.
9:00AM A27.00004 Experimental signatures of quantum annealing¹, SERGIO BOIXO, ISI - USC — Quantum annealing is a general strategy for solving optimization problems with the aid of quantum adiabatic evolution. How effective is rapid decoherence in precluding quantum effects in a quantum annealing experiment, and will engineered quantum annealing devices effectively perform classical thermalization when coupled to a decohering thermal environment? Using the D-Wave machine, we report experimental results for a simple problem which takes advantage of the fact that for quantum annealing the measurement statistics are determined by the energy spectrum along the quantum evolution, while in classical thermalization they are determined by the spectrum of the final Hamiltonian. We establish an experimental signature which is consistent with quantum annealing, and at the same time inconsistent with classical thermalization, in spite of a decoherence timescale which is orders of magnitude shorter than the adiabatic evolution time. For larger and more difficult problems, we compare the measurement statistics of the D-Wave machine to large-scale numerical simulations of simulated annealing and simulated quantum annealing, implemented through classical and quantum Monte Carlo simulations. For our test cases the statistics of the measured annealing time exhibit decoherence uncertainties - indistinguishable from a simulated quantum annealer with suitably chosen parameters, but significantly different from a classical annealer.


9:36AM A27.00005 Benchmarking the D-Wave adiabatic quantum optimizer via 2D-Ising spin glasses, ZHIHUI WANG, SERGIO BOIXO, TAMEEM ALBASH, DANIEL LIDAR, University of Southern California — We present results on benchmarking the D-Wave One quantum optimizer chip using random 2D Ising spin problems. Finding the ground state of the 2D Ising model with randomly assigned local fields and couplings is NP-hard. The chip attempts to find the ground state via quantum annealing, interpolating between a transverse field and the final Ising Hamiltonian. The experimentally obtained final states are checked against exact results and the performance of the chip is characterized by the probability of finding the ground state and the estimated annealing time for finding the ground state with high probability. By analyzing results for 8 to 108 spins, the scaling of the estimated annealing time as a function of the number of spins is compared with the computation time required by classical solvers. The correlation between classical and quantum hardness is also studied. Furthermore, we analyze the correlation between the experimental success probability and the minimum energy gap during the quantum annealing, as well as the interplay between the adiabatic condition and thermalization.

10:00AM A27.00007 Computational performance and scaling of adiabatic quantum annealing processors¹, TROELS FRIMODT RØNNOW, SERGEI ISAKOV, Institut f. Theoretische Physik, ETH Zürich, DAVE WECKER, Microsoft Corporation, SERGIO BOIXO, Center for Quantum Information Science & Technology - Information Sciences Institute, MATTHIAS TROYER, Institut f. Theoretische Physik, ETH Zürich — We characterise the recent 128 qubit quantum annealer processor, D-Wave One, through investigation of hardness and scaling of "time-to-solution" for several thousand realisations of ± J spin glass problems, ranging from 8 to 108 qubits in size. We compare statistics of the results to classical- and simulated quantum annealing. Within both processors noise and calibration uncertainties, we find that the results generated by the D-Wave One are statistically indistinguishable from results generated by a simulated quantum annealer while significantly different from those of a classical annealer. An intriguing feature is the strong bimodal separation of the instances into two categories: hard and easy. This feature is not observed for the classical annealer. Based on the similarities between the simulated quantum annealer and D-Wave One, we make predictions for the 512 qubit processor, D-Wave Two.

¹ John Martinis, Department of Physics, University of California

10:12AM A27.00008 Error correction in adiabatic quantum computation, KEVIN YOUNG, MOHAN SAROVAR, ROBIN BLUME-KOHOUT, Sandia National Laboratories, SANDIA NATIONAL LABORATORIES TEAM — In conventional quantum computing models (e.g. the circuit-model) it is well understood that error suppression alone does not provide a mechanism to remove the entropy generated by errors from the encoded system. Since the thermodynamic argument is independent of the computational model it is expected that error suppression alone is insufficient for fault-tolerant quantum computing. From a thermodynamic perspective this is because error suppression alone does not provide a mechanism to remove the entropy generated by errors from the encoded system. Since the thermodynamic argument is independent of the computational model it is expected that error suppression alone is insufficient for fault-tolerant quantum computing in the adiabatic quantum computing (AQC) model also. In this talk we provide a scheme for performing error correction for AQC and discuss the differences between our method and those used in quantum circuit model implementations.

10:24AM A27.00009 Experimental Quantum Error Correction, KRISTEN PUDENZ, DANIEL LIDAR, University of Southern California — We demonstrate an experimentally implemented quantum error correcting code (QECC) in an adiabatic quantum computation (AQC) setting. In AQC, the computation proceeds by slowly changing the controls of the system to move from an initial Hamiltonian with an easily prepared ground state to a final Hamiltonian whose ground state embodies the solution to the problem. Our QECC is a repetition code in the computational basis, and encodes the final Hamiltonian of the computation. In this way, we provide an energy penalty for excursions outside the codespace which increases as the AQC progresses.

We supplement this with classical decoding of the results at the end of the computation, so that the computation may finish in a state other than the ground state and still solve the problem, as long as it stays within the low-lying spectrum of decodable states. We will show experimental results demonstrating that AQCs encoded with our QECC exhibit better success rates than both unencoded and classically encoded versions.

10:36AM A27.00010 Adiabatic quantum computational properties of Hopf link, OMAR SHEHAB, University of Maryland, Baltimore County — Topological quantum computation has recently become an active field of research with a promise of tackling decoherence and error correction. However, research on adiabatic quantum computation has been limited to low dimensional topological constructs. We study the properties of a Hopf link related to adiabatic quantum computation. The graph and Seifert surface for the link are calculated. The Ising model representing the Hopf link is then derived from the surface. The Edwards-Anderson Hamiltonian is also solved for the Ising model. The associated eigenfunction and eigenvalues are then used to investigate computational problems which can be represented by the ground state of the adiabatic Hamiltonian. We also consider a type II Reidemeister move on the link. The graph and Seifert surface are calculated for the new link. Then the Edwards-Anderson Hamiltonian is solved for the associated Ising model. The constraints of adiabatic evolution are calculated for both cases. Finally, computational problems are investigated which can be represented by the ground state of the adiabatic Hamiltonian.
11:15AM B25.00001 Delocalised oxygen as the origin of two-level defects in Josephson junctions, JARED COLE, TIMOTHY DUBOIS, Chemical and Quantum Physics, School of Applied Sciences, RMIT University, Melbourne 3001, Australia, MANOLO PER, Virtual Nanoscience Laboratory, CSIRO Materials Science and Engineering, Parkville 3052, Australia, SALVY RUSSO, Chemical and Quantum Physics, School of Applied Sciences, RMIT University, Melbourne 3001, Australia — One of the key problems facing superconducting qubits and other Josephson junction devices is the decohering effects of bi-stable material defects. We show that these defects can arise from delocalisation of the atomic position of the oxygen in the oxide forming the Josephson junction barrier. Using a microscopic model, we compute experimentally observable parameters for phase qubits. Such defects are charge neutral but have non-zero response to both applied electric field and strain. This explains the observed long coherence time of two-level defects in the presence of charge noise, while still coupling to the junction electric field and substrate phonons.

11:27AM B25.00002 Noise from Two-Level Systems in Superconducting Resonators, C. NEILL, R. BAREND, Y. CHEN, B. CHIARO, E. JEFFREY, J. KELLY, M. MARIANTONI, A. MEGRANT, J. MUTUS, S. OHYA, D. SANK, A. VAISNENCHER, J. WENNER, T. WHITE, A. N. CLELAND, J. M. MARTINIS, UC Santa Barbara — Two-level systems (TLSs) present in amorphous dielectrics and surface interfaces are a significant source of decoherence in superconducting qubits. Linear microwave resonators offer a valuable instrument for characterizing the strongly power-dependent response of these TLSs. Using quarter-wavelength coplanar waveguide resonators, we monitored the microwave response of the resonator at a single near-resonant frequency versus time at varying microwave drive powers. We observe a time dependent variation of the resonator's internal dissipation and resonance frequency. The amplitude of these variations saturates with power in a manner similar to loss from TLSs. These results provide a means for quantifying the number and distribution of TLSs.

11:39AM B25.00003 Universal dielectric loss in amorphous solids in Josephson qubits from simultaneous bias and microwave fields, ALEXANDER BURIN, Tulane University, KEVIN OSBORN, LPS University of Maryland, KHALIL MOE, LPS, University of Maryland — We calculate the microwave dielectric loss of an ensemble of two-level systems in amorphous solids within superconducting qubits using a time-varying electric bias field. We find that this loss becomes universal in a wide range of temperatures and frequencies of the AC drive field, corresponding to the bare linear dielectric permittivity in the low-temperature limit. This non-equilibrium theory allows the separate extraction of the TLS density and their dipole size in experiments and can be used to reduce the destructive effect of decoherence.

11:51AM B25.00004 Polaronic model of Two Level Systems in amorphous solids, KARTIEK AGARWAL, Harvard University, IVAR MARTIN, Los Alamos National Laboratory, EUGENE DEMLER, MIKHAIL LUKIN, Harvard University — Motivated by recent experiments studying effects of elastic strain on two level systems (TLSs) in Josephson Junctions, we consider interaction of the electronic TLS with phonons. We demonstrate that including strong polaronic effects is crucial for analyzing these systems. Our model not only gives a quantitative understanding of the TLS relaxation and dephasing as probed in Josephson junction qubits, but also provides a microscopic justification for phenomenological models used to describe experiments with bulk amorphous solids. Our model explains such surprising observations of recent experiments as the existence of minima in the energy of some TLSs as a function of strain and maximum of the relaxation time in such minima. We argue that better understanding of the microscopic nature of TLSs can be used to improve properties of quantum devices, from dramatic enhancement of TLS relaxation time by putting them inside phononic crystals to creating new types of strongly interacting optomechanical systems.

12:03PM B25.00005 Superconducting Titanium Nitride Coplanar Resonators: Relationships between performance and deposition parameters1, B. CHIARO, S. OHYA, A. MEGRANT, C. NEILL, R. BAREND, B. CAMPBELL, Y. CHEN, J. KELLY, M. MARIANTONI, J. MUTUS, P. O’MALLEY, P. ROUSHAN, D. SANK, A. VAISNENCHER, J. WENNER, T. WHITE, C.J. PALMSTROM, B.A. MAZIN, A.N. CLELAND, J.M. MARTINIS, UC Santa Barbara — Superconducting coplanar waveguide (CPW) resonators are widely used structures in the fields of photon detection and quantum information processing. Recently, there has been a growing interest in titanium nitride (TiN) thin films due to their widely tunable critical temperature, large surface inductance, and ability to produce high intrinsic quality factor (Q) resonators. We have deposited nearly stoichiometric TiN films on Si substrates by reactive magnetron sputtering. By increasing the deposition pressure and adjusting the N2 flow rate to maintain stoichiometry, the film stress was changed from ~100 MPa to >3000 MPa and the Q of CPW resonators made from these films increased from ~10^4 to ~10^6 for single photon excitations measured at ~100 mK. In this talk, we discuss relationships between deposition parameters, film properties, and microwave electrodynamic responses in these resonators.

1S. O. acknowledges the Japan Society for the Promotion of Sciences (JSPS) for a Postdoctoral Fellowship for Research Abroad.

12:15PM B25.00006 Characterization of quantum-regime dielectric loss of aluminum oxide using superconducting LC resonators, CHUNQING DENG, MARTIN OTTO, ADRIAN LUPASCUSI, University of Waterloo — We report low-temperature measurements of dielectric loss of thin layers of aluminum oxide. The experiments are performed by measuring the microwave transmission of coplanar waveguides coupled to LC resonators where the capacitor contains the dielectric to be characterized. We develop a method, based on systematic approximations of transfer functions, to analyze the measured transmission curves. The fit of the resonance curves yields not only the loss tangent of the dielectric, but also the relation between the voltage on the capacitor and the excitation voltage. The latter is a nonlinear relation which has to be properly taken into account when analyzing the power dependence of dielectric loss. We find that the loss tangent of the aluminum oxide increases with decreasing capacitor voltage and temperature and reaches a constant value around 2 x 10^-3 at sub-single photon levels. Our results are qualitatively in agreement with the two-level system defect model. Despite large loss, compact resonators based on these dielectrics have potential applications in microwave amplifiers. These results are relevant to understanding decoherence in superconducting quantum devices.
12:39 PM B25.00008 Observation of Cavity QED in thick dielectric films, Bahman Sarabi, Laboratory for Physical Sciences, University of Maryland - College Park, A.N. Ramanayaka, S. Gladchenko, M.J.A. Stoutimore, Laboratory for Physical Sciences, M.S. Khalil, Laboratory for Physical Sciences, University of Maryland - College Park, K.D. Osborn, Laboratory for Physical Sciences — Cavity QED in amorphous dielectrics is investigated by measuring five linear superconducting resonators with thick dielectric films and capacitor volumes ranging from 80 µm³ to 5000 µm³. In the smallest volume dielectrics we observe additional resonances which may be explained by CQED, despite the dielectric volume which is many orders of magnitude larger than Josephson junction barrier volumes. In addition to the volume dependence of the CQED resonances, we will report on the stability of the resonances in time and the phase noise. This research allows new fundamental studies on TLS phenomena in meso-volume amorphous dielectrics.

12:51 PM B25.00009 TLS-like temperature and power dependence for loss in superconducting coplanar resonators, S. Gladchenko, M.J.A. Stoutimore, M. Khalil, K.D. Osborn, Laboratory for Physical Sciences, MD, USA — Loss in 2D superconducting coplanar resonators and qubits is often limited by two-level systems thought to be on the metal and substrate surfaces. While these TLSs are thought to be similar to those found in amorphous dielectrics, their nature is generally different. In most experiments, loss in coplanar resonators shows power and temperature dependence which disagrees with TLS theory. Here we will show new data from high-quality Al on sapphire coplanar resonators which is in qualitative agreement with TLS theory, and discuss the quantitative differences to TLS theory. The data on surface TLS behavior will be compared to resonator measurements of ALD-grown thin films.

1:03 PM B25.00010 Non-equilibrium two-level system dynamics probed with a biased bridge resonator, Moes Khalil, Sergiy Gladchenko, M.J.A. Stoutimore, University of Maryland and Laboratory for Physical Sciences, F.C. Wellstood, University of Maryland, K.D. Osborn, Laboratory for Physical Sciences — We have designed a biased bridge resonator (BBR), which allows us to probe amorphous dielectric films by simultaneously applying a quasi-static electric bias field in addition to a microwave electric field. The BBR is made with a bridge arrangement of capacitors using superconducting aluminum electrodes and operated at millikelvin temperatures. Measurements of a universal amorphous dielectric film at high microwave amplitudes and a sufficiently fast bias field ramp reveals a non-equilibrium dielectric loss equal to its intrinsic steady state value. This phenomenon is explained by a theory which uses the dynamics of charged two-level systems undergoing Landau-Zener transitions to remain in their ground state. We will compare the experimental data to Monte Carlo simulations of the theory which allow for the separate extraction of the dipole moment and the spectral density of two-level systems.

1:15 PM B25.00011 Observation of the dynamics of two-state parametric fluctuators in superconducting flux qubits, Adrian Lupascu, Mustafa Bal, Mohammad Ansari, Institute for Quantum Computing, Department of Physics and Astronomy, and Waterloo Institute for Nanotechnology, University of Waterloo — Spectroscopic measurements of a few persistent current qubit samples yield data in which the spectroscopic lines are doublets. The doublet splitting decreases with increasing qubit transition frequency. In three devices with a relatively low Josephson to charging energy ratio $E_J/E_c$, the maximum splitting ranges between 30 and 270 MHz. The splitting value is found to have variations over time scales of the order of days. The doublet structure was not observed in two other samples with larger $E_J/E_c$. Assuming a model in which the qubit experiences a parametric fluctuation that changes its frequency, we perform an experiment to probe the time scale of this fluctuation. We repeat a sequence in which the qubit is reset by energy relaxation, then driven with weak Rabi $\pi$ pulses on one of the spectroscopy lines, and finally measured. The time correlation of the series of measurement results displays an exponential decay, consistent with a telegraph noise component in the qubit frequency. The correlation does not depend on time if the qubit is either not excited or driven with a strong Rabi pulse. The transition rate was found to vary between 8 kHz and 38 kHz for temperatures between 43 and 165 mK. We discuss quasiparticle poisoning and other possible source of this effect.

1:27 PM B25.00012 Low-frequency two level systems and $1/f$ noise in Al/AlOx/Al Josephson junctions for superconducting qubits: achieving a noiseless junction, Christopher Nugroho, Vladimir Orlyanchik, Dale Van Harlingen, University of Illinois at Urbana-Champaign — The characterization of low-frequency two level systems (TLS) provides a connection between the generic $1/f$ noise in Josephson junctions to the TLS observed in qubit energy spectroscopy. We present measurements of the tunneling-resistance noise in nanoscale Al/AlOx/Al shadow evaporated junctions with areas $< (100 \text{ nm})^2$. As the junction area or the temperature is decreased we observed a crossover from ensemble-averaged $1/f$ noise to a random telegraph noise from isolated TLSs. From the area threshold for the onset of non-gaussianity, we estimate a density of TLS in the amorphous AlOx barrier consistent with the magnitude of $1/f$ noise in larger junctions and the density of high frequency TLSs from qubit spectroscopy. Furthermore we may deduce the potential landscape of the TLSs by characterizing the switching times and signal variance as a function of voltage bias and temperature. In some junctions no fluctuators are active, giving rise to immeasurably small noise signal. We discuss the implication of our findings to qubit coherence times.

1:39 PM B25.00013 Josephson Phase Qubits Incorporating Novel Coherent Materials, U. Patel, Y. Gao, D. Hover, G. Ribeil, S. Sendelbach, R. McDermott, University of Wisconsin, Madison — The Josephson phase qubit is an attractive candidate for scalable quantum information processing in the solid state; however, qubit coherence is currently limited by coupling to spurious microscopic defects in the materials used to realize the circuit. Here we demonstrate that the incorporation of crystalline, defect-free dielectrics into the circuit leads to a dramatic enhancement of energy relaxation times. In addition we describe the realization of improved superconductor-insulator interfaces with extremely low levels of excess low-frequency flux noise, and we discuss efforts to incorporate these interfaces into the qubit circuit in order to extend pure dephasing times. We describe qubit fabrication and tomographic characterization and discuss ultimate limits to qubit coherence.

1:51 PM B25.00014 Optimization of Transmon Qubit Fabrication, Josephine Chang, Mary Beth Rotherwell, George Keefe, IBM T.J. Watson Research Center, IBM Quantum Computing Group Team — Rapid advances in the field of superconducting transmon qubits have refined our understanding of the role that substrate and interfaces play in qubit decoherence. Here, we review strategies for enhancing coherence times in both 2D and 3D transmon qubits through substrate design, structural improvements, and process optimization. Results correlating processing techniques to decoherence times are presented, and some novel structures are proposed for further consideration.

We acknowledge support from IARPA under contract W911NF-10-1-0324
Quantum estimation, meet Computational Statistics; Computational Statistics, meet Quantum Estimation. CHRIS FERRIE, Center for Quantum Information and Control and Department of Physics and Astronomy, University of New Mexico, CHRIS GRANADE, Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, JOSHUA COMBES, Center for Quantum Information and Control and Department of Physics and Astronomy, University of New Mexico — Quantum estimation, that is, post processing data to obtain classical descriptions of quantum states and processes, is an intractable problem—scaling exponentially with the number of interacting systems. Thankfully there is an entire field, Computational Statistics, devoted to designing algorithms to estimate probabilities for seemingly intractable problems. So, why not look to the most advanced machine learning algorithms for quantum estimation tasks? We did. I’ll describe how we adapted and combined machine learning methodologies to obtain an online learning algorithm designed to estimate quantum states and processes.

Conventional full state tomography reaches its limit already for a moderate number of qubits and hence novel methods for the verification and benchmarking of quantum devices are called for. We show how the complete reconstruction of density matrices is possible even if one relies only on local information about the state. This results in an experimental effort that is linear in the number of qubits and efficient post-processing — in stark contrast to the exponential scaling of standard tomography. Whenever full tomography is not needed but instead less information required, one would expect that even fewer measurements suffice. Taking entanglement content of solid state samples and bosons in lattices as an example, we show how it may be quantified unconditionally using already routinely performed measurements only.


Finding systematic errors in tomo-graphic data: Characterising ion-trap quantum computers. THOMAS MONZ, University of Innsbruck — Quantum state tomography has become a standard tool in quantum information processing to extract information about an unknown system. Several recipes exist to post-process the data and obtain a density matrix; for instance using maximum-likelihood estimation. These evaluations, and all conclusions taken from the density matrices, however, rely on valid data - meaning data that agrees both with the measurement model and a quantum model within statistical uncertainties. Given the wide span of possible discrepancies between laboratory and theory model, data ought to be tested for its validity prior to any subsequent evaluation. The presented talk will provide an overview of such tests which are easily implemented. These will then be applied onto tomographic data from an ion-trap quantum computer.

Adaptive quantum gate-set tomography1, ROBIN BLUME-KOHOUT, Sandia National Laboratories — Quantum information hardware needs to be characterized and calibrated. This is the job of quantum state and process tomography, but standard tomographic methods have an Achilles heel: to characterize an unknown process, they rely on a set of absolutely calibrated measurements. But many technologies (e.g., solid-state qubits) admit only a single native measurement basis, and other bases are measured using unitary control. So tomography becomes circular — tomographic protocols are using gates to calibrate themselves! Gate-set tomography confronts this problem head-on and resolves it by treating gates relationally. We abandon all assumptions about what a given gate operation does, and characterize entire universal gate sets from the ground up using only the observed statistics of an [unknown] 2-outcome measurement after various strings of [unknown] gate operations. The accuracy and reliability of the resulting estimate depends critically on which gate strings are used, and benefits greatly from adaptivity.

1 Sandia National Labs is a multiprogram laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Dept. of Energy's National Nuclear Security Administration, under contract DE-AC04-94AL85000


Quantum Estimation, meet Computational Statistics; Computational Statistics, meet Quantum Estimation. CHRIS FERRIE, Center for Quantum Information and Control and Department of Physics and Astronomy, University of New Mexico, CHRIS GRANADE, Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, JOSHUA COMBES, Center for Quantum Information and Control and Department of Physics and Astronomy, University of New Mexico — Quantum estimation, that is, post processing data to obtain classical descriptions of quantum states and processes, is an intractable problem—scaling exponentially with the number of interacting systems. Thankfully there is an entire field, Computational Statistics, devoted to designing algorithms to estimate probabilities for seemingly intractable problems. So, why not look to the most advanced machine learning algorithms for quantum estimation tasks? We did. I’ll describe how we adapted and combined machine learning methodologies to obtain an online learning algorithm designed to estimate quantum states and processes.

Conventional full state tomography reaches its limit already for a moderate number of qubits and hence novel methods for the verification and benchmarking of quantum devices are called for. We show how the complete reconstruction of density matrices is possible even if one relies only on local information about the state. This results in an experimental effort that is linear in the number of qubits and efficient post-processing — in stark contrast to the exponential scaling of standard tomography. Whenever full tomography is not needed but instead less information required, one would expect that even fewer measurements suffice. Taking entanglement content of solid state samples and bosons in lattices as an example, we show how it may be quantified unconditionally using already routinely performed measurements only.


1:27PM B26.00008 Quantum adiabatic Markovian Master Equations, TAMEE ALBASH, SERGIO BOIXO, DANIEL LIDAR, PAOLO ZANARDI, University of Southern California — We develop from first principles Markovian master equations suited for studying the quantum evolution of a system evolving adiabatically while coupled weakly to a thermal bath. We derive two sets of equations in the adiabatic limit, one using the rotating wave approximation that results in a master equation in Lindblad form, the other without the rotating wave approximation but not in Lindblad form.

1:39PM B26.00009 Quantum process tomography of energy and phase relaxation through adaptive measurements, MARKKU STENBERG, FRANK WILHELM, Saarland University — Quantum process tomography tends to be very time consuming when multiple degrees of freedom are studied simultaneously. We propose a method of efficient quantum process tomography to estimate the energy and phase relaxation rates in qubits. The method applies Bayesian inference to adaptively choose measurements based on the previously obtained measurement outcomes. We adopt sequential Monte-Carlo approach to perform the Bayesian updates and make use of a fast numerical implementation of the algorithm. We compare the performance of our method to conventional offline (implemented after experimental data collection) strategies and illustrate how our method can speed up quantum process tomography.

1:51PM B26.00010 A quantum neural network computes its own relative phase, ELIZABETH BEHRMAN, Mathematics and Physics, Wichita State University, Wichita, KS 67260-0033 — Complete characterization of the state of a quantum system made up of subsystems requires determination of relative phase, because of interference effects between the subsystems. For a system of qubits used as a quantum computer this is especially vital, because the entanglement, which is the basis for the quantum advantage in computing, depends intricately on phase. We present here a first step towards that determination, in which we use a two-qubit quantum system as a quantum neural network, which is trained to compute and output its own relative phase.

2:03PM B26.00011 Modeling quantum noise for efficient testing of fault-tolerant circuits, EASWAR MAGESAN, Massachusetts Institute of Technology, DANIEL PUZZUOLO, CHRISTOPHER E. GRANADE, DAVID G. CORY, University of Waterloo-Institute for Quantum Computing — Simulating fault-tolerant properties of quantum circuits is important for the design of large-scale quantum information processors. For general circuits and noise models, these simulations quickly become intractable in the size of the encoded circuit. We introduce methods for approximating a noise process by one which allows for efficient Monte Carlo simulation of properties of encoded circuits. The approximations are as close to the original process as possible without overestimating their ability to preserve quantum information, a key property for obtaining more honest estimates of threshold values. We numerically illustrate the method with physically relevant noise models.

Monday, March 18, 2013 11:15AM - 2:03PM –
Session B27 GQI: Focus Session: Adiabatic Quantum Computing II

11:15AM B27.00001 On optimal methods for adiabatic quantum state transformations, ROLANDO SOMMA, Los Alamos National Laboratory — Many problems in science could be solved by preparing the low-energy quantum state (or any eigenstate) of a Hamiltonian. A common example is the Boolean satisfiability problem, where each clause can be mapped to the energy of an interacting many-body system, and the problem reduces to minimizing the energy. In quantum computing, adiabatic quantum state transformations (ASTs) provide a tool for preparing the quantum state. ASTs are conventionally implemented via slow or adiabatic perturbations to the Hamiltonian, relying on the quantum adiabatic theorem. Nevertheless, more efficient implementations of ASTs exist. In this talk I will review recently developed methods for ASTs that are more efficient and require less assumptions on the Hamiltonians than the conventional implementation [1,2]. Such methods involve measurements of the states along the evolution path and have a best-case implementation cost of $L/G$, where $L$ is the length of the evolved state path and $G$ is a lower bound to the spectral gap of the Hamiltonians. I will show that this cost is optimal [3] and comment on results of the gap amplification problem, where the goal is to reduce the cost by increasing $G$ [4].


We acknowledge support from NSF through the CCF program and the LDPh programs at Los Alamos National Laboratory and Sandia National Laboratories.

11:51AM B27.00002 Quantum Adiabatic Markovian Master Equations, TAMIE ALBASH, SERGIO BOIXO, DANIEL LIDAR, PAOLO ZANARDI, University of Southern California — We develop from first principles Markovian master equations suited for studying the time evolution of a system evolving adiabatically while coupled weakly to a thermal bath. We derive two sets of equations in the adiabatic limit, one using the rotating wave approximation that results in a master equation in Lindblad form, the other without the rotating wave approximation but not in Lindblad form. We use our formalism to study the evolution of Ising spin Hamiltonians and compare to experimental results from the D-Wave One Rainier chip. In particular, we study an Ising Hamiltonian that gives markedly different predictions for the ground state spectrum when solved using classical thermal annealing versus quantum annealing, and our master equations give qualitatively consistent results with the results of the D-Wave chip.
algorithm such as local adiabatic evolution, adaptive methods, local search in Hamiltonian space and others. Although forays have been made into open-system quantum simulation [3], the strict algorithmic aspect has not been explored yet is necessary to account fully for resource consumption to deliver bounded-error answers to computational questions. An open-system quantum simulator would encompass classical and closed-system simulation and also solve outstanding problems concerning, e.g., dynamical phase transitions in non-equilibrium systems, establishing long-range order via dissipation, verifying the simulatability of open-system dynamics on a quantum Turing machine. We construct an efficient autonomous algorithm for designing an efficient quantum circuit to simulate many-body open-system dynamics described by a local Hamiltonian plus decoherence due to separate baths for each particle. The execution time and number of gates for the quantum simulator both scale polynomially with the system size.


12:3PM B27.00003 Quantum Simulation for Open-System Dynamics

10:30PM B27.00004 Complexity of the Quantum Adiabatic Algorithm

12:15PM B27.00004 Complexity of the Quantum Adiabatic Algorithm, ITAY HEN, UC Santa Cruz and NASA Ames Research Center — The Quantum Adiabatic Algorithm (QAA) has been proposed as a mechanism for efficiently solving optimization problems on a quantum computer. Since adiabatic computation is analog in nature and does not require the design and use of quantum gates, it can be thought of as a simpler and perhaps more profound method for performing quantum computations that might also be easier to implement experimentally. While these features have generated substantial research in QAA, to date there is still a lack of solid evidence that the algorithm can outperform classical optimization algorithms. Here, we discuss several aspects of the quantum adiabatic algorithm: We analyze the efficiency of the algorithm on several “hard” (NP) computational problems. Studying the size dependence of the typical minimum energy gap of the Hamiltonians of these problems using quantum Monte Carlo methods, we find that while for many problems the minimum gap decreases exponentially with the size of the problem, indicating that the QAA is not more efficient than existing classical search algorithms, for other problems there is evidence to suggest that the gap may be polynomial near the phase transition. We also discuss applications of the QAA to “real life” problems and how they can be implemented on currently available (albeit prototypical) quantum hardware such as “D-Wave One”, that impose quantum restrictions as to which types of problems may be tested. Finally, we discuss different approaches to find improved implementations of the algorithm such as local adiabatic evolution, adaptive methods, local search in Hamiltonian space and others.

12:51PM B27.00005 Power law scaling for the adiabatic algorithm for search engine ranking

1:03PM B27.00006 Frustration and ground state entanglement in 2D lattices

1:15PM B27.00007 Cycloid trajectory for a spin in a rotating magnetic field

1:27PM B27.00008 Fibonacci wires

1:39PM B27.00009 Dynamical scaling in infinitely correlated many-body systems through a quantum phase transition

This work was supported in part by ARO, DOD (W911NF-09-1-0439) and NSF (CCR-0635355, DMR 0906951). A.F. acknowledges support from the NSF REU program (PHY-PIF-1104660)
we will discuss the potential applications of hybrid polarization-OAM states of the same photon that are invariant under arbitrary rotations around the propagation direction, and vice versa. The scheme Bell-inequality violation. The core of our toolbox is a liquid crystal device, named “q-plate,” that maps polarization-encoded qubits into qubits encoded in the feasibility of alignment-free quantum key-distribution, and perform proof-of-principle demonstrations of alignment-free entanglement distribution and OAM properties. By developing a complete toolbox for the efficient encoding and decoding of quantum information in such photonic qubits, we demonstrate Just as the circular polarization states are eigenstates of the spin angular momentum of light, the helical-wavefront Laguerre-Gaussian modes are eigenmodes of quantum additivity noise channels, including quantum analogues of the AWGN channel. Our main technical tool is a quantum entropy power inequality that controls the entropy production as two quantum signals combine at a beam splitter. Its proof involves a new connection between entropy production rates and a quantum Fisher information, and uses a quantum diffusion that smooths arbitrary states towards gaussians.

3:06PM C11.00002 Security of continuous-variable quantum key distribution against general attacks1, ANTHONY LEVERREUR, INRIA Rocquencourt — We prove the security of Gaussian continuous-variable quantum key distribution with coherent states against arbitrary attacks in the finite-size regime. In contrast to previously known proofs of principle (based on the de Finetti theorem), our result is applicable in the practically relevant finite-size regime. This is achieved using a novel proof approach, which exploits phase-space symmetries of the protocols as well as the postselection technique introduced by Christandl, Koenig and Renner (Phys. Rev. Lett. 102, 020504 (2009)).

3:42PM C11.00003 Fully device-independent quantum key distribution, THOMAS VIDICK, Massachusetts Institute of Technology (MIT) — The laws of quantum mechanics allow unconditionally secure key distribution protocols. Nevertheless, security proofs of traditional quantum key distribution (QKD) protocols rely on a crucial assumption, the trustworthiness of the quantum devices used in the protocol. In device-independent QKD, even this last assumption is relaxed: the devices used in the protocol may have been adversarially prepared, and there is no a priori guarantee that they perform according to specification. Proving security in this setting had been a central open problem in quantum cryptography. We give the first device-independent proof of security of a protocol for quantum key distribution that guarantees the extraction of a linear amount of key even when the devices are subject to a constant rate of noise. Our only assumptions are that the laboratories in which each party holds his or her own device are spatially isolated, and that both devices, as well as the eavesdropper, are bound by the laws of quantum mechanics. All previous proofs of security relied either on the use of many independent pairs of devices, or on the absence of noise.

4:18PM C11.00004 Quantum hacking, VADIM MAKAROV, University of Waterloo — -

5:04PM C11.00005 Complete experimental toolbox for alignment-free quantum communication1, FABIO SCIARRINO, Dipartimento di Fisica, Sapienza Università di Roma — Quantum communication employs the counter-intuitive features of quantum physics for tasks that are impossible in the classical world. It is crucial for testing the foundations of quantum theory and promises to revolutionize information and communication technologies. However, to execute even the simplest quantum transmission, one must establish, and maintain, a shared reference frame. This introduces a considerable overhead in resources, particularly if the parties are in motion or rotating relative to each other. We experimentally show how to circumvent this problem with the transmission of quantum information encoded in rotationally invariant states of single photons. Our approach exploits multiple degrees of freedom of single photons. In particular, the polarization and transverse spatial modes stand out for this purpose. Just as the circular polarization states are eigenstates of the spin angular momentum of light, the helical-wavefront Laguerre-Gaussian modes are eigenmodes of its orbital angular momentum (OAM). We implement photonic qubit invariant under rotation around the optical axis by combining the polarization with OAM properties. By developing a complete toolbox for the efficient encoding and decoding of quantum information in such photonic qubits, we demonstrate the feasibility of alignment-free quantum key-distribution, and perform proof-of-principle demonstrations of alignment-free entanglement distribution and Bell-inequality violation. The core of our toolbox is a liquid crystal device, named “q-plate,” that maps polarization-encoded qubits into qubits encoded in hybrid polarization-OAM states of the same photon that are invariant under arbitrary rotations around the propagation direction, and vice versa. The scheme should find applications in fundamental tests of quantum mechanics and satellite-based quantum communication. We will discuss the potential applications of this scheme to real quantum communication network.

1European project PHORBITECH

Monday, March 18, 2013 2:30PM - 5:18PM –

2:30PM C25.00001 Approaching 10 Milliseconds for Aluminum Cavities in the Quantum Regime, MATTHEW REAGOR, HANHEE PAIK, GIANLUIGI CATELANI, LUYAN SUN, CHRISTOPHER AXELINE, TERESA BRECHT, JACOB BLUMOFF, LUIGI FRUNZIO, LEONID GLAZMAN, ROBERT SCHOOLKOPF, Department of Physics and Applied Physics, Yale University — One of the most promising solid state quantum computing architectures couples superconducting qubits to microwave resonators (circuit QED), a system in which three-dimensional microwave cavities have become a valuable resource. Participation-ratio calculations predict at least four orders of magnitude longer lifetimes in 3D cavities than their planar resonator counterparts with equal material losses. Motivated by this principle, we report multiple superconducting aluminum cavities with lifetimes on the order of 10ms at single photon power and millikelvin temperatures. We also present details on extracting the materials properties and the noise performance of a long lived superconducting cavity resonator, including bounds on the intrinsic dephasing time (T0) of such a resource.
2:42PM C25.00002 Materials Effects in 3D-Cavity Transmon Qubits. DANIELA F. BOGORIN, MATTHEW WARE, STEPHEN SOROKANICH, B.L.T. PLOURDE, Syracuse University, Physics Department — Recent experiments have demonstrated significant increases in the coherence of superconducting transmon qubits coupled to three-dimensional microwave cavities. We are investigating the effects of different materials for forming such cavities, as well as various surface treatments of the cavity walls, including electropolishing and electroplating. In addition, we are exploring the influence of the superconducting material that forms the qubit capacitor along with the material that forms the substrate on which the qubit is fabricated.

2:54PM C25.00003 Coherence of Superconducting Whispering Gallery Resonators1. ZLATKO MINEV, IOAN POP, DOMINIC KWOK, MICHEL DEVORET, Applied Physics Department, Yale University — Quantum signal processing applications rely on the design of microwave resonators with quality factors at the single photon level exceeding a million. We present a novel on-chip whispering gallery mode resonator formed by two superconducting rings on separate wafers facing each other. The mode energy is principally housed in the lossless vacuum between the rings. We measure internal quality factors of a few million at the single photon level. The superconducting whispering gallery resonator is easily integrable with superconducting qubits. It also constitutes a new tool to characterize thin film material properties.

1Work supported by IARPA, ARO, NSF and YINQE.

3:06PM C25.00004 Deterministic creation of Schrodinger cat states in a superconducting waveguide cavity , BRIAN VLASTAKIS, GERHARD KIRCHMAIR, ZAKI LEHTHAS, Yale University Dept. of Applied Physics, SIMON NIGG, Yale University Dept. of Physics, LUIGI FRUNZIO, Yale University Dept. of Applied Physics, STEVEN GIRVIN, Yale University Dept. of Physics, ROBERT SCHOELKOPF, Yale University Dept. of Applied Physics — Significant progress has recently been made in improving the coherence of superconducting qubits by using the 3D cQED architecture. This current design is static, not allowing for the modulation of couplings and nonlinearities in situ. This limitation may prove to be an obstacle toward scaling this implementation into more complex systems. We present a new architecture which integrates high Q-factor 3D resonators with flux-tunable superconducting transmon qubits. In this talk, we will demonstrate full control over qubit frequency with minimal degradation to qubit and cavity lifetime. This capability allows the rapid and precise control over the system Hamiltonian to choose optimal couplings and nonlinearities as dictated by the experiment.

3:18PM C25.00005 Tunable 3D cQED: Implementation and Characterization, KEVIN CHOU, MATTHEW REED, NISSIM OFEK, JACOB BLUMOFF, BRIAN VLASTAKIS, GERHARD KIRCHMAIR, ZAKI LEHTHAS, Yale University Dept. of Applied Physics, SIMON NIGG, Yale University Dept. of Physics, LUIGI FRUNZIO, Yale University Dept. of Applied Physics, STEVEN GIRVIN, Yale University Dept. of Physics, ROBERT SCHOELKOPF, Yale University Dept. of Applied Physics — Significant progress has recently been made in improving the coherence of superconducting qubits by using the 3D cQED architecture. The current design is static, not allowing for the modulation of couplings and nonlinearities in situ. This limitation may prove to be an obstacle toward scaling this implementation into more complex systems. We present a new architecture which integrates high Q-factor 3D resonators with flux-tunable superconducting transmon qubits. In this talk, we will demonstrate full control over qubit frequency with minimal degradation to qubit and cavity lifetime. This capability allows the rapid and precise control over the system Hamiltonian to choose optimal couplings and nonlinearities as dictated by the experiment.

3:30PM C25.00006 Tunable 3D cQED: Applications to Quantum Optics and Quantum Information, MATTHEW REED, KEVIN CHOU, NISSIM OFEK, JACOB BLUMOFF, BRIAN VLASTAKIS, GERHARD KIRCHMAIR, ZAKI LEHTHAS, Yale University Dept. of Applied Physics, SIMON NIGG, Yale University Dept. of Physics, LUIGI FRUNZIO, Yale University Dept. of Applied Physics, STEVEN GIRVIN, Yale University Dept. of Physics, ROBERT SCHOELKOPF, Yale University Dept. of Applied Physics — The ability to control the frequency of a superconducting qubit on nanosecond timescales has been used, among other things, to generate multi-qubit entanglement. The recently developed 3D cQED architecture has yielded dramatic coherence improvements and novel methods of entangling fixed-tuned qubits, but has until now lacked the ability to control qubit frequencies in situ. Adding this would grant several abilities. First, the coupling of a qubit to the cavity bus could be modulated to control both the inherited nonlinearities and the dispersive shift of the oscillator. Second, controlling the interactions between individual qubits, particularly those coupled to more than one cavity, could be used to shuttle quantum information between subsystems. Third, a small change to the physical implementation could yield efficient individual qubit QND readout or reset. These abilities are readily applicable to demonstrations of hardware-efficient quantum error correction, entanglement distillation between distant pairs of qubits, and teleportation of quantum information. In this talk, we will discuss our recent results toward achieving these capabilities using the tunable 3D cQED architecture introduced previously.

3:42PM C25.00007 Extended coherence times of superconducting transmon qubits1. ERIK LUCERO, MATTHIAS STEFFEN, JAY GAMBITTA, DAVID ABRAHAM, ANTONIO CORCOLES, IBM T. J. Watson Research Center, IBM QUANTUM COMPUTING TEAM — As part of the IBM quantum computing effort, we are building on the pioneering work [1] and recent advances [2] on transmon qubits enclosed in three-dimensional cavities (“3D qubits”). To continue the advance of superconducting qubit architectures for surface code implementations it is clear that we must understand what is limiting coherence times and work to mitigate its effects. By leveraging the reduced fabrication requirements (compared to two-dimensional qubits) and full-device electromagnetic simulation, 3D qubits provide an insightful experiment test-bed to help determine the participation of decoherence mechanisms (e.g. materials, surfaces, radiation) in superconducting qubits. We report on coherence times that go beyond those reported recently [2], making 3D qubits a viable architecture for a prototype quantum processor. [1] Paik, et al., Phys Rev. Lett. 107 240501 [2] Rigetti et al., Phys. Rev. B 86, 10506

1We acknowledge support from IARPA under contract W911NF-10-1-0324

3:54PM C25.00008 Fluxonium Qubit in a 3D Cavity: Design and Implementation1. I.M. POP, K. GEERLINGS, N. MASLUK, A. KAMAL, Applied Physics Department, Yale University, G. CATELANI, Forschungszentrum Juelich, Peter Gruenberg Institut, L. GLAZMAN, M.H. DEVORET, Applied Physics Department, Yale University — We describe the implementation of a fluxonium artificial atom [1] with improved coherence times. Our qubit is inductively coupled to a Josephson junction resonator on a sapphire substrate, placed inside a 3D copper cavity. The keystone of the fluxonium qubit is its superinductance, which consists of an array of 90 Josephson junctions. We describe superinductance design improvements [2] which effectively eliminate spurious phase-slips and raise the self-resonant modes of the superinductance well above the frequency of the qubit. Networks of Josephson junctions will be useful for designing custom symmetries in cQED Hamiltonians.


1Work supported by IARPA, ARO, NSF and YINQE.
A Study of the Multi-Mode Purcell Effect for a Transmon in 3D Circuit QED

4:18PM C25.00010
ANDREI PETRENKO, LUYAN SUN, JACOB BLUMOFF, SIMON NIGG, STEVE GIRVIN, ROBERT SCHOELKOPF, Yale University Department of Applied Physics — Although superconducting 3D transmon qubits offer a promising path toward realizing an architecture for quantum computation, they are still limited by decoherence processes that are not yet fully understood. Qubit $T_1$ relaxation due to the Purcell Effect presents one such limitation on coherence times, but thus far a complete model of Purcell processes for transmons in 3D cavities, beyond the approximation of a single cavity mode and lumped element circuit model, has been absent. Employing a simple model to vary the decay rate $\kappa$ (or quality factor $Q$) of our cavities in situ we explore in detail how multiple cavity modes contribute to qubit $T_1$ decay in the Purcell regime. In addition, we show the continued dependence of qubit $T_1$ on cavity $\kappa$ as we systematically decouple from our cavity and are no longer Purcell-limited and how this dependence is related to a steady rise in qubit excited state population. Our findings are consistent with theory we have developed based on an effective circuit model for the cavity-qubit system, and set the stage for continuing the study of the multi-mode Purcell Effect by means of in-situ tuning of not just the cavity coupling, but the qubit frequency itself.

4:30PM C25.00011
Entanglement of two superconducting qubits in a three-dimensional architecture via monochromatic two-photon excitation

4:42PM C25.00012
Measurement of a three-dimensional circuit QED system with a down-converting parametric amplifier

4:54PM C25.00013
Ultra-broadband microwave travelling-wave parametric amplifier for qubit readout

5:06PM C25.00014
High fidelity all-microwave controlled-phase gate for superconducting qubits by cavity vacuum displacement

Monday, March 18, 2013 2:30PM - 5:30PM –
Session C26 GQI: Semiconductor Qubits - Gates and Robust Control
Aachen
2:30PM C26.00001 Interplay of charge and spin coherence in Landau-Zener interferometry in double quantum dots, HUGO RIBEIRO. University of Konstanz — Landau-Zener-Stückelberg-Majorana (LZSM) physics has been exploited to coherently manipulate two-electron spin states in a GaAs double quantum dot (DQD) at a singlet (S)-triplet (T$_1^*$) anti-crossing. The anti-crossing results from the hyperfine interaction with the nuclear spins of the host material [1,2]. However, the fluctuations of the nuclear spin bath result in spin dephasing within T$_2^*$ $\sim$ 10 – 20 ns. As a consequence, the sweep through the anti-crossing would have to be performed on a timescale comparable to T$_2^*$ to achieve LZSM oscillations with 100% visibility. Moreover, the S-T$_1^*$ anti-crossing is located near the (1,1) – (2,0) interdot charge transition, where $(n_l,n_r)$ denotes the number of electrons in the left and right quantum dot. As a result the singlet state involved in the dynamics is a superposition of (1,1) and (2,0) singlet states. Here we show that it is possible to increase the oscillation visibility while keeping sweep times less than T$_2^*$ using a tailored pulse with a detuning dependent level velocity. The pulse includes a slow level velocity portion that is chosen to coincide with the passage through the S-T$_1^*$ anti-crossing and two fast level velocity portions. The latter minimize the time spent in regions where spin and charge degrees of freedom are entangled, which renders the qubit susceptible to charge noise. The slow level velocity portion of the pulse results in a stronger effective coupling between the spins states, which increases the oscillations visibility [3,4]. In particular, we were able to obtain a visibility of $\sim$ 0.5 for LZSM oscillations. This constitutes an important step towards the implementation of a Hadamard gate.


$^*$Work performed in collaboration with Jason Petta, Guido Burkard, Hong Lu, and Arthur Gossard. Research at Princeton supported by the Sloan and Packard Foundations and the NSF. H. R. and G. B. acknowledge funding from the DFG within SPP 1285 and SFB 767.

3:06PM C26.00002 Decoherence-protected nuclear spin quantum register in diamond, VIATCH-ESLAV DOBROVITSKI, WAN JUNG KUO, Ames Laboratory US DOE, Iowa State University, Ames, IA, 50011, USA, RONALD HANSON, TIM H. TAMINIAU, Delft University of Technology, 2600 GA Delft, the Netherlands — We analyze the decoherence-protected operation of a quantum register based on the nuclear spins surrounding a nitrogen-vacancy (NV) center in diamond. Combination of the decoherence protection with the quantum gates is achieved by applying the decoupling pulses to the NV center’s electronic spin in resonance with the motion of one of the nuclear spins [1,2]. In this way, many weakly coupled (tens of kHz) nuclei located far from the NV center can be combined in a quantum register. We study the limits, set by realistic experimental parameters, on the size of such a register and on the duration of the quantum gates needed for its operation. We also consider the ways of accelerating the quantum gate operation, and integration of the decoherence-protected gates with the decoupling of the nuclear spins themselves. We conclude that creation of such registers is feasible with current experimental capabilities. Work at the Ames Laboratory was supported by the Department of Energy - Basic Energy Sciences under Contract No. DE-AC02-07CH11358. [1] T. van der Sar et al., Nature 484, 82 (2012). [2] T. H. Taminiau et al., Phys. Rev. Lett. 109, 137602 (2012).

3:18PM C26.00003 Enhancement of Inter-qubit Coupling in Singlet-Triplet Qubits by Floating Metal Gate, SHANNON HARVEY, MICHAEL SHULMAN, OLIVER DIAL, Harvard University, HENDRIK BLUMH, RWTH Aachen University, VLADIMIR UMANSKY, Weizmann Institute of Science, AMIR YACOBY, Harvard University — Spin qubits in semiconductors are promising systems for quantum computing, because they have long coherence times and are potentially scalable. However, their weak interaction with the environment, which gives their long coherence times, also makes inter-qubit interactions weak. Numerous proposals use electrostatic coupling between qubits for entangling operations, but these interactions require the qubits to be near one another. These proposals also suggest that adding a metallic gate between two qubits could increase coupling and allow the qubits to be spatially separated. We present results on two singlet-triplet (S-T$_1^*$) qubits connected by a floating metallic gate. Previous work on two-qubit operations, which use a capacitive coupling, showed that the inter-qubit coupling is weak and requires the qubits to be in close proximity. We find that the inter-qubit coupling is increased with the inclusion of a floating metal gate, which improves entangling operation fidelities and allows for these qubits to be spatially separated. Together, these improvements open the door to a scalable architecture for quantum information processing for all semiconductor spin qubit platforms.

3:30PM C26.00004 Probing quantum phase transitions on a spin chain with a double quantum dot, YUN-PIL SHIM. University of Wisconsin-Madison, SANGCHUL OH, University at Buffalo, State University of New York, JIANJIA FEI, University of Wisconsin-Madison, XUEDONG HU, University at Buffalo, State University of New York, MARK FRIESSEN, University of Wisconsin-Madison — We propose a local, projective scheme for detecting quantum phase transitions (QPTs) in a quantum dot spin chain [1]. QPTs in qubit systems are known to produce singularities in the entanglement, which could in turn be used to probe the QPT. Current proposals to measure the entanglement are challenging however, because of their nonlocal nature. We present numerical and analytical evidence that entanglement in a double quantum dot (DQD) coupled locally to a spin chain exhibits singularities at the critical points of the spin chain, and that these singularities are reflected in the singlet probabilities of the DQD. This result suggests that a DQD can be used as an efficient probe of QPTs through projective singlet measurements. We propose a simple experiment to test this concept in a linear triple quantum dot. [1] Y.-P. Shim et al., arXiv:1209.5445

$^*$This work was supported in part by the DARPA/MTO QuEST program through a grant from AFOSR.

3:42PM C26.00005 Coherent electron transfer between distant quantum dots in a linear array, FLORIS BRAAKMAN, PIERRE BARTHELEMY, LIEVEN VANDERSYPEN, TU Delft, KAVLI INSTITUTE OF NANOSCIENCE TEAM — Tunnel coupled quantum dots form the basis for electronic charge and spin qubits in the mesoscopic regime. The tunnel coupling gives rise to quantum coherent phenomena such as exchange oscillations of neighboring spins. However, tunnel coupling strength between non-neighbouring sites is negligible and it is therefore desirable to develop a form of long range coupling. In a linear array of three quantum dots, we demonstrate an effective tunnel coupling between the outer dots through virtual occupation of discrete levels in the center dot. The coupling strength depends strongly on the detuning between center and outer dot levels. The observation of Landau-Zener-Stueckelberg oscillations demonstrates the coherent nature of the coupling. In principle the effective long-range tunnel coupling should also allow coherent exchange of remote spins.

3:54PM C26.00006 Dynamically Corrected Pulse Sequences for the Exchange Only Qubit, GARRETT HICKMAN, JASON KESTNER, University of Maryland, Baltimore County — In the exchange-only qubit, hyperfine interactions of qubit electrons with neighboring atoms introduce decoherence into the basis states and mix them with a third leaked state. We theoretically derive a scheme for performing arbitrary single-qubit rotations on the exchange-only qubit while canceling all hyperfine-induced errors to first order. We compare numerically the performance of the resulting pulse sequences with that of the simplest naive implementations for a range of hyperfine interaction strengths. While for typical operations these sequences are roughly 50 times longer than a simple uncorrected pulse, error is significantly reduced. We show that for hyperfine field inhomogeneities less than one thirtieth of the maximum exchange strength, typical hyperfine-induced errors are reduced by at least an order of magnitude.

$^*$Work performed in collaboration with Jason Petta, Guido Burkard, Hong Lu, and Arthur Gossard. Research at Princeton supported by the Sloan and Packard Foundations and the NSF. H. R. and G. B. acknowledge funding from the DFG within SPP 1285 and SFB 767.
Composite pulses robust against charge noise and magnetic field noise for universal control of a singlet-triplet qubit\textsuperscript{1}, XIN WANG, EDWIN BARNES, Condensed Matter Theory Center, University of Maryland, College Park, JASON P. KESTNER, Department of Physics, University of Maryland, Baltimore County, and Condensed Matter Theory Center, University of Maryland, College Park, LEV S. BISHOP, SANKAR DAS SARMA, Condensed Matter Theory Center and Joint Quantum Institute, University of Maryland, College Park — We generalize our SUPCODE pulse sequences\textsuperscript{1} for singlet-triplet qubits to correct errors from imperfect control. This yields gates that are simultaneously corrected for both charge noise and magnetic field gradient fluctuations, addressing the two dominant $T_2^*$ processes. By using this more efficient version of SUPCODE, we are able to introduce this capability while also substantially reducing the overall pulse time compared to the previous sequence. We show that our sequence remains realistic under experimental constraints such as finite bandwidth. [1] Wang et al., “Composite pulses for robust universal control of singlet-triplet qubits” Nat. Commun. 3, 997 (2012)

Dynamically corrected gates for singlet-triplet spin qubits with control-dependent errors\textsuperscript{1}, N. TOBIAS JACOBSON, WAYNE M. WITZEL, ERIK NIELSEN, MALCOLM S. CARROLL, Sandia National Laboratories — Magnetic field inhomogeneity due to random polarization of quasi-static local magnetic impurities is a major source of environmentally induced error for singlet-triplet double quantum dot (DQD) spin qubits. Moreover, for singlet-triplet qubits this error may depend on the applied controls. This effect is significant when a static magnetic field gradient is applied to enable full qubit control. Through a configuration interaction analysis, we observe that the dependence of the field inhomogeneity-induced error on the DQD bias voltage can vary systematically as a function of the controls for certain experimentally relevant operating regimes. To account for this effect, we have developed a straightforward prescription for adapting dynamically corrected gate sequences that assume control-independent errors into sequences that compensate for systematic control-dependent errors. We show that accounting for such errors may lead to a substantial increase in gate fidelities.

High fidelity gates in quantum dot spin qubits\textsuperscript{1}, MARK FRIESEN, TECK SENG KOH, S. N. COPPERSMITH, University of Wisconsin - Madison — A variety of logical qubits and quantum gates have been proposed for quantum computer architectures using top-gated quantum dots. Despite their differences, we show that many combinations of qubits and gates can be evaluated on an equal footing by optimizing the gating protocols for maximum fidelity. Here, we evaluate single-qubit gate operations for two types of logical-qubits: singlet-triplet qubits and quantum dot hybrid qubits. In both cases, transitions between the qubit states are controlled by the exchange interaction between the dots, which in turn depends on the tunnel coupling and the detuning. We compute the fidelities for three exchange gate protocols: a dc pulsed gate, an ac resonant gate, and a static magnetic field gradient is applied to enable full qubit control. Through a configuration interaction analysis, we observe that the dependence of the field inhomogeneity-induced error on the DQD bias voltage can vary systematically as a function of the controls for certain experimentally relevant operating regimes. To account for this effect, we have developed a straightforward prescription for adapting dynamically corrected gate sequences that assume control-independent errors into sequences that compensate for systematic control-dependent errors. We show that accounting for such errors may lead to a substantial increase in gate fidelities.

Theoretical hyperfine decay functions in triple quantum dots\textsuperscript{1}, THADEUS LADD, HRL Laboratories, LLC — Coherent oscillations in multiple quantum dots decay due to hyperfine interactions with nuclear spins. The decay functions observed in several double-dot experiments\textsuperscript{1} agree well with simple formulae derived using the group SU(2), which is defined by exchange and hyperfine interactions in the singlet-triplet system\textsuperscript{2}. We show that in triple dots, this theory generalizes to SU(3), with convenient representation in the basis of states of the exchange-only qubit in a decoherence-free subsystem\textsuperscript{3}. Using some intuition from SU(3), we derive analytic formulae for the hyperfine decay functions expected in coherent oscillations in triple dots\textsuperscript{4}.

High fidelity gates for exchange-only qubits in triple-quantum-dots\textsuperscript{1}, JIANJIA FEI, University of Wisconsin - Madison, JO-TZU HUNG, University at Buffalo, State University of New York, TECK SENG KOH, YUN-PIL SHIM, University of Wisconsin - Madison, SANDCHUL OH, University at Buffalo, State University of New York, SUSAN COPPERSMITH, University of Wisconsin - Madison, XUEDONG HU, University at Buffalo, State University of New York, MARK FRIESEN, University of Wisconsin - Madison — One of the main attractions of implementing exchange-only qubits in quantum dots is their ease of control. Gate operations are performed by changing the voltages on the top-gates, to vary the tunnel coupling and/or the detuning between the dots. One of the main challenges is that when exchange interactions are turned on, charge noise will cause dephasing. Here, we explore optimal strategies for implementing logical qubit rotations in exchange-only qubits. We take into account charge noise, and challenges due to hyperfine interactions, including leakage outside the logical qubit space, and dephasing caused by fluctuations of the local nuclear fields. Our method is based on optimizing the experimentally tunable parameters to maximize the fidelity of the gate operation. /newline/newline The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressly or implied, of the U.S. Department of Defense.

\textsuperscript{1}This work was supported in part by ARO (W911NF-08-1-0482) and NSF (DMR-0805045, PHY-1104660).
5:18PM C26.00013 Constructing Two-Qubit Gates for Exchange-Based Quantum Computing, DANIEL ZEUCH, Dept. of Physics, University of Konstanz, Dept. of Physics and NHHMF, Florida State University, ROBERT CIPRI, N.E. BOSESTEEL, Dept. of Physics and NHHMF, Florida State University — Exchange pulses are local unitary operations obtained by turning on and off the isotropic exchange interaction between pairs of spin-1/2 particles, for example electron spins in quantum dots. We present a procedure for analytically constructing sequences of exchange pulses for carrying out leakage free two-qubit gates on logical three-spin qubits. At each stage of our construction we reduce the problem to that of finding a sequence of rotations for an effective two-level system. The resulting pulse sequences are 39 pulses long, longer than the original 19-pulse sequence of DiVincenzo et al. [1] and the more recent 18-pulse sequence of Fong and Wandzura [2], both of which were obtained numerically. Like the latter sequence, our sequences work regardless of the total spin of the six spins used to encode two qubits. After introducing our method, we prove that any leakage-free sequence of exchange pulses must act on at least five of the six spins to produce an entangling two-qubit gate.


Monday, March 18, 2013 2:30PM - 5:30PM –
Session C27 GQI: Quantum Computing, Quantum Algorithms, and Quantum Simulation 329 -
Alan Aspuru-Guzik, Harvard University

2:30PM C27.00001 Quantum Computing through Quantum Networks, CHENG WU, Missouri University of Science and Technology — Entanglement of two Aharonov-Bohm (AB) rings, or two artificial atoms, is similar to the entanglement of spins from two electrons. The directions of the angular momentum of two AB rings serve as the inputs for a basic two-bit computing in the quantum network. The question is whether the read-out is to be performed under a short and weak external perturbation? We found that a stronger entanglement than the situation needed for a quantum superposition combines with a strong external terminal connections is the only solution for robust classical readouts. A “half-adder” example will be presented. There has to be an inter-relation between internal and external coupling strengths. They are so adjusted for each other so that read-outs are possible.

2:42PM C27.00002 Analytically solvable driven time-dependent two-level quantum systems1. EDWIN BARNES, SANKAR DAS SARMA, Condensed Matter Theory Center, University of Maryland — Analytical solutions to the time-dependent Schrodinger equation describing a driven two-level system are invaluable to many areas of physics, but they are also extremely rare. Here, we present a simple algorithm based on a type of partial reverse-engineering that generates an unlimited number of exact analytical solutions for a general time-dependent Hamiltonian. We demonstrate this method by presenting several new exact solutions that are particularly relevant to qubit control in quantum computing applications. We further show that our formalism easily generates analytical control protocols for performing sweeps across energy level anti-crossings that execute perfect Landau-Zener interferometry and rapid adiabatic passage near the quantum speed limit. [1] Phys. Rev. Lett. 199, 004041 (2012)

1Work supported by LPS-CMTC, CNAM and IARPA

2:54PM C27.00003 Compiled Quantum Factoring Circuits, OMAR GAMEL, DANIEL JAMES, University of Toronto — Shor’s factoring algorithm is held as one of the most promising and useful applications of quantum computing. It allows one to factor large numbers in polynomial time, undermining the most common cryptographic schemes in use today, such as RSA cryptography. The well known algorithm is based on the quantum fourier transform to find the period of a function, and also makes heavy use of the modular exponentiation operation, given by,

\[ U : a \cdot b \rightarrow ax^a \pmod{N}, \]

where \( N \) is the number to be factored, and \( x \) is a random positive integer coprime with \( N \). The modular exponentiation is the bottleneck of the algorithm, the portion that uses the most time. The generic algorithm can factorize any \( N \) in time order \( (\log N)^4 \), assuming sufficient memory space for intermediate calculations. Reducing the memory available (as long as it still lies above a certain threshold) increases the time taken by multiplicative factors, keeping its order the same in \( \log(N) \). However, for a given \( N \), or class of \( N \)’s to factorize, the generic algorithm may be suboptimal, and can be optimized to result in substantial savings in both memory needed and operation time. The different suboperations involved in modular exponentiant

3:06PM C27.00004 Quantum Algorithm for Solving an NP-Complete Problem1, HEFENG WANG, FULLI LI, Department of Applied Physics, Xi’an Jiaotong University, Xi’an 710049, China — When a probe qubit is coupled to a quantum register that represents a physical system, the probe qubit will exhibit a dynamical response only when it is resonant with a transition in the system. Using this principle, we propose a quantum algorithm for solving a specific NP-complete problem, the 3-bit Exact Cover problem, EC3. We show that on a quantum computer, the number of qubits increases linearly with the size of the EC3 problem, while the efficiency of the algorithm is independent of the size of the problem. Our results indicate that quantum computers may be able to outperform classical computers in solving NP-complete problems.

1We acknowledge the support of the National Nature Science Foundation of China (Grant No.11275145 and 11074199)

3:18PM C27.00005 Quantum Steering as a Quantum Game1, SAI VINJANAMPATHY, JING-LING CHEN, MILE GU, National University of Singapore, L.C. KWEEK, National University of Singapore and National Institute of Education and Institute of Advanced Studies, Nanyang Technological University, 1 Nanyang Wa — “Steerable states” are a subset of entangled states, that contain in them the set of Bell non-local states. A bipartite state shared by Alice and Bob is called steerable if by performing measurements, the ensemble that Alice can produce on Bob’s side is unexplained by any local hidden variable theory. We will provide an operational interpretation of quantum steering by proposing a quantum game. The probability that the players win this game will be related to quantum steering. Furthermore, we will show how the various hierarchies between entanglement, steering and Bell non-locality are preserved by this quantum game.

1National Basic Research Program (973 Program) of China under Grant No. 2012CB921900, NSF of China (Grant Nos. 10975075 and 11175089) and by National Research Foundation and Ministry of Education of Singapore

3:30PM C27.00006 Quantum Data Fitting, NATHAN WIEBE, University of Waterloo — We provide a new quantum algorithm that efficiently determines the quality of a least-squares fit over an exponentially large data set by building upon an algorithm for solving systems of linear equations efficiently (Harrow et al., Phys. Rev. Lett. 103, 150502 (2009)). In many cases, our algorithm can also efficiently find a concise function that approximates the data to be fitted and bound the approximation error. In cases where the input data is a pure quantum state, the algorithm can be used to provide an efficient parametric estimation of the quantum state and therefore can be applied as an alternative to full quantum state tomography given a fault tolerant quantum computer.
3:42PM C27.00007 Virtual Parallel Computing and a Search Algorithm Using Matrix Product States\textsuperscript{1}, EDUARDO MUCCIOLI, University of Central Florida, CLAUDIO CHAMON, Boston University — We propose a form of parallel computing on classical computers that is based on matrix product states. The virtual parallelization is accomplished by representing bits with matrices and by evolving these matrices from an initial product state that encodes multiple inputs. Matrix evolution follows from the sequential application of gates, as in a logical circuit. The action by classical probabilistic one-bit and deterministic two-bit gates such as NAND are implemented in terms of matrix operations and, as opposed to quantum computing, it is possible to copy bits. We present a way to explore this method of computation to solve search problems and count the number of solutions. We argue that if the classical computational cost of testing solutions (witnesses) requires less than $O(n^2)$ local two-bit gates acting on $n$ bits, the search problem can be fully solved in subexponential time. Therefore, for this restricted type of search problem, the virtual parallelization scheme is faster than Grover’s quantum algorithm.

\textsuperscript{1}This work was supported in part by NSF Grants No. CCF-1116590 and No. CCF-1117241.

3:54PM C27.00008 Google in a Quantum Network, GIUSEPPE DAVIDE PAPARO, Universidad Complutense — In [1] we introduce the characterization of a class of quantum PageRank algorithms in a scenario in which some kind of quantum network is realizable out of the current classical internet web, but no quantum computer is yet available. This class of algorithms represents a quantization of the PageRank protocol currently employed to list web pages according to their importance. The PageRank algorithm’s ranking ability has been instrumental to give structure to the web. This class of algorithms may be able to rank nodes in a quantum network. Furthermore, in this class, we have found an instance of this class of quantum protocols that outperforms its classical counterpart and may break the classical hierarchy of web pages depending on the topology of the web.


4:06PM C27.00009 Discrete-time quantum walk with history dependence, ZLATKO DIMCIOVIC, YEVENIY KOVCHEGOV, Oregon State University — We study a discrete time quantum walk (DTQW) with explicit correlation (or, memory/history dependence) over previous steps, implemented by a unique evolution operator. Monitoring the paths affects their interferences and we expect appearance of anomalies and classical features, while the process stays unitary. For 2-step-memory we obtain a closed-form generating function, with amplitude asymptotic. The trademark ballistic peaks of DTQW remain but a sharp central peak over a few sites appears. For deeper correlations we have so far obtained a full numerical solution for up to 20 memory-steps, evolved over 10,000’s of time-steps. As memory increases, the amplitude first develops noisy peaks in the middle, and by around 10 step-deep memory the dominant central peak settles, while the runaway peaks typical of DTQW are all but gone. This central distribution is unlike the Gaussian curve of classical walks, the spreading is still ballistic (albeit slow), the shape stabilizes, and we observe universality. These (and some other) properties appear stable. This behavior starkly differs from previous known results. We use a multidimensional coin, but the precise operator form, explicitly encoding memory dependence in the evolution, comes from our (coincident) interchange framework.

4:18PM C27.00010 Renormalization Group for Quantum Walks\textsuperscript{1}, STEFAN FALKNER, STEFAN BOETTCHER, Department of Physics, Emory University, Atlanta, GA 30322; USA, RENATO PORTUGAL, Laboratorio Nacional de Computacao Cienfica, Petropolis, RJ 25651-075; Brazil — A renormalization group (RG) treatment of quantum walks holds significant promise for insights into quantum transport phenomena and search algorithms for quantum computing. The generality of this approach has a good chance to elucidate salient characteristics of quantum walks on higher-dimensional lattices which at this point are unobtainable with other methods and are even difficult to study numerically. Key questions concern the scaling properties of (unitary) quantum evolution depending on the lattice type. Is there a single exponent describing the mean-square displacement of quantum walks, similar to the scenario observed in ordinary random walks, or is there a spectrum of modes, each with their own exponent? Does quantum interference ensure that these exponents are always smaller than for the respective classical random walks? To what extent do translational invariance and other lattice properties matter? Generally, what is the nature of universality in quantum walks? Our preliminary results on effectively one-dimensional lattices demonstrates how RG can be used to study quantum random walks and their asymptotic behavior.

\textsuperscript{1}This work was supported by DMR-grant #1207431 from the NSF.

4:30PM C27.00011 Using the graph isomorphism problem to probe differences between discrete- and continuous-time quantum random walks\textsuperscript{1}, KENNETH RUDINGER, JOHN KING GAMBLE, University of Wisconsin-Madison Department of Physics, ERIC BACH, University of Wisconsin-Madison JOYNT, S. N. COPPERMITH, University of Wisconsin-Madison Department of Physics — Though continuous-time and discrete-time quantum walks appear superficially similar, recent studies have demonstrated potential differences in terms of algorithmic power. We investigate these disparities in the context of the graph isomorphism problem. It has been previously demonstrated that discrete-time walks of two non-interacting particles can never distinguish certain graphs. While it has been proven that continuous-time walks of two non-interacting particles can never distinguish these graphs, it has been proven that continuous-time walks of two non-interacting particles can never distinguish these graphs. We show the origins of this difference in distinguishing power, and find that, even for identical walks, subtle differences in the certificate construction algorithm can non-trivially impact the walk’s distinguishing power.

\textsuperscript{2}This work was supported in part by ARO, DOD (W911NF-09-1-0439) and NSF (CCR-0635355).

4:42PM C27.00012 Experimental 1D quantum simulation using an oxide nanoelectronics platform\textsuperscript{1}, MEGAN KIRKENDALL, DONGYUE YANG, PATRICK IRVIN, JEREMY LEVY, University of Pittsburgh, SANGWOO RYU, CHANG-BEOM EOM, University of Wisconsin-Madison — We are interested in developing a solid state quantum simulation platform which could be used to study important Hamiltonians like the Hubbard model and investigate phenomena such as high temperature superconductivity. Using the nanoscale control that has been demonstrated in modifying the 2DEG at the LaAlO$₃$/SrTiO$₃$ interface\textsuperscript{3} we are attempting to create an artificial system with which to study these phenomena that is decoupled from the underlying lattice. We use conductive AFM lithography to create one-dimensional structures at the LaAlO$₃$ surface.

\textsuperscript{3}We acknowledge support from the AFOSR.


4:54PM C27.00013 ABSTRACT WITHDRAWN —
5:06PM C27.00014 Experimental Boson Sampling, ANDREW WHITE, MATTHEW BROOME, ALESSANDRO FEDRIZZI, SALEH RAHIMI-KESHARI, TIMOTHY RALPH, University of Queensland, JUSTIN DOVE, SCOTT AARONSON, Massachusetts Institute of Technology — Quantum computers are unnecessary for exponentially-efficient computation or simulation if the Extended Church-Turing thesis—a foundational tenet of computer science—is correct. The thesis would be directly contradicted by a device that efficiently performs a task believed to be intractable for classical computers. Such a task is **Boson Sampling**: obtaining a distribution of $n$ bosons scattered by some linear-optical unitary process. Here we test the central premise of Boson Sampling, experimentally verifying that the amplitudes of 3-photon scattering processes are given by the permanents of submatrices generated from a unitary describing a 6-mode integrated optical circuit. We find the protocol to be robust, working even with the unavoidable effects of photon loss, non-ideal sources, and imperfect detection. Strong evidence against the Extended-Church-Turing thesis will come from scaling to large numbers of photons, which is a much simpler task than building a universal quantum computer.

5:18PM C27.00015 Opening up the Quantum Three-Box Problem with Undetectable Measurements, RICHARD GEORGE, University College London, LUCIO ROBLEDO, TU Delft, OWEN MARONEY, University of Oxford, MACHIEL BLOK, HANNES BERNIEN, TU Delft, DANIEL TWITCHEN, MATTHEW MARKHAM, E6, JOHN MORTON, University College London, ANDREW BRIGGS, University of Oxford, RONALD HANSON, TU Delft — One of the most striking features of quantum mechanics is the profound effect exerted by measurements alone. Sophisticated quantum control is now available in several experimental systems, exposing discrepancies between quantum and classical mechanics whenever measurement induces disturbance of the interrogated system. In practice, such discrepancies may frequently be explained as the back-action required by quantum mechanics adding quantum noise to a classical signal. Here we implement the ‘three-box’ quantum game (Aharonov, et al. 1991) by utilising state-of-the-art control and measurement of the nitrogen vacancy centre in diamond. In this protocol, the back-action of quantum measurements adds no detectable disturbance to the classical description of the game. Quantum and classical mechanics then make contradictory predictions for the same experimental procedure, however classical observers are unable to invoke measurement-induced disturbance to explain the discrepancy. We quantify the disturbance of our measurements and obtain data ruling out any classical model by 7.8 sigma, excluding state-definiteness from our system. Our experiment is then equivalent to a Kochen-Specker test of quantum non-contextuality that successfully addresses the measurement detectability loophole.

**Tuesday, March 19, 2013 8:00AM - 11:00AM**

Session F3 GQI DAMOP: Invited Session: Quantum Computing in AMO Ballroom III - Ivan Deutsch, University of New Mexico

8:00AM F3.00001 Quantum Computation with Trapped Rydberg Atoms, MARK SAFFMAN, University of Wisconsin — Highly excited atomic Rydberg states provide strong, long range dipolar interactions which can be used to create entanglement between atoms, between atoms and optical photons, and between atoms and microwave photons. I will review recent progress in this rapidly developing area including optical trapping of Rydberg atoms, experiments with a 2D array of qubits, and progress towards a coherent quantum interface between neutral atom and superconducting qubits.

1Work supported by NSF, DARPA, IARPA

8:36AM F3.00002 Quantum computation with atomic ensembles, KLAUS MOELMER, University of Aarhus — No abstract available.

9:12AM F3.00003 Hybrid quantum information processing, AKIRA FURUSAWA, The University of Tokyo — There are two types of schemes for quantum information processing (QIP). One is based on qubits, and the other is based on continuous variables (CVs), where the computational basis for qubit QIP is $\{ |0 \rangle, |1 \rangle \}$ and that for CV QIP is $\{ |x \rangle \} (-\infty < x < \infty)$. A universal gate set for qubit QIP is $\{ \text{bit flip } \sigma_x, \text{phase flip } \sigma_z, \text{`Hadamard gate'} H, \text{`$\pi$/8 gate'}, \text{`controlled NOT (CNOT) gate'} \}$. Similarly, a universal gate set for CV QIP is $\{ \text{`$x$-displacement' } D(x), \text{`$p$-displacement' } D(ip), \text{`Fourier gate'} F, \text{`cubic phase gate'} e^{ikx}, \text{`quantum non-demolition (QND) gate'} \}$. There is one-to-one correspondence between them. CV version of `bit flip $\sigma_x$' is $\text{`$x$-displacement' } D(x)$, which changes the value of the computational basis. Similarly, CV version of `phase flip $\sigma_z$' is $\text{`$p$-displacement' } D(ip)$, where `phase flip $\sigma_z$' switches the `value' of `conjugate basis' of qubit $\{|+\rangle, |-\rangle \} (|\pm \rangle = (|0 \rangle \pm |1 \rangle)/\sqrt{2})$ and `$p$-displacement' $D(ip)$ changes the value of CV conjugate basis $\{|p\rangle \}$. `Hadamard' and `Fourier' gates transform computational bases to respective conjugate bases. CV version of `$\pi$/8 gate' is a `cubic phase gate' $e^{i k x}$ and CV version of CNOT gate is a QND gate. However, the origin of nonlinearity for QIP is totally different, here the very basic nonlinear operation is calculation of multiplication and of course it is the heart of information processing. The nonlinearity of qubit QIP comes from a CNOT gate, while that of CV QIP comes from a cubic phase gate. Since nonlinear operations are harder to realize compared to linear operations, the most difficult operation for qubit is a CNOT gate, while the counter part, a QND gate, is not so difficult. CNOT and QND gates are both entangling gates, it follows that creating entanglement is easier for CV QIP compared to qubit QIP. Here, creating entanglement is the heart of QIP. So, it is a big advantage of CV QIP. On the other hand, the fidelity of CV QIP is not so high because perfect fidelity needs infinite energy, which comes from the infinite dimensionality of CV QIP. To overcome the difficulty, “hybrid” approach is proposed. In this approach, qubits are used as inputs for CV QIP. It is possible because qubits can be regarded as a special case of CVs. So, we can circumvent the infinite dimensionality problem of CV QIP by using qubits as the inputs. The basic example is qubit teleportation with a CV teleporter, where the qubit is a so-called “dual-rail” qubit with a single photon; $c_{ij}[1,0] + c_{ij}[0,1]$. We recently succeeded in creating time-bin qubits with single photons, and now we are working on the teleportation experiment with the technology developed for teleportation of highly nonclassical wave packets of light.
9:48AM F3.00004 Photonic quantum technologies. JEREMY O'BRIEN, University of Bristol — Of the approaches to quantum computing [1], photons are appealing for their low-noise properties and ease of manipulation [2], and relevance to other quantum technologies [3], including communication, metrology [4] and measurement [5]. We report an integrated waveguide approach to photonic quantum circuits for high performance, miniaturization and scalability [6–10]. We address the challenges of scaling up quantum circuits using new insights into how controlled operations can be efficiently realised [11], demonstrating Shor's algorithm with consecutive CNOT gates [12] and the iterative phase estimation algorithm [13]. We have shown how quantum circuits can be reconfigured, using thermo-optic phase shifters to realise a highly reconfigurable quantum circuit [14], and electro-optic phase shifters in lithium niobate to rapidly manipulate the path and polarization of telecom wavelength single photons [15]. We have addressed miniaturisation how quantum circuits can be reconfigured, using thermo-optic phase shifters to realise a highly reconfigurable quantum circuit [14], and electro-optic phase shifters in lithium niobate to rapidly manipulate the path and polarization of telecom wavelength single photons [15]. We have demonstrated generation of orbital angular momentum states of light [18]. We have incorporated microfluidic channels for the delivery of samples to measure the concentration of a blood protein with entangled states of light [19]. We have begun to address the integration of superconducting single photon detectors [20] and diamond [21,22] and non-linear [23,24] single photon sources. Finally, we give an overview of recent work on fundamental aspects of quantum measurement, including a quantum version of Wheeler's delayed choice experiment [25].


10:24AM F3.00005 Quantum information processing with trapped ions1. JOHN GAEBLER, National Institute for Standards and Technologies — Trapped ions are one promising architecture for scalable quantum information processing. Ion qubits are held in multizonel traps created from segmented arrays of electrodes and transported between trap zones using time varying electric potentials applied to the electrodes. Quantum information is stored in the ions' internal hyperfine states and quantum gates to manipulate the internal states and create entanglement are performed with laser beams and microwaves. Recently we have made progress in speeding up the ion transport and cooling processes that were the limiting tasks for the operation speed in previous experiments. We are also exploring improved two-qubit gates and new methods for creating ion entanglement.

1This work was supported by IARPA, ARO contract No. EAO139840, ONR and the NIST Quantum Information Program

Tuesday, March 19, 2013 8:00AM - 11:00AM –
Session F25 GQI: Superconducting Qubits: Read-out, Feedback and Stabilization
327 - Will Oliver, Massachusetts Institute of Technology

8:00AM F25.00001 Non-linear processes in thin titanium nitride transmission lines for parametric amplification. MICHAEL VISSERS, JIANSONG GAO, SUPTARSHI CHAUDHURI, CLINT BOCKSTIEGEL, MARTIN SANDBERG, DAVID P. PAPPAS, National Institute of Standards and Technology - Boulder — Nitride superconductors, such as titanium nitride and niobium titanium nitride, are a non-linear, low dissipation medium at microwave frequencies. The lossless nonlinearity may be probed and utilized. Important applications include generation of higher harmonics, e.g. 3f, and a microwave version of the optical paramagnetic amplifier, i.e. the degenerate-pump case of four-photon mixing (FPM). An amplifier based on these principles should allow for very wide bandwidth, low noise (quantum limited) and high dynamic range devices. These measurements are performed via a single layer, 3 meter long TiN spiral and measured at temperatures below 100 mK. Initial results of the design, fabrication, testing, and impedance optimization of a titanium nitride based parametric amplifier are presented.

8:12AM F25.00002 Efficiency of a microwave photon detector based on a current-biased Josephson junction1. AMRIT POUDEL, CANRAN XU, MAXIM VAVILOV, Department of Physics, University of Wisconsin-Madison — In this talk we discuss the efficiency of a microwave photon detector based on a current-biased Josephson junction driven by a classical microwave source. We consider the evolution of the junction in the presence of the environment and tunneling events to the voltage state. We calculate the switching time distribution to the voltage state and evaluate the efficiency of the photon detector as a function of input power and the junction parameters. We present conditions for the optimal power matching between the detector and the microwave source.

1This work is supported by the ARO under grant W911NF-11-1-0030 and the NSF under grant DMR-1105178.

8:24AM F25.00003 Optimization of single shot readout of a transmon qubit using a SLUG microwave amplifier1, YANBING LIU, SRIKANTH SRINIVASAN, Princeton University, DAVID HOVER, ROBERT MCDERMOTT, University of Wisconsin, Madison, ANDREW HOUCK, Princeton University — We report on measurement of a superconducting transmon qubit using a number of optimization techniques and a low noise amplifier. Optimization is performed over power and frequency, and a genetic algorithm is employed to optimize the readout fidelity as a function of the measurement pulse shape. In addition, a superconducting low-inductance undulatory galvanometer (SLUG), a SQUID-based microwave amplifier, is used to reduce system noise. The SLUG amplifier has very high dynamic range and low noise over a relatively wide frequency range. Both the SLUG amplifier and genetic algorithm lead to improved readout fidelity over analytic pulse shaping and HEMT amplification.

1Thanks support from IARPA
8:36AM F25.00004 Large gain quantum-limited qubit state measurement using a two mode nonlinear cavity. SAEED KHAN, AASHISH CLERK, McGill University, Dept. of Physics — A single nonlinear cavity dispersively coupled to a qubit functions as a large gain detector near a bifurcation, but also has an unavoidable large backaction that prevents QND measurement at weak couplings [1]. We show theoretically that a modified setup involving two cavities (one linear, one nonlinear) and a dispersively coupled qubit allows for a far more optimal measurement. In particular, operating near a point of bifurcation, one is able to both achieve a large gain as well as a near quantum-limited backaction. We present analytic results for the gain and noise of this detector and a heuristic understanding of the physics, thus presenting a complete description of this new way of performing weak qubit state measurements. The setup we describe can easily be realised in experiments with superconducting circuits involving Josephson junctions [2,3].


8:48AM F25.00005 A >10 GHz JPC with Trans-Gain for Qubit Readout1. K. SLIWA, A. NARLA, M. HATRIDGE, F. SCHACKERT, B. ABDO, S. SHANKAR, L. FRUNZIO, M.H. DEVORET, Applied Physics Department, Yale University — For multi-qubit circuit QED experiments, it is desirable to work with cavities at frequencies >10 GHz to allow for design flexibility. However, performance of following electronics can be best optimized at low frequencies (3-5 GHz). These seemingly contradictory requirements can be naturally reconciled using the Josephson Parametric Converter (JPC). The JPC is a quantum limited amplifier comprised of two non-degenerate resonators coupled via a ring of Josephson junctions. It can bridge frequency ranges separated by more than an octave via its trans-gain, a process in which a signal incident on one port is frequency converted and transmitted with gain on the other port. Here we present data on the trans-gain of a JPC with one resonator at 11.5 GHz and the other at 4.5 GHz which could be used in such a readout scheme without any significant compromise on gain, dynamic range, or bandwidth.

1Work supported by: IARPA, ARO, NSF, and IBM.

9:00AM F25.00006 Characterization of a Multi-Layer Parametric Amplifier with On-Chip Bias Line C. NEILL, T. WHITE, R. BARENDJS, J. BOCHMANN, B. CAMPBELL, Y. CHEN, B. CHIARO, E. JEFFREY, J. KELLY, M. MARIANTONI, A. MEGRANT, J. MUTUS, C. LAFLAMME, P. O’MALLEY, S. OHYA, P. ROUSHAN, D. SANK, A. VAJSENCHER, J. WENNER, A.N. CLELAND, J.M. MARTINIS, UC Santa Barbara — Single shot dispersive readout of superconducting qubits requires a near quantum limited microwave amplifier. Based on the parametric amplifier design from UC Berkeley, we have developed a parametric amplifier using the UCSB multilayer fabrication with a single ended input and an on-chip flux bias line. These changes enable us to use a smaller and simpler chip mount with separate signal and flux ports. The high bandwidth of the flux port allows us to flux pump the amplifier and should allow dynamic frequency tuning on ns timescales. Flux pumping also requires fewer components in the measurement line, reducing signal loss. With this design we have achieved parametric amplification using two kinds of input pumping and three kinds of flux pumping; for each mode we have characterized gain bandwidth product, saturation power, and noise temperature.

9:12AM F25.00007 Increasing dynamic range in microwave parametric amplifiers J. MUTUS, R. BARENDJS, J. BOCHMANN, B. CAMPBELL, Y. CHEN, B. CHIARO, E. JEFFREY, J. KELLY, M. MARIANTONI, A. MEGRANT, C. NEILL, P. O’MALLEY, S. OHYA, P. ROUSHAN, D. SANK, A. VAJSENCHER, J. WENNER, T. WHITE, A.N. CLELAND, J.M. MARTINIS, UC Santa Barbara — Parametric amplifiers have long been of interest in quantum information due to their high gain and near quantum limited performance. In collaboration with UC Berkeley, we are improving upon their proven parametric amplifier design, which consists of a lumped element LC resonator, with a SQUID providing a tunable nonlinear inductance. In order to improve the dynamic range of these amplifiers, multiple SQUIDs are used in series in order to distribute the non-linearity across many junctions. We report on the design of a single-ended amplifier using our 7-layer fabrication process, combining photo and electron beam lithography. We explore the experimental optimization of such a design, specifically the impact of adding additional SQUIDs on overall device performance.

9:24AM F25.00008 Improved JPC performance via a low inductance, lumped element design1. A. NARLA, K. SLIWA, M. HATRIDGE, S. SHANKAR, F. SCHACKERT, B. ABDO, L. FRUNZIO, R.J. SCHÖLKOPF, M.H. DEVORET, Applied Physics Department, Yale University — The Josephson Parametric Converter (JPC), a linear, non-degenerate, nearly quantum-limited amplifier, is a promising tool for quantum information applications. We propose a new JPC design characterized by the use of multi-pF parallel-plate capacitors. By decreasing the geometric inductance of the system, higher critical-current Josephson junctions can be used. Both the bandwidth and dynamic range can thus be increased by a factor of two relative to existing microstrip devices. When integrated with a shunted ring of Josephson junctions [1], these devices should also be tunable over more frequency ranges separated by more than an octave via its trans-gain, a process in which a signal incident on one port is frequency converted and transmitted with gain on the other port. Here we present data on the trans-gain of a JPC with one resonator at 11.5 GHz and the other at 4.5 GHz which could be used in such a readout scheme without any significant compromise on gain, dynamic range, or bandwidth.

1Work supported by: IARPA, ARO, and NSF.

9:36AM F25.00009 Optimizing bandwidth and dynamic range of lumped Josephson parametric amplifiers1. A. EDDINS, R. VIJAY, C. MACKLIN, QNL, UC Berkeley, Z. MINEV, Yale University, I. SIDDIQI, QNL, UC Berkeley — Superconducting parametric amplifiers have revolutionized the field of quantum measurement by providing high gain, ultra-low noise amplification. They have been used successfully for high-fidelity qubit state measurements, probing nano-mechanical resonators, quantum feedback, and for microwave quantum optics experiments. Though several designs exist, a simple and robust architecture is the Lump Josephson Parametric Amplifier (LJPA). This device consists of a capacitively shunted SQUID directly coupled to a transmission line to form a low quality factor (Q) nonlinear resonator. We discuss amplifiers which can be tuned over the full 4-8 GHz band with 20-25 dB of gain and 10 - 50 MHz of signal bandwidth. However, similar to other parametric amplifiers employing a resonant circuit, the LJPA suffers from low dynamic range and has a -1 dB gain compression point of order -130 dBm. We explore new designs comprised of an array of SQUIDs to improve the dynamic range. We will present the results of numerical simulations and preliminary experiments. We will also briefly discuss improvements obtained from different biasing methods and packaging.

1This research was supported by the Army Research Office under a QCT grant.
10:00AM F25.00011 Stabilizer quantum error correction toolbox for superconducting qubits†, SIMON NIGGG, STEVEN GIRVIN, Yale University — Rudimentary quantum error correction (QEC) has been achieved in a superconducting qubit circuit [1]. Realization of topological protection and QEC based on stabilizer codes will require protocols for QND measurement of multi-qubit Pauli operators on arbitrary selected subsets of qubits. Initial progress towards this goal has been achieved with four-qubit stabilizer pumping in a trapped ion system [2]. We present a general protocol for stabilizer measurement and pumping in a system of N superconducting qubits. We assume always-on, fixed dispersive couplings χ to a single mode of a high-Q microwave resonator in the strong-dispersive limit defined by χ ≫ 1/T 2, κ, where T 2 is the qubit coherence time and κ is the cavity line width. In this limit, we show how to measure an arbitrary weight M ≤ N Pauli operator, by entangling the multi-qubit state with two distinguishable coherent states of the cavity. Together with a fast cavity readout (τ meas ≪ 1/κ), which can be achieved by tunable coupling to a low-Q cavity mode, this enables the efficient measurement of multi-qubit Pauli operators.

1 Work supported by IARPA, ARO and NSF.

10:12AM F25.00012 Autonomous stabilization of an entangled state of two transmon qubits†, S. SHANKAR, Z. LEGHTAS, M. HATRIDGE, A. NARLA, U. VOOL, S.M. GIRVIN, Applied Physics Department, Yale University, M. MRRAHIMI, Applied Physics Department, Yale University and INRIA, Paris-Rocquencourt, M.H. DEVORET, Applied Physics Department, Yale University — Recent circuit QED (cQED) experiments on superconducting transmon qubits have shown good progress towards measurement-based quantum feedback, that allow the stabilization of interesting quantum states, such as an entangled state of two qubits. These experiments crucially depend on fast, high-fidelity, quantum non-demolition qubit readout using superconducting parametric amplifiers as well as high-speed room-temperature electronics. We describe an alternate autonomous-feedback strategy to stabilize two qubits dispersively coupled to a single cavity into an entangled state, while obviating the need for an optimized measurement chain. The system Hamiltonian is designed to be in the strong dispersive cQED regime where the dispersive shifts of the two qubits are tuned to be equal (χ/2π = 5 MHz) and larger than the cavity linewidth (κ/2π = 1.5 MHz). By applying continuous microwave drives at the cavity and qubit frequencies, the system is forced into the desired quantum state. The stabilization rate of this scheme is of order κ which can be made much faster than all decoherence rates 1/T 1, 1/T 2, that take the system out of the entangled state. We will discuss initial experimental progress towards the goal of autonomous high-fidelity entanglement.

†This work was supported by the Swiss NSF, the US NSF DMR-1004406 and ARO W911NF-09-1-0514.

10:24AM F25.00013 Efficient Experimental Characterization of a Feedback Scheme for Qubit Initialization, YVES SALATHE, CHRISTOPHER EICHLER, THOMAS KARG, PHILIPP KURPIERS, CHRISTIAN LANG, ANDREAS WALLRAFF, ETH Zurich — Quantum feedback based on high-efficiency projective measurements has a variety of potential applications such as active qubit initialization and quantum teleportation. Here, we experimentally investigate active initialization of a single transmon qubit in circuit quantum electrodynamics using parametric amplification similar to the experiment by Ristè et. al. [1]. We implement the feedback scheme using field-programmable gate array (FPGA) electronics which conditions a π-pulse on the outcome of a prior quantum nondemolition measurement. Our processing unit also records multi-dimensional histograms which reveal the correlations between the initial and final state of the feedback process. We use these histograms to characterize the efficiency of our feedback implementation without the necessity of storing all individual single-shot measurement traces. The presented histogram-based measurement technique has potential applications in other experiments which involve feedback such as quantum teleportation.


10:36AM F25.00014 Superconducting qubit parameter optimization for remote entanglement†, N. ROCH, M.E. SCHWARTZ, C. MACKLIN, R. VIJAY, I. SIDDIQI, QNL, UC Berkeley — The combination of coherent lifetimes in excess of 100 microseconds and robust operation of low noise parametric amplifiers has enabled experiments in which high fidelity continuous measurement can be performed, opening the door for measurement based quantum feedback. The first experiment realized in this regime aimed at stabilizing a dynamical state of a superconducting qubit using a closed feedback loop [1]. We explore the prospects of extending this unprecedented control to engineered networks comprised of several superconducting qubits and microwave cavities, with the particular goal of stabilizing a central feature of quantum mechanics: the entanglement. We will discuss the optimal choice of hardware—qubit, cavity, and circuitry—as well as measurement protocols for maximizing entanglement.


†This research was supported by the Army Research Office under a QCT grant.

10:48AM F25.00015 Progress towards measurement-induced entanglement of remote superconducting qubits†, M.E. SCHWARTZ, N. ROCH, C. MACKLIN, R. VIJAY, I. SIDDIQI, QNL, UC Berkeley — Generation and distribution of entanglement are critical capabilities for quantum computation and simulation. In superconducting qubits, entanglement can be achieved via direct qubit-qubit coupling on chip. In contrast to this type of local interaction, we present experiments and simulations targeted at generating entanglement between remote (non-coupled) 3D transmons. Entanglement is achieved via joint measurement in a basis that does not project, and thus does not dephase, the odd-parity Bell manifold (|01⟩/|10⟩). The experiments rely on coherent state detection, rather than photon-counting, and are a step towards deterministic feedback stabilization of remote qubit entanglement. We also model the effects of experimental realities, including excess amplifier noise, cable insertion loss, and finite qubit coherence times.

†This research was supported by the Army Research Office under a QCT grant, and by the Fannie and John Hertz Foundation.
Tuesday, March 19, 2013 8:00AM - 10:48AM –
Session F26 GQI: Quantum Cryptography, Quantum Communication, and Quantum Measurement 328 - Graeme Smith, IBM

8:00AM F26.00001 Quantum to classical randomness extractors, STEPHANIE WEHNER, CQT, Singapore, MARIO BERTA, ETH Zurich, OMAR FAWZI, McGill University — The goal of randomness extraction is to distill (almost) perfect randomness from a weak source of randomness. When the source yields a classical string $X$, many extractor constructions are known. Yet, when considering a physical randomness source, $X$ is itself ultimately the result of a measurement under an underlying quantum system. When characterizing the power of a source to supply randomness it is hence a natural question to ask, how much classical randomness we can extract from a quantum system. To tackle this question we here introduce the notion of quantum-to-classical randomness extractors (QC-extractors). We identify an entropic quantity that determines exactly how much randomness can be obtained. Furthermore, we provide constructions of QC-extractors based on measurements in a full set of mutually unbiased bases (MUBs), and certain single qubit measurements. As the first application, we show that any QC-extractor gives rise to entropic uncertainty relations with respect to quantum side information. Such relations were previously only known for two measurements. As the second application, we resolve the central open question in the noisy-storage model [Wehner et al., PRL 100, 220502 (2008)] by linking security to the quantum capacity of the adversary’s storage device.

8:12AM F26.00002 Quantum secret sharing with minimized quantum communication, BEN FORTESCU, Southern Illinois University, GILAD GOUR, University of Calgary — Standard techniques for sharing a quantum secret among multiple players (such that certain subsets of the players can recover the secret while others are denied all knowledge of the secret) require a large amount of quantum communication to distribute the secret, which is likely to be the most costly resource in any practical scheme. Two known methods for reducing this cost are the use of imperfect “ram” secret sharing (in which security is sacrificed for efficiency) and classical encryption (in which certain elements of the players’ shares consist of classical information only). We demonstrate how one may combine these methods to reduce the required quantum communication below what has been previously achieved, in some cases to a provable minimum, without any loss of security. The techniques involved are closely-related to the properties of stabilizer codes, and thus have strong potential for being adapted to a wide range of quantum secret sharing schemes.

8:24AM F26.00003 Quantum teleportation over 143 kilometres using active feed-forward, XIAOSONG MA, THOMAS HERBST, THOMAS SCHEIDL, DAQING WANG, SEBASTIAN KROPATSCHEK, WILLIAM NAYLOR, ALEXANDRA MECH, IQOQI Vienna, BERNHARD WITTMANN, JOHANNES KOFLER, Univ of Vienna, ELENA ANISIMOVA, VADIM MAKAROV, THOMAS JENNEWIN, IQC, RUPERT URSIN, ANTON ZEILINGER, IQOQI Vienna — Quantum teleportation is a quintessential prerequisite of many quantum communication protocols. By using quantum teleportation, one can circumvent the no-clone theorem and faithfully transfer unknown quantum states to a private location even when the location is even unknown over arbitrary distances. Ever since the first experimental demonstrations of quantum teleportation of independent qubits and of squeezed states, researchers have progressively extended the communication distance in teleportation. Here we report the first long-distance quantum teleportation experiment with active feed-forward in real time. The experiment employed two optical links, quantum and classical, over 143 km free space between the two Canary Islands of La Palma and Tenerife. To achieve this, the experiment had to employ a combination of advanced techniques such as a frequency-uncorrelated polarization-entangled photon pair source, ultra-low-noise single-photon detectors, and entanglement-assisted clock synchronization. The average teleportated state fidelity was well beyond the classical limit of 2/3.

8:36AM F26.00004 Ultrafast quantum communications over long distances using quantum encoding, SRERAMAN MURALIDHARAN, LIANG JIANG, Yale University — Quantum repeaters provide a way of enabling long distance quantum communication by establishing entangled qubits between remote locations. The first generation quantum repeater protocols involve time consuming entanglement purification steps that demand a long lived quantum memory and two-way classical communication that makes them slow. This problem can be circumvented by the new generation quantum repeater protocols that use quantum encoding, one-way classical communication and classical error correction techniques. Furthermore, each quantum repeater station only needs short lived quantum memory bits, the number of which has favorable poly-logarithmic scaling with the distance. We investigate the tolerance of these schemes against photon losses and depolarizing errors, and discuss the possibility of realizing these schemes in physical systems with the current state of art.

8:48AM F26.00005 Generating and verifying entanglement of itinerant microwave modes, H.S. KU, W.F. KINDEL, JILA and University of Colorado at Boulder, S.C. GLANCY, E. KNILL, L.R. VALE, G.C. HILTON, K.D. IRWIN, NIST, K.W. LEHNERT, JILA, NIST and University of Colorado at Boulder — Entanglement is a critical resource for quantum information science. In particular, shared entanglement between pairs of electromagnetic fields propagating on two physically separate channels is required for quantum communication protocols with continuous variables. Moreover, the ability to entangle propagating microwave modes provides possible schemes to create quantum communication channels between localized superconducting qubits. In this talk, we will present an experimental demonstration of this type of entanglement. We generate the entangled state by combining a squeezed state and vacuum on a balanced beam splitter. The entanglement is then revealed by strong correlations between the quadrature amplitudes of the two output modes of the beam splitter. Crucial for an eventual teleportation demonstration, the two modes are measured efficiently and with independent choice of measured quadratures.

9:00AM F26.00006 Microwave Photon Counter Based on Josephson Junctions, GUILHEM RIBEILL, UMESHKUMAR PATEL, JOSEPH SUTTLE, ROBERT MCDERMOTT, University of Wisconsin - Madison Department of Physics — We describe progress in the development of a microwave photon counter based on the current biased Josephson junction; absorption of a single photon causes the junction to switch to the voltage state, producing a large and easily measured classical signal. We discuss a self-resetting bias scheme based on a superconducting kinetic inductor that causes the junction to reset automatically to the active state following photon absorption. We investigate detector quantum efficiency and dark rate, and discuss applications to mesoscopic noise and circuit quantum electrodynamics.

9:12AM F26.00007 Utilization of an Electron Multiplying CCD camera for applications in quantum information processing, MONIKA PATEL, JIAN CHEN, JONATHAN HABIF, Raytheon BBN Technologies — Electron Multiplying Charge-Coupled Device (EMCCD) cameras utilize an on-chip amplification process which boosts low-light signals above the readout noise floor. Although traditionally used for biological imaging, they have recently attracted interest for single-photon counting and entangled state characterization in quantum information processing applications. In addition, they exhibit some photon number-resolving capacity, which is attractive from the point-of-view of several applications in optical continuous-variable computing, such as building a cubic phase gate. We characterize the Andor Luca-R EMCCD camera as an affordable tool for applications in optical quantum information. We present measurements of single-photon detection efficiency, dark count probability as well as photon-number resolving capacity. We demonstrate an upper bound on the noise performance and detection efficiency of the EMCCD detector array. We find that the readout noise floor is a Gaussian distribution centered at 500 counts/pixel/frame at high EM gain setting. We also characterize the trade-off between quantum efficiency and detector dark-count probability.
9:24AM F26.00008 High-efficiency Cooper pair splitting demonstrated by two-particle conductance resonance and positive noise cross-correlation, YUVAL RONEN, ANINDYA DAS, MOTY HEIBLUM, DIANA MAHALLI, ANDREY KRETININ, HADAS SHTRIKMAN, Weizmann Institute of Science, MOTY HEIBLUM LAB TEAM — Entanglement is at the heart of the Einstein-Podolsky-Rosen paradox, where the non-locality is a necessary ingredient. Cooper pairs in superconductors can be split adiabatically, thus forming entangled electrons. Here, we fabricate such an electron splitter by contacting an aluminum superconductor strip at the centre of a suspended InAs nanowire. The nanowire is terminated at both ends with two normal metallic drains. Dividing each half of the nanowire by a gate-induced Coulomb blockaded quantum dot strongly impedes the flow of Cooper pairs due to the large charging energy, while still permitting passage of single electrons. We provide conclusive evidence of extremely high efficiency Cooper pair splitting via observing positive two-particle correlations of the conductance and the shot noise of the split electrons in the two opposite drains of the nanowire. Moreover, the actual charge of the injected quasiparticles is verified by shot noise measurements.

9:36AM F26.00009 An operational approach to indirectly measuring tunneling time, YUNJIN CHOI, ANDREW JORDAN, University of Rochester — The tunneling time through an arbitrary one-dimensional barrier is investigated using the dwell time operator approach. Since the tunneling time contains a natural post-selection (we only average over particles that successfully tunnel), the tunneling time can be related to the weak value of the dwell time operator. We analyze the situation by considering a specific measurement context containing experimentally observable quantities, since measuring the dwell time operator directly is not strictly achievable in the laboratory. Therefore, we reconstruct the average value of the dwell time operator applying the contextual values formalism [J. Dresel and A. N. Jordan, Phys. Rev. A 85, 022123 (2012)] for generalized measurements based on the Larmor clock [M. Büttiker, Phys. Rev. B 27, 6178 (1983)].

9:48AM F26.00010 A Stochastic Path Integral Formulation for Continuous Quantum Measurement, AREEYA CHANTASRI, JUSTIN DRESSEL, ANDREW JORDAN, Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA — We consider the continuous quantum measurement of a two-level system, for example, a double-quantum dot weakly measured by a quantum point contact. In a weak measurement regime, the measurement outcome at each time step is non-deterministic and fluctuates around its mean value. While the stochastic master/Schrödinger equations are commonly used to study the state of the qubit, we propose an alternative formalism — the stochastic path integral — which can compute moments and correlation functions of the measurement outcomes, and the distributions of possible qubit states. By constructing a probability functional of the measurement outcomes in a path integral form, the moments can be computed from perturbative expansions, which can be resumed to exact solutions in some cases. We show that this approach reproduces and extends existing solutions derived using different methods, and introduces a new way to compute conditioned moments and correlation functions. We also show how real-time feedback can be naturally included in this approach.

10:00AM F26.00011 Weak values are universal in von Neumann measurements¹, JUSTIN DRESSEL, ANDREW JORDAN, University of Rochester — We refute the widely held belief that the quantum weak value necessarily pertains to weak measurements. To accomplish this, we use the transverse position of a free particle as the detector for the conditioned von Neumann measurement of a system observable. For any coupling strength, any initial states, and any choice of conditioning, the averages of the detector position and momentum are completely described by the real parts of three generalized weak values in the joint Hilbert space. Higher-order detector moments also have similar weak value expansions. Using the Wigner distribution of the initial detector state, we find compact expressions for these weak values within the reduced system Hilbert space, demonstrating that the effective preselection for a measured system weak value is decohered by the detector. As an optical application of the approach, we consider an arbitrary Hermite-Gauss mode for a paraxial beam-like detector. For non-Gaussian modes the momentum shift involves the imaginary part of the system weak value plus an additional weak-value-like correction.

¹This work was supported in part by the SPDR Program, RIKEN. SA and FN acknowledge ARO, NSF grant No. 0726909, JSPS-RFBR contract No. 12-02-92100, Grant-in-Aid for Scientific Research (S), MEXT Kakenhi on Quantum Cybernetics, and the JSPS via its FIRST program.

10:12AM F26.00012 Implementing general quantum measurements on linear optical and solid-state qubits¹, YUKIHIRO OTA, SAHEL ASHHAB², FRANCO NORI³, RIKEN — We show a systematic construction for implementing general measurements on a single qubit, including both strong (or projection) and weak measurements. We mainly focus on linear optical qubits. The present approach is composed of simple and feasible elements, i.e., beam splitters, beam waves, plates, and polarization beam splitters. We show how the parameters characterizing the measurement operators are controlled by the linear optical elements. We also propose a method for the implementation of general measurements in solid-state qubits. Furthermore, we show an interesting application of the general measurements, i.e., entanglement amplification.

¹YO is partially supported by the SPDR Program, RIKEN. SA and FN acknowledge ARO, NSF grant No. 0726909, JSPS-RFBR contract No. 12-02-92100, Grant-in-Aid for Scientific Research (S), MEXT Kakenhi on Quantum Cybernetics, and the JSPS via its FIRST program.

²University of Michigan

³University of Michigan

10:24AM F26.00013 Embedded SIC-POVMs¹, HOAN BUI DANG, Perimeter Institute for Theoretical Physics and University of Waterloo, KATE BLANCHFIELD, INGEMAR BENGTSSON, Stockholms University, MARCUS APPLEBY, Perimeter Institute for Theoretical Physics — Symmetric informationally complete (SIC) sets of quantum states have applications in foundational studies of quantum mechanics, quantum tomography, quantum communication, quantum cryptography, and classical signal processing. However, their existence in every dimension has not been proven, and no general construction has been known. During our study of linear states in Weyl-Heisenberg orbits [1], we discovered 2-dimensional SICs embedded in a 6-dimensional Hilbert space. This offers a robust construction for 2-dimensional SICs, and may potentially impact the SIC existence problem. In this talk, I will explain how this construction works, and present numerical results for some other dimensions. References: [1] Hoan Bui Dang, Kate Blanchfield, Ingemar Bengtsson, D. M. Appleby, "Linear Dependencies in Weyl-Heisenberg Orbits," arXiv:1211.0215.

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


¹This work was supported in part by the U. S. Office of Naval Research (Grant No. N00014-09-1-0247).
8:00AM F27.00001 Majorana fermions in 1D superconducting wires subject to disorder and other spatial inhomogeneities. WADE DEGOTTARDI, Argonne National Laboratory, DIPTIMAN SEN, Indian Institute of Science, SMITHA VISHVESHWARA, University of Illinois at Urbana-Champaign — We present a systematic study of the role that disordered and quasiperiodic potentials play in the topology of 1D p-wave superconducting systems characterized by boundary Majorana modes. We forge a connection between Majorana wave functions and the localization properties of the corresponding normal state system (i.e., one which, though otherwise identical, lacks superconducting order). This enables the leveraging of the vast body of literature on Anderson localization to extensively map the topological phase diagram in superconducting wires. We find that the phase boundary is extremely sensitive to the detailed form of the potential. Our analysis provides a mapping between the limits of weak and strong disorder, in some cases, we are able to find the full phase boundary analytically. A noteworthy discovery is a tell-tale singularity in the phase boundary at the point corresponding to the quantum Ising model, a feature which offers a window into the physics of Majorana fermions. Our results can be directly applied to a spin-1/2 XY chain in a transverse magnetic field which is quasiperiodic or disordered.

8:12AM F27.00002 Universal transport signatures of Majorana fermions in superconductor-Luttinger liquid junctions. JASON ALICEA, California Institute of Technology, LUKASZ FIDKOWSKI, UC Berkeley, NETANEL LINDNER, California Institute of Technology, ROMAN LUTCHYN, Station Q, MATTHEW FISHER, UC Santa Barbara — One of the most promising proposals for engineering Majorana fermions employs a spin-orbit-coupled nanowire proximate to an s-wave superconductor. When only part of the wire's length contacts to the superconductor, the remaining conducting portion serves as a natural lead that can be used to probe these Majorana modes via tunneling. The enhanced role of interactions in 1D dictates that this configuration should be viewed as a superconductor-Luttinger liquid junction. We demonstrate that low-energy transport in such junctions is universal, and governed by fixed points describing either perfect normal reflection or perfect Andreev reflection. In addition to capturing (in some instances) the familiar Majorana-mediated zero-bias anomaly in a new framework, we show that interactions yield dramatic consequences in certain regimes. Implications for conductance and local density of states measurements will be discussed.

8:24AM F27.00003 Coherent oscillations between single fluxonium qubit and Majorana fermion qubit. CHANG-YU HOU, Caltech and UC Riverside, DAVID PEKKER, Caltech, VLADIMIR MANUCHARYAN, EUGENE DEMLER, Harvard University — We propose a hybrid device that couples a Majorana qubit to a superconducting fluxonium qubit. The devices consists of a conventional s-wave superconductor (e.g. Nb) ring interrupted by a narrow gap and a section of topological 1D wire bridging across the gap. Such topological 1D wire can be realized by using a semiconducting nanowire with strong spin orbit scattering (e.g. InSb) subjected to magnetic field. The nanowire hosts a topological qubit formed by four Majorana fermions and acts as a Josephson junction that completes the superconducting ring and makes a fluxonium qubit. As the current-phase relation of the Josephson junction is controlled by the state of the Majorana qubit, the fluxonium and Majorana qubit are naturally coupled. We demonstrate how this coupling can be exploited to construct two qubit operations. Remarkably, quantum information can be transformed between two distinct types of qubits solely using well-controlled operations on the fluxonium qubit.

8:36AM F27.00004 Majorana Zero Modes in Semiconductor Nanowires in Contact with Higher-Tc Superconductors. YOUNG-HYUN KIM, JENNIFER CANO, UCSB, CHETAN NAYAK, Station Q, UCSB — We present the prospects for stabilizing Majorana zero modes in semiconductor nanowires that are proximity-coupled to higher-temperature superconductors. We begin with the case of iron pnictides which, though they are s-wave superconductors, are believed to have superconducting gaps that change sign. We then consider the case of cuprate superconductors. We show that a nanowire on a step-like surface, especially in an orthorhombic material such as YBCO, can support Majorana zero modes at an elevated temperature.

8:48AM F27.00005 Coherent population trapping of hyperfine-coupled single spins in diamond. ANDREW GOLTER, NIMA DINYARI, HAILIN WANG, University of Oregon — Coherent population trapping (CPT) provides a highly sensitive means for probing the energy level structure of an atomic system. For diamond nitrogen vacancy (NV) centers, this technique offers an alternative to the standard optically-detected magnetic resonance (ODMR) for measuring the hyperfine structure of the electronic ground states. Here, we report an experimental study using CPT to probe the hyperfine splitting of these states as well as the Tuchendler-Townes effect induced by a strong resonant microwave field. This nuclear spin dependent CPT was also employed along with other coherent spin operations for the initialization and manipulation of hyperfine-coupled nuclear spins. In addition, the use of CPT process to incorporate NV centers into a cavity QED system will be discussed.

9:00AM F27.00006 Phonon sideband studies of the spin-triplet optical transition in diamond nitrogen-vacancy centers. AUDRIUS ALKAUSKAS, Materials Department, University of California, Santa Barbara, DAVID M. TOYLI, BOB B. BUCKLEY, DAVID D. AIVSCHALOM, Center for Spintronics and Quantum Computation, University of California, Santa Barbara, CHRIS G. VAN DE WALLE, Materials Department, University of California, Santa Barbara — In the past decade, the nitrogen-vacancy center in diamond has emerged as a promising solid-state system for quantum-information processing, and also for nanoscale magnetic, electric, and thermal sensing. All of these applications are partly enabled because the spin of the center can be measured through photoluminescence. This calls for a deeper understanding of the photoluminescence spectrum, in particular its phonon side-band. In this work we study the coupling of lattice vibrations to the triplet (3E–3A2) optical transition from first-principles electronic structure calculations. Our formulation includes both quasi-localized and bulk phonons, and leads to an excellent agreement of the calculated and the measured photoluminescence lineshape. This good agreement enables the application of the developed methodology to other defects in semiconductors that are currently being investigated as viable quantum bits.

9:12AM F27.00007 Measurement-Only Topological Quantum Computation via Tunable Interactions. PARSAM BONDERS, Station Q, Microsoft Research — I examine, in general, how tunable interactions may be used to perform anyonic teleportation and generate braiding transformations for non-Abelian anyons. I explain how these methods are encompassed by the “measurement-only” approach to topological quantum computation. The physically most relevant example of Ising anyons or Majorana zero-modes is considered in detail, particularly in the context of Majorana nanowires.
9:24AM F27.00008 Quantum information processing using quasiclassical electromagnetic interactions between qubits and electrical resonators\textsuperscript{1}, ANDREW KERMAN, MIT Lincoln Laboratory — Electrical resonators are widely used in quantum information processing with any qubits that are manipulated via electromagnetic interactions. In most cases they are engineered to interact with qubits via real or virtual exchange of (typically microwave) photons, and the resonator must therefore have both a high quality factor and strong quantum fluctuations, corresponding to the strong-coupling limit of cavity QED. Although great strides in the control of quantum information have been made using this so-called “circuit QED” architecture, it also comes with some important disadvantages. In this talk, we discuss a new paradigm for coupling qubits electromagnetically via resonators, in which the qubits do not exchange photons with the resonator, but instead exert quasi-classical, effective “forces” on it. We show how this type of interaction is similar to that induced between the internal state of a trapped atomic ion and its center-of-mass motion by the photon recoil momentum, and that the resulting entangling operations are insensitive both to the state of the resonator and to its quality factor. The methods we describe are applicable to a variety of qubit-resonator systems, including superconducting and semiconducting solid-state qubits, and trapped molecular ions.\textsuperscript{1}This work is sponsored by the ASDR&E under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

9:36AM F27.00009 Generation and characterization of hypercubic cluster states in the optical frequency comb, MORAN CHEN, PEI WANG, Department of Physics, University of Virginia, NICOLAS MENICUCCI, School of Physics, The University of Sydney, OLIVIER PFISTER, Department of Physics, University of Virginia — We report on experimental progress toward generating and characterizing a very large quantum wire cluster state of the continuous electromagnetic variables (“Qmodes”) in the optical frequency comb of an optical parametric oscillator (OPO). We also present a proposal for creating higher-dimensional graph states by entangling the linear cluster states of several OPOs, each OPO adding a dimension to the graph (line, square grid, cube, hypercube). Besides the scalable (in number, size, and dimension) creation of sophisticated quantum graphs over hundreds to thousands of Qmodes, this work also constitutes a considerable experimental simplification of our previous proposal for generating a square-grid cluster state in a single OPO.

9:48AM F27.00010 Entangled Photon Holes, TODD PITTMAN, JUNLIN LIANG, JAMES FRANKSON, UMBC, Baltimore MD 21250 — Entangled photon hole (EPH) states represent a new form of entanglement that is based on the existence of “missing pairs” of photons in two optical modes. In contrast to the more familiar photon pairs entangled in polarization or other variables, the entanglement in EPH states arises from the absence of the photon pairs themselves. We will review recent experimental work on the generation of these states, and theoretical work showing that they can be relatively insensitive to loss and amplification noise in certain situations. We will also report on our recent efforts to generate time-bin EPH states which have different properties than energy-time EPH states.

10:00AM F27.00011 Information-efficient phase imaging with heralded single photons, REIHEANE SHAHROKHSHAHI, NIRANJAN SRIDHAR, OLIVIER PFISTER, Department of Physics, University of Virginia, SAIKAT GUHA, JONATHAN HABIF, Raytheon-BBN, AARON MILLER, Department of Physics, Albion College, ADRIANA LITA, BRICE CALKINS, THOMAS GERRITTS, ANTIA LAMAS-LINARES, SAE WOO NAM, National Institute of Standards and Technology — We report progress toward the experimental realization of information-efficient quantum imaging, here at two bits per photon. A heralded single-photon source ($\phi^+(0) < 0.08$) is used as the input to a 4x4 multiport interferometer, compactly implemented using both polarization and spatial degrees of freedom. The interferometer can be used to read out all 4 Hadamard phase codes with a single photon. We investigate the use of cavity-enhanced spontaneous parametric downconversion for the coherent source of heralded photons. The photon-number-resolving ability of high-quantum-efficiency transition edge sensors is used for the heralding and detection.

10:12AM F27.00012 A Two-Qubit Geometric Phase Gate for Localized Electron Spin Qubits using Cavity Polariton Resonance, SHRUTI PURI, NA YOUNG KIM, E. L. Ginztion Laboratory, Stanford University, California, USA, YOSHIIISA YAMAMOTO, E. L. Ginztion Laboratory, Stanford University, California, USA, National Institute of Informatics, Tokyo, Japan — We propose a two-qubit geometric phase gate, in which the interaction between a pair of localized electron spins, is mediated by quantum well microcavity exciton-polaritons. The entanglement between the electrons is a result of their spin dependent Coulomb exchange interaction with the exciton-polaritons. This optical coupling, resembling the electron-electron Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions, offers high speed, high fidelity two-qubit gate operation with moderate cavity quality factor Q. The long ranged interaction by microcavity polaritons (order of micrometers) makes this gate suitable for fault tolerant operations. By the use of electrostatic quantum dots, the errors caused by unwanted excitations to charged excitons or trions are eliminated. The errors due to the finite lifetime of the polaritons can be minimized by optimizing the optical pulse parameters (duration and energy). The proposed design maximizes entanglement and ensures scalability.

10:24AM F27.00013 Quantum Computing using Photons, AHMED ELHALAWANY, MICHAEL LEUENBERGER, University of Central Florida — In this work, we propose a theoretical model of two-quantum bit gates for quantum computation using the polarization states of two photons in a microcavity. By letting the two photons interact non-resonantly with four quantum dots inside the cavity, we obtain an effective photon-photon interaction which we exploit for the implementation of an universal XOR gate. The two-photon Hamiltonian is written in terms of the photons’ total angular momentum operators and their states are written using the Schwinger representation of the total angular momentum.

10:36AM F27.00014 Charge pumping by a surface acoustic wave in an undoped quantum well: a potential single-photon source, S.K. SON, Y. CHUNG, Cavendish Laboratory, University of Cambridge, UK, J. PEDROS, Technical University of Madrid, Spain, C.I.B. FORD, C.H.W. BARNES, J.P. GRIFFITHS, G.A.C. JONES, I. FARRER, D.A. BITCHE, Cavendish Laboratory, University of Cambridge, UK — Single-electron transfer between distant quantum dots using gates, and to transport a stream of single electrons or holes along a narrow, empty channel using SAWs. The potential has a steep slope at the edges of the inducing gates, but we have modelled the potential profile of the active region to find designs in which the polarization is uniform enough to allow the SAW potential to drag electrons out of the induced region, towards the region of holes. Recombination of each electron with one of the holes should produce a photon and we are investigating the use of this device as a single-photon source. If the electrons are spin-polarized then their spins can be detected by measuring the circular polarisation of the photons, and this may be useful for spin readout in a quantum processor, as a result of a quantum repeater in quantum cryptography.

10:48AM F27.00015 ABSTRACT WITHDRAWN –

Tuesday, March 19, 2013 11:15AM - 2:03PM – Session G25 GQI: Itinerant Photons, Squeezed States, and Entanglement 327 - Lev Bishop, University of Maryland
11:27AM G25.00002 Catching Microwave Photons in a Superconducting Resonator with Tum- 

11:27AM G25.00003 Radiative decay of a superconducting qubit in squeezed vacuum1, S.J. WEBER, K.W. MURCH, QNL, UC Berkeley, K.M. BECK, Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, E. GINOSAR, Advanced Technology Institute and Department of Physics, University of Surrey, I. SIDDIQI, QNL, UC Berkeley — When the conventional vacuum 
fluctuations of the electromagnetic environment are replaced by the asymmetric, reduced fluctuations associated with squeezed vacuum, the radiative properties of an atom are predicted to be dramatically altered. We present measurements of the transverse and longitudinal decay rates of a superconducting qubit that couples predominantly to a continuum of squeezed electromagnetic vacuum. We use a lumped element Josephson parametric amplifier to squeeze vacuum fluctuations by up to 10 dB with a bandwidth of 20 MHz. The amplifier output is directly coupled to a transmon qubit in a microwave cavity. We observe a dependence of the transverse decay rate on the relative angle between the squeezed axis and the qubit. In particular, at certain angles, we observe an improvement in the qubit T2 time above its nominal value.

1This work was supported by the IARPA CSQ program.

11:39AM G25.00003 Radiative decay of a superconducting qubit in squeezed vacuum1, S.J. WEBER, K.W. MURCH, QNL, UC Berkeley, K.M. BECK, Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, E. GINOSAR, Advanced Technology Institute and Department of Physics, University of Surrey, I. SIDDIQI, QNL, UC Berkeley — When the conventional vacuum 
fluctuations of the electromagnetic environment are replaced by the asymmetric, reduced fluctuations associated with squeezed vacuum, the radiative properties of an atom are predicted to be dramatically altered. We present measurements of the transverse and longitudinal decay rates of a superconducting qubit that couples predominantly to a continuum of squeezed electromagnetic vacuum. We use a lumped element Josephson parametric amplifier to squeeze vacuum fluctuations by up to 10 dB with a bandwidth of 20 MHz. The amplifier output is directly coupled to a transmon qubit in a microwave cavity. We observe a dependence of the transverse decay rate on the relative angle between the squeezed axis and the qubit. In particular, at certain angles, we observe an improvement in the qubit T2 time above its nominal value.

1This work was supported by the IARPA CSQ program.

12:03PM G25.00005 Extracting Past-Future Vacuum Correlations Using Circuit QED1, BORJA PEROPADRE1, Instituto de Fisica Fundamental, CSIC, CARLOS SABIN1, School of Mathematical Sciences, The University of Nottingham, MARCO DEL REY, Instituto de Fisica Fundamental, CSIC, EDUARDO MARTIN-MARTINEZ4, Institute for Quantum Computing, Dept. Applied Math., University of Waterloo & Perimeter Institute. In this work we propose a realistic circuit QED experiment to test the extraction of past-future vacuum entanglement to a pair of superconducting qubits. A qubit P—for past—interacts with a field along an open transmission line for an interval $T_{on}$ and then, after a time-lapse $T_{off}$ of no interaction, a second qubit F—for future—starts interacting for a time $T_{on}$ in a symmetric fashion. After this protocol, past-future quantum correlations will have transferred to the qubits, even if the qubits do not coexist at the same time. We show that this experiment can be realized with current technology and discuss its utility as a possible implementation of a quantum memory.

1Spanish MICINN Projects No. FIS2011-29287 and No. FIS2009-10061 and CAM research consortium QUITEMAD Grant No. S2009-ESP-1594.

12:15PM G25.00006 Observation of the squeezed state of microwave photons by resolving the even-number Fock states in circuit QED1, KYUNG-SUN MOON, Dept. of Physics, Yonsei Univ. — We theoretically propose an elegant way to detect the microwave parametric down conversion in the circuit QED system. The qubit energy splitting $E_{q}$ is tuned to be quite close to the fundamental frequency $\omega_1$ of the microwave photon and the frequency of the pump beam is chosen to be $\omega_2$. We place the qubit at the two-thirds away from the center of the central resonator, which will make the capacitive coupling to the third harmonic mode to be negligible. Since the qubit acts as an optical 
coupler in our system, one may expect that the following process $a_1^+a_1^+a_2$ may appear and compete with the squeezing process $a_1^+a_2^+a_2$, which will seriously degrade the quality of squeezing by mixing into the channel. Since the coupling to the third harmonic mode is negligible for our system, we expect instead to observe the clear squeezing of the microwave photon with frequency $\omega_3$. We calculate the absorption spectrum of the qubit, which is experimentally measurable and will clearly reveal the squeezed states as the coherent superposition of the even-number Fock states.

1This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology(2012R1A1A206927).
12:27PM G25.00007 Generation of Nonclassical States of Microwave Radiation via Single Photon Detection, EMILY PRITCHETT, LUKE GOVIA, FRANK WILHELM, Saarland University — We describe the creation of nonclassical states of microwave radiation via ideal dichotomic single photon detection, i.e., a detector that only indicates presence or absence of photons. Ideally, such a detector has a back action in the form of the subtraction operator. Using the non-linearity of this back action, it is possible to create nonclassical states of microwave radiation, including squeezed and cat-like states, starting from a coherent state. We discuss the applicability of this protocol to current experimental designs of Josephson Photomultipliers (JPMs).

12:39PM G25.00008 Path Entanglement of Continuous-Variable Quantum Microwaves, E. P. MENZEL, F. DEPEPE, P. EDER, L. ZHONG, M. HAEBERLEIN, A. BAUST, E. HOFFMANN, A. MARX, R. GROSS, Walther-Meissner-Institut and TU Muenchen, Germany, R. DI CANDIA, E. SOLANO, Universidad del Pais Vasco UPV/EHU and Ikerbasque, Spain, D. BALLESTER, University College London, UK, M. IHMIG, TU Muenchen, Germany, K. INOMATA, RIKEN Advanced Science Institute, Japan, T. YAMAMOTO, NEC Smart Energy Research Laboratories and RIKEN, Japan Y. NAKAMURA, The University of Tokyo and RIKEN, Japan — Entanglement is a quantum mechanical phenomenon playing a key role in quantum communication and information processing protocols. Here, we report on frequency-degenerate entanglement between continuous-variable quantum microwaves propagating along two separated paths. In our experiment, we combine a squeezed and a vacuum state via a beam splitter. Overcoming the challenges imposed by the low photon energies in the microwave regime, we reconstruct the squeezed state and, independently from this, detect and quantify the produced entanglement via correlation measurements (E. P. Menzel et al., arXiv:1210.4413). Our work paves the way towards quantum communication and teleportation with continuous variables in the microwave regime.

This work is supported by SFB 631, German Excellence Initiative via NIM, EU projects SOLID, CCQED and PROMISCE, MEXT Kakenhi, “Quantum Cybernetics”, JSPS FIRST Program, the NICT Commissioned Research, EPSRC EP/H050434/1, Basque Government IT472-10, and Spanish MICINN FIS2009-12773-C02-01.

12:51PM G25.00009 Cooper Pair Transistor Embedded in a dc-Biased High-Q Microwave Cavity, JULIANG LI, FEI CHEN, JOEL STETTENHEIM, Dartmouth College, A.J. SIROIS, University of Colorado, Boulder, R.W. SIMMONDS, National Institute of Standards and Technology, Boulder, M.P. BLENCOWE, A.J. RIMBERG, Dartmouth College — A Cooper pair transistor (CPT) is directly coupled to a high-Q microwave cavity, which allows introduction of a dc bias to the CPT without significantly degrading the cavity Q. In the subgap region of the CPT, the dc bias generates a tunable oscillating current through the CPT via the ac Josephson effect. Evidence of such self-oscillations has been observed as current peaks in our dc measurements, which are in good agreement with calculated cavity modes, and indicate the strong coupling between the CPT and the cavity. Tunneling Cooper pairs can both emit photons into and absorb photons from microwave cavity modes. Photons emitted into the cavity are also directly probed and are in good agreement with dc measurements. Recent experimental results including the importance of careful filtering of the DC bias lines will be discussed. This work is supported by the NSF, AFOSR and DARPA.

1:03PM G25.00010 Photon Emission from a Self-Oscillating Cavity-Embedded Cooper Pair Transistor1, FEI CHEN, JULIANG LI, JOEL STETTENHEIM, Dartmouth College, A. J. SIROIS, University of Colorado, Boulder, R. W. SIMMONDS, National Institute of Standards and Technology, Boulder, M. P. BLENCOWE, A. J. RIMBERG, Dartmouth College — A strongly non-linear superconducting device consisting of a Cooper pair transistor embedded in a dc voltage biased microwave cavity is investigated. The current-driven Cooper pair transistor (CPT) is driven via the ac Josephson effect by an applied dc bias and exhibits self-oscillation without an external ac drive. Photon emission arising from both sequential tunneling and cotunneling processes of Cooper pairs has been observed. We have characterized the measured photon field by heterodyne quadrature detection and have reconstructed its quasi-probability distribution by implementing an iterative procedure for maximum-likelihood estimation of its density matrix. The CPT offers an interesting system for studying nonlinear quantum dynamics and the quantum-to-classical transition.

1 This work is supported by the NSF, AFOSR and DARPA

1:15PM G25.00011 The Quantum-Classical Correspondence for a Self-Oscillating Cavity-Embedded Cooper Pair Transistor System1, ERIND BRAHIMI, FEI CHEN, JULIANG LI, JOEL STETTENHEIM, Dartmouth College, ANDREW ARMOUR, University of Nottingham, ALEX RIMBERG, MILES BLENCOWE, Dartmouth College — We provide a theoretical model for our recent experiment involving a dc voltage biased Cooper pair transistor (CPT) that strongly drives a high quality factor microwave cavity via the ac Josephson effect. Depending on the tunable dc voltage bias, the model shows that the CPT can generate a range of non-trivial quantum states involving large average microwave photon number. Using a Floquet basis approach to solving for the quantum dynamics and a Wigner function representation of the state, we compare some of the model photon state predictions with experiment. The good agreement validates the CPT as a novel platform for exploring the quantum-classical correspondence in strongly nonlinear, macroscopic systems.

1 This work is supported by the NSF and the Carl Zeiss Foundation

1:27PM G25.00012 Shaping the Spontaneous Emission Pulse from a Superconducting Qubit1, SRIKANTH SRINIVASAN, YANBING LIU, GENCYN ZHANG, Princeton University, TERRI YU, Yale University, JAY GAMBITTA, IBM T.J. Watson Research Center, STEVEN GRIVIN, Yale University, ANDREW HOUCH, Princeton University — We report on measurements of spontaneous emission in a circuit quantum electrodynamics system. A superconducting qubit with tunable coupling to a coplanar waveguide cavity is operated in a regime where the qubit relaxation time, and consequently the spontaneous emission rate, is dominated by the interaction strength. This fast control knob on the coupling strength is used to shape the emitted single photon’s wavepacket. The independent control over the coupling allows the dressed qubit frequency to remain truly constant during the emission. The wavepacket shape becomes important in experiments where quantum information needs to be transported between various nodes in a quantum network. The transfer can happen with a very high fidelity if the wavepacket is time-symmetric, since emission by the source and absorption by the destination become time reversed processes.

1 Authors would like to thank IARPA for their generous support.

1:39PM G25.00013 Emergent Non-Adiabatic Wavefunctions for Strongly Dissipative Qubits, SOUMYA BERA, SERGE FLORENS, Institute Neel, Grenoble, HAROLD BARANGER, Duke University, NICOLAS ROCH, ENS, Paris, AHSAN NAZIR, Imperial College London, ALEX W. CHIN, University of Cambridge — We show that a qubit strongly interacting with its environment leads to highly entangled states with emerging non-adiabatic features (Schrodinger-cat-like states of the environment). The model we consider is a two-level-system (qubit) coupled to a continuum of quantum oscillators (bosons), which can be realized, for instance, by a superconducting qubit coupled to a transmission line of photons. We show that the joint system is remarkably well described by a generalized variational coherent state ansatz, an ansatz which is justified by comparing exact quantum tomography of the states found through Numerical Renormalization Group (NRG) calculations. Our coherent state ansatz includes not only the well-known polaronic contributions but also non-adiabatic anti-polaron contributions; these later contributions are critical for an accurate description of the strong coupling regime. We calculate the entanglement entropy of the qubit plus a single bosonic mode with the rest of the system; this joint entropy peaks for a bosonic mode around the Kondo scale, an effect due to the anti-polaronic contribution.
the bus and interacts dispersively with the target qubit, as a fundamental two-qubit interaction.

randomized benchmarking and tomography. We also investigate the fast swap style cPhase gate [Strauch PRL 2003], where the control qubit is swapped into

Barbara — Using a newly developed frequency tunable transmon qubit (“Xmon”), we are beginning to construct the fundamental gates and architecture for a

easy to couple to four elements and is dispersively read out, making it

type of transmon qubit, the Xmon, which shows long coherence, allows for straightforward coupling to multiple elements, and has a low parasitic coupling. The

1 We acknowledge support from IARPA under contract W911NF-10-1-0324.

11:51AM G26.00001 Quantum process verification methods and applications to superconducting qubits1 , JAY GAMBITTA, IBM T.J. Watson Research Center — Determining how well a quantum gate is implemented on a quantum device is of fundamental importance. Such a characterization allows a direct comparison between different architectures for computation as well as an understanding of the performance of the building blocks of a quantum computer. In this talk I will show that the standard approach of process tomography is grossly inaccurate in the case where the states and measurement operators used to interrogate the system are generated by gates that have some systematic error, a situation all but unavoidable in any practical setting. I will then present some recent proposals with experimental implementations that are resilient to this type of noise.

12:27PM G26.00003 Compressed Sensing Quantum Process Tomography of Superconducting Qubit Gates1 , ANDREY RODIONOV, ALEXANDER N. KOROTKOV, University of California, Riverside, ROBERT L. KOSUT, SC Solutions, Sunnyvale, CA, MATTEO MARIANTONI, DANIEL SANK, JAMES WENNER, JOHN M. MARTINIS, University of California, Santa Barbara — We have developed a new type of transmon qubit, the Xmon, which shows long coherence, allows for straightforward coupling to multiple elements, and has a low parasitic coupling. The Xmon is UCSB’s building block for a superconducting multiqubit processor. The Xmon easily couples to four elements and is dispersively read out, making it compatible for use in a surface code quantum processor. At present, we are experimenting testing multiqubit chips for demonstrating single and two qubit state prepartion and gates with high fidelity.

2 Supported by IARPA/ARO and ARO MURI

12:39PM G26.00004 Xmons: Transmon qubits for a scalable architecture , RAMI BARENDTS, J. KELLY, D. SANK, J. BOCHMANN, B. CAMPBELL, Y. CHEN, B. CHIARO, E. JEFFREY, M. MARIANTONI, A. MEGRANT, J. MUTUS, C. NEILL, P. O’MALLEY, S. OHYA, P. ROUSHAN, A. VAINSENCHER, J. WENNER, T. WHITE, A.N. CLELAND, J.M. MARTINIS, UC Santa Barbara — We have developed a new type of transmon qubit, the Xmon, which shows long coherence, allows for straightforward coupling to multiple elements, and has a low parasitic coupling. The Xmon is UCSB’s building block for a superconducting multiqubit processor. The Xmon easily couples to four elements and is dispersively read out, making it compatible for use in a surface code quantum processor. At present, we are experimentally testing multiqubit chips for demonstrating single and two qubit state preparation and gates with high fidelity.

12:51PM G26.00005 Benchmarking gates in a qubit-bus-qubit tunable transmon architecture , JULIAN KELLY, R. BARENDTS, J. BOCHMANN, B. CAMPBELL, Y. CHEN, B. CHIARO, E. JEFFREY, M. MARIANTONI, A. MEGRANT, J. MUTUS, C. NEILL, P. O’MALLEY, S. OHYA, P. ROUSHAN, D. SANK, A. VAINSENCHER, J. WENNER, T. WHITE, A.N. CLELAND, J.M. MARTINIS, UC Santa Barbara — Using a newly developed frequency tunable transmon qubit (”Xmon”), we are beginning to construct the fundamental gates and architecture for a quantum computer. We show experimental data for gates in a qubit-bus-qubit configuration. We quantify the fidelity of a set of single qubit gates with both randomized benchmarking and tomography. We also investigate the fast swap style cPhase gate [Strauch PRL 2003], where the control qubit is swapped into the bus and interacts dispersively with the target qubit, as a fundamental two-qubit interaction.
1:03PM G26.00006 Characterization of addressability by simultaneous randomized benchmarking1, JOHN SMOLIN, IBM Research, JAY GAMBETTA TEAM, ANTONIO CORCOLES TEAM, SETH MERKEL TEAM, IBM QUANTUM COMPUTING GROUP TEAM — The control and handling of errors arising from cross-talk and unwanted interactions in multi-qubit systems is an important issue in quantum information processing architectures. We introduce a benchmarking protocol that provides information about the amount of addressability present in the system and implement it on coupled superconducting qubits. The protocol consists of randomized benchmarking each qubit individually and then simultaneously, and the amount of addressability is related to the difference of the average gate fidelities of those experiments. We present the results of two similar superconducting transmon qubits with different amounts of cross-talk and unwanted interactions, which agree with predictions based on simple models for the amount of residual coupling.

1We acknowledge support from IARPA under contract W911NF-10-1-0324.

1:15PM G26.00007 Implementation of a Robust Tomography Toolbox, COLM RYAN, BLAKE JOHNSON, MARCUS DA SILVA, Raytheon BBN Technologies, SHELBY KIMMEL, Massachusetts Institute of Technology, THOMAS OHKII, Raytheon BBN Technologies, IBM MQCO TEAM — Recent advances in coherence times and control techniques have dramatically improved gate fidelities in superconducting qubits. Already, estimates of these small errors are dominated by errors in the state preparation and measurement pulses of quantum process tomography. Randomized benchmarking (RB) provides a way to isolate gate errors, but only for estimating the fidelity of Clifford operations. Here we implement several extensions to RB that provide more detailed information about specific gates while maintaining the key RB advantage of being robust to state and measurement errors. We will show: interleaved benchmarking results to characterize the average fidelity of specific gates; simultaneous benchmarking to characterize addressability errors with multiple qubits; and robust tomography results that show a full unital characterization of a trace preserving operation. Taken together these provide a full suite of characterization tools useful to any quantum experimentalist.

1:27PM G26.00008 Robust Tomography using Randomized Benchmarking1, MARCUS SILVA, Quantum Information Processing Group, Raytheon BBN Technologies, SHELBY KIMMEL, Center for Theoretical Physics, MIT, BLAKE JOHNSON, COLM RYAN, THOMAS OHKII, Quantum Information Processing Group, Raytheon BBN Technologies — Conventional randomized benchmarking (RB) can be used to estimate the fidelity of Clifford operations in a manner that is robust against preparation and measurement errors — thus allowing for a more accurate and relevant characterization of the average error in Clifford gates compared to standard tomography protocols. Interleaved RB (IRB) extends this result to the extraction of error rates for individual Clifford gates. In this talk we will show how to combine multiple IRB experiments to extract all information about the unital part of any trace preserving quantum process. Consequently, one can compute the average fidelity to any unitary, not just the Clifford group, with tighter bounds than IRB. Moreover, the additional information can be used to design improvements in control.

1MS, BJ, CR and TO acknowledge support from IARPA under contract W911NF-10-1-0324.

1:39PM G26.00009 Experimental realization of non-abelian geometric gates with a superconducting three-level system, ABDUFARRUKH ABDUMALIKOV, J. M. FINK, K. JULIUSSON, M. PECHAL, S. BERGER, A. WALLRAFF, S. FILIPP, Department of Physics, ETH Zurich — Geometric gates hold promise to provide the building blocks for robust quantum computation. In our experiments, we demonstrate a superconducting three-level system (transmon) to realize non-adiabatic non-abelian geometric gates. As computational basis we choose the ground and second excited states, while the first excited state acts as an ancilla state. The gates are realized by applying two resonant drives between the transmon levels. During the geometric gate ration of the amplitudes of the two drive tone is kept constant. Different gates are obtained for different ratio of the drive tones. We implement a Hadamard, a NOT and a phase gate with the fidelities of 95%, 98%, and 97% as determined by full process tomography and maximum likelihood methods. We explicitly show the non-abelian nature of gates by applying two non-commuting gates in alternating order. The demonstrated holonomic gates are not exclusive to superconducting quantum devices, but can also be applied to other three level systems with similar energy level structure.

1:51PM G26.00010 Implementation of a five-cavity / four-qubit 3D circuit QED system1, DOUGLAS MCCLURE, CHAD RIGETTI, JAY GAMBETTA, STEFANO POLETTO, ERIK LUCERO, MARK KETCHEN, MATTHIAS STEFFEN, IBM T.J. Watson Research Center — Surface code error correction schemes, which have emerged as a guiding paradigm for the development of small prototype quantum processors, have a natural implementation on a skew square 2D lattice of cavities and qubits. We describe the experimental realization of a modular segment containing a unit cell of this lattice in a device consisting of five 3D waveguide cavities and four superconducting transmon qubits. In this system, we demonstrate high-fidelity one- and two-qubit gates with low crosstalk. Moreover, this device provides an extensible framework for tests of protocols needed for error correction processors, have a natural implementation on a skew square 2D lattice of cavities and qubits. We describe the experimental realization of a modular segment containing a unit cell of this lattice in a device consisting of five 3D waveguide cavities and four superconducting transmon qubits. In this system, we demonstrate high-fidelity one- and two-qubit gates with low crosstalk. Moreover, this device provides an extensible framework for tests of protocols needed for error correction in much larger systems.

1We acknowledge support from IARPA under contract W911NF-10-1-0324.

2:03PM G26.00011 Quantum lost property: A possible operational meaning for the Hilbert-Schmidt product, MATTHEW PUSEY, TERRY RUDOLPH, Imperial College London — Minimum error state discrimination between two mixed states ρ and σ can be aided by the receipt of “classical side information” specifying which states from some convex decompositions of ρ and σ apply in each run. I will quantify this phenomena by the average trace distance, and give lower and upper bounds on this quantity as functions of ρ and σ. The lower bound is simply the trace distance between ρ and σ, trivially seen to be tight. The upper bound is , and we conjecture that this is also tight. I will show how to reformulate this conjecture in terms of the existence of a pair of “unbiased decompositions”, which may be of independent interest. Time permitting, I will outline the evidence for this conjecture. Based on http://arxiv.org/abs/1208.2550

Tuesday, March 19, 2013 11:15AM - 1:51PM – Session G27 GQI: Quantum Error Correction and Quantum Control 329 - Leonid Pryadko, University of California, Riverside

11:15AM G27.00001 Towards Fault-Tolerant Dynamical Decoupling, GREGORY QUIROZ, DANIEL LIDAR, University of Southern California — Dynamical Decoupling (DD) is a error suppression technique which combats decoherence by applying strong and fast pulses to a quantum system to effectively average system-environment interactions. Although many DD constructions have been designed which exhibit suppression of interactions to high orders in time-dependent perturbation theory, this result is predominately in the ideal pulse limit as DD effectiveness degrades significantly in the presence of additional errors generated by faulty pulses. Here, we present a decoupling scheme which provides robustness to certain forms of pulse errors and utilizes concatenation to attain high order error suppression. Using numerical simulations, we convey the advantages of this scheme over additional robust DD constructions and provide evidence for the possibility of arbitrary order error suppression in the presence of pulse errors.
Fault-Tolerant Storage of Quantum Information by Large Block Codes

Ching-Yi Lai, Todd Brun, University of Southern California, USC TEAM — An important issue in the implementation of a quantum computer is to protect quantum information from decoherence. Concatenated quantum codes and topological quantum codes are extensively studied for fault-tolerant quantum computation. However, there is not much research on large block codes in any fault-tolerant scheme. Here we propose a method for storage of quantum information by a large block code, which has a high code rate and high distance. To access or protect the quantum information stored in a large block code requires only the fault-tolerant implementation of the gates from the Clifford group. We derive the lifetime of the quantum information stored in a large block code by CSS code construction.

Progress in analytical investigations of the achievement of fault tolerance in quantum computing

Gerald Gilbert, Yaakov Weinstein, MITRE Quantum Information Science Group — We describe progress made in understanding and assuring fault tolerance in quantum computation. We introduce and explore analytical techniques for explicitly determining the logical state of a quantum computer undergoing dynamical evolution according to an arbitrary quantum algorithm. We carry out detailed analyses of the effects of errors, paying special attention to the general case of non-equiequivalent errors, i.e., the important and realistic situation in which the probabilities for \( \sigma_x \), \( \sigma_y \) and \( \sigma_z \) errors are not necessarily the same (\( \sigma_x \), \( \sigma_y \) and \( \sigma_z \) are the Pauli operators).

Simulating the Transverse Ising Model on a Quantum Computer: Error Correction with the Surface Code

 Hao You, Michael Geller, Phillip Stancil, Department of Physics and Astronomy, University of Georgia — We estimate the resource requirements for the quantum simulation of the ground state energy of the one-dimensional quantum transverse Ising model (TIM), based on the surface code implementation of a fault-tolerant quantum computer. The surface code approach has one of the highest known tolerable error rates (\( \approx 1\% \)) which makes it currently one of the most practical quantum computing schemes. Compared to results of the same model using the concatenated Steane code, the current results indicate that the simulation time is comparable but the number of physical qubits for the surface code is \( 1-2 \) orders of magnitude larger than that of the concatenation code. Considering that the error threshold requirements of the surface code is four orders of magnitude higher than the concatenation code, building a quantum computer with a surface code implementation appears more promising given current physical hardware capabilities. We would like to acknowledge valuable discussions with Joydip Ghosh, Matteo Mariantoni, Andrew Sornborger, James Whitfield and Zhongyuan Zhou. This work was supported by the National Science Foundation through grant CFI 1029764.

Resilience of topological error-correction codes to concurrent qubit and measurement errors

Ruben S. Andrist, Perimeter Institute for Theoretical Physics, Institute for Quantum Computing, and Department of Physics and Astronomy, University of Waterloo, Jonathan Baugh, Institute for Quantum Computing and Department of Physics, University of Waterloo, Raymond Laflamme, Institute for Quantum Computing, and Quantum Information Systems, University of Waterloo, Perimeter Institute for Theoretical Physics — It has been a milestone in realizing quantum computing, to enhance our control over physical systems so that making quantum processors performing accurately and precisely in presence of environmental noise. For practical uses, quantum error correction should be employed in multi-run cycles in order to keep the encoded qubit, that is carrying the information, safe from noise. We have been working towards implementing multi-run quantum error correction in molecular systems that involve electron and nuclear spins. Electron spins of a molecular sample are used for pumping up the nuclear spin polarizations, in addition to addressing and manipulating the nuclear spins. The required experimental conditions for having access to refreshable ancilla qubits are very much enhanced by a careful design of the molecular sample. We report the progress and prospects towards overcoming the experimental challenges in terms of sample preparation; irradiation imposed free electron samples, free radical molecular spin systems, and triplet state photoexcitable co-crystal samples.

Quantum error correction with soft-pulse dynamically corrected gates with always-on qubit couplings on bipartite lattices

Amrit De, Leonid P. Pryadko, University of California - Riverside — We suggest a scalable implementation of a universal set of high fidelity quantum gates on a bipartite lattice with always-on Ising couplings using dynamical decoupling (DD) sequences with second-order self-refocusing pulses. In addition to decoupling the unwanted parts of the inter-qubit interaction, the constructed gates also protect the qubits against low-frequency phase noise. This allows heterogeneous concatenation of DD and quantum error correction. We illustrate the technique by simulating the encoding/decoding and repeated ancilla based measurements for 4- and 5-qubit quantum error detecting/correcting codes on a spin chain and on a star graph.

Protecting OAM states of light from the decoherence effects of a turbulent atmosphere

Jose Raoul Gonzalez Alonso, Todd Brun, University of Southern California — While there are many advantages to using the polarization of photons to encode quantum information, a major disadvantage is that the limited dimension of the Hilbert space that describes the polarization state allows only the encoding of one qubit per photon. However, if one uses the orbital angular momentum (OAM) of photons then the Hilbert space that describes the OAM state of a photon is infinite dimensional. Thus, it is possible to encode more than one qubit per photon. This advantage can be exploited in quantum key distribution (QKD) and in quantum secure direct communications. However, unlike the polarization of a photon, the OAM is prone to the decoherence effects produced by interactions with a turbulent atmosphere. In this work, we derive an expression for these decoherence effects, and numerically simulate them to find a Kraus error map. We then theoretically demonstrate encoding and information recovery methods that could mitigate such unwanted effects.
12:51PM G27.00009 Unitary Transformations in a Large Hilbert Space 1
BRIAN ANDERSON, HECTOR SOSA MARTINEZ, AARON SMITH, University of Arizona, CARLOS RIOFRIO, CHARLIE BALDWIN, IVAN DEUTSCH, University of New Mexico, POUL JESSEN, University of Arizona — Quantum systems with Hilbert space dimension greater than two (qudits) provide an alternative to qubits as carriers of quantum information, and may prove advantageous for quantum information tasks if good laboratory tools for qudit manipulation and readout can be developed. We have implemented a protocol for arbitrary unitary transformations in the 16 dimensional hyperfine ground manifold of Cesium 133 atoms, using phase modulation of rf and microwave magnetic fields to drive the atomic evolution. Our phase modulation waveforms are designed numerically using a variant of the highly efficient GRAPE algorithm. The fidelity of the resulting transformations is verified experimentally through randomized benchmarking, which indicates an average fidelity better than 97% across a sample of random unitaries. Our toolbox for quantum control is in principle applicable for a broad class of physical systems, such as large spins or anharmonic oscillators.

1Support from IARPA MQCO, DARPA QuEST, and NSF Materials World Network.

1:03PM G27.00010 Resonant Microwave Control of a Symmetric Exchange-Only Spin Qubit 1
J. MEDFORD, Harvard University, J. BEIL, Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, J. M. TAYLOR, Joint Quantum Institute, NIST, H. LU, A. C. GOSSARD, Materials Department, University of California, Santa Barbara, C. M. MARCUS, Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen — We demonstrate two-axis control of an exchange-only spin qubit in a GaAs triple quantum dot using a resonant microwave excitation. The qubit is operated in a regime where two separate exchange interactions are active simultaneously, suppressing leakage out of the qubit subspace and providing some immunity to charge noise. Spectroscopic probes of the qubit reveal that the resonance frequency can be adjusted between 100 MHz and 1.5 GHz with a voltage applied to the middle quantum dot. We find a coherence time $T_2 \sim 20 \mu s$ for a 64 pulse Carr-Purcell-Meiboom-Gill dynamical decoupling sequence. Finally, analysis of the coherence time for multiple sequences reveals a power spectrum $S(\omega) \sim \omega^{-0.9}$, which suggests that the fluctuating Overhauser fields are not the dominant source of dephasing in this system.

1This work was supported by DOE BES

1:15PM G27.00011 Decay of the rotating-frame spin echo and its application to sensing the local environment of a NV center 1
VAGHARSH MKHITARYAN, XIAO-XUAN HUANG, VIATCHESLAV DOBROVITSKI, Ames Laboratory and Iowa State University, Ames, Iowa 50011, USA — We study a NV electron spin subjected to a strong driving field, which reverses its sign with the period $\tau$ (multi-pulse Solomon echo), and analyze the rotating-frame echo decay at long times (large number of reversals). The form and the rate of the echo decay is calculated analytically and numerically, by modelling the decohering spin environment as a magnetic noise. For short $\tau$ the decay is strongly suppressed, being of the 4th order in $\tau$ (vs. 3rd order in the regular Carr-Purcell decoupling, and 2nd order in the standard continuous-wave decoupling). This ensures exceptional decoupling stability with respect to the slow fluctuations of the external magnetic field. Moreover, we find that the decay rate depends non-monotonically on the correlation time of the environment, decreasing for both very fast and very slow spin baths. Using these results, we demonstrate how the multi-pulse version of the Solomon echo can be harnessed to sense and analyze in detail the local spin environment of the NV center.

1This project was supported by DRPA-QuEst Grant No. MSN118850.

1:27PM G27.00012 Sudden Decoherence Transitions for Quantum Discord 1
HYUNGJIN LIM, ROBERT JOYNT, University of Wisconsin-Madison — We formulate the computation of quantum discord in terms of the generalized Bloch vector, focusing on the case of 2 qubits. This provides useful insights on the time evolution of quantum coherence for the open stem, particularly the comparison of entanglement and discord. We introduce a numerical method for calculating quantum discord for a special class of multipartite states. In agreement with previous work in low-dimensional cases (L. Mazzola et al., Phys. Rev. Lett. 104, 200401 (2010), we find situations in which there is a sudden transition from classical to quantum decoherence characterized by the discord remaining relatively robust (classical decoherence) until a certain point from where it begins to decay quickly whereas the classical correlation decays more slowly (quantum decoherence). We propose a general condition to observe this phenomenon.

1This work has been partially supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under Grant 111T292.

1:39PM G27.00013 Correlation Dynamics of Qubit-Qutrit Systems in a Classical Dephasing Environment 1
GOKTUG KARPAT, BARIS CAKMAK, ZAFTER GEDIK, Faculty of Engineering and Natural Sciences, Sabanci University — We study the time evolution of classical and quantum correlations for hybrid qubit-qutrit systems in independent dephasing environments. Our discussion involves a comparative analysis of the Markovian dynamics of negativity, quantum discord, geometric measure of quantum discord and classical correlation. In the presence of multilocal dephasing noise, we demonstrate the phenomenon of frozen quantum discord for qubit-qutrit states. We show that geometric discord can also get frozen for a class of separable states in this case. On the other hand, when only the qutrit is under the action of a dephasing channel, we observe that the partial coherence left in the system might enable quantum discord to remain invariant throughout the whole dynamics even though the entanglement in the qubit-qutrit state disappears in a finite time interval.

1This work has been partially supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under Grant 111T292.

Tuesday, March 19, 2013 2:30PM - 5:18PM –
Session J26 GQI: Semiconductor Qubits - Spin Measurement and Noise
328 - Bill Coish, McGill University

2:30PM J26.00001 Taming spin decoherence in silicon 1
STEPHEN LYON, Princeton University — Electron spins in semiconductor hosts have been candidate qubits since the early days of experimental quantum computing research, but it was generally assumed that the solid state environment would limit coherence to times much shorter than that seen in isolated atoms or ions. The longest measured electron spin coherence, measured in isotopically enriched silicon, was of order 1 ms. However, over the last 8 or 10 years the measured electron spin coherence times have steadily increased as materials and experimental techniques have improved. Much of the decoherence observed in the early ensemble Electron Spin Resonance (ESR) experiments arose from interactions amongst the spins being measured. In the most highly enriched bulk silicon measured to date, the residual silicon isotopes with nuclear magnetic moments affect the coherence of electrons bound to phosphorus donors on about a 1 second time scale. The remaining decoherence is still dominated by interactions between the donor spins, even in very lightly doped Si. Other decoherence processes have been shown to be at least an order of magnitude weaker. Recent work suggested that longer spin coherence would be obtained in bismuth doped Si, where magnetic-field insensitive “clock transitions” occur in the GHz frequency range. Recent experiments are bearing out these suggestions.

1This work was supported in part by the ARO and NSF.
3:06PM J26.00002 Spin-bath autocorrelation functions directly from quantum theory¹. WAYNE WITZEL, Sandia National Laboratories, NM, KEVIN YOUNG, Sandia National Laboratories, CA, SANKAR DAS SARMA, University of Maryland, College Park — Cluster expansion techniques have enabled accurate modeling of the effects of a bath of local spins on solid state spin qubits with proven predictive power. These calculations are performed in the context of specific echo decay experiments (Hahn echo, CPMG, etc.). Classical noise, on the other hand, is described by a single autocorrelation function (or spectral density, equivalently) that is applicable to any control-specific experiment. Such a description is very useful in searching for optimal controls to produce high fidelity quantum logic gates using well-studied techniques. We demonstrate a cluster expansion method for directly computing autocorrelation functions as expectation values in the quantum spin-bath setting and show that it is a sufficient description of the noise effects for certain regimes, particularly in the high fidelity regime of interest. We use this approach to study the theoretical impact of using optimized pulse sequences tailored to individual qubits in enriched silicon.

¹Sandia National Laboratories is a multi-program 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-AC04-94AL85000.

3:18PM J26.00003 Error in a spin-SWAP gate due to hyperfine interaction in a double quantum dot¹, JO-TZU HUNG, Department of Physics, University at Buffalo, State University of New York, LUKASZ CYWINSKI, Institute of Physics, Polish Academy of Sciences, XUEDONG HU, Department of Physics, University at Buffalo, State University of New York — We study the SWAP gate for two exchange-coupled electron spins under the influence of hyperfine (hf) interaction in a double quantum dot. A gate error develops during such a gate because hf interaction causes dephasing between any pair of two-spin states. We find that this gate error is initial-state-dependent. For example, an initial state in the $S_z = 0$ subspace suffers only from $S - T_1$ dephasing, leading to smaller gate error than in the case of other initial states. We calculate the gate fidelity for typical initial states, and compare the resulting gate errors. We also analyze the effects of inhomogeneous broadening on the gate fidelity in the presence of a random Overhauser field.

³We acknowledge support from US ARO, DARPA QuEST, NSF PIF, and the Homing Programme of the Foundation for Polish Science.

3:30PM J26.00004 Electron Spin Relaxation and Coherence Times in Si/SiGe Quantum Dots², R.M. JOCK, JIANHUA HE, A.M. TYRRYSKIN, S.A. LYON, Princeton University, C.-H. LEE, S.-H. HUANG, C.W. LIU, National Taiwan University — Single electron spin states in Si/SiGe quantum dots have shown promise as qubits for quantum information processing. Recently, electron spins in gated Si/SiGe quantum dots have displayed relaxation ($T_1$) and coherence ($T_2$) times of 250 µs at 350mK. The experiments used conventional X-band (10 GHz) pulsed Electron Spin Resonance (pESR) on a large area (3.5 x 20 mm²), double gated, undoped Si/SiGe heterostructure, which was patterned with $2 \times 10^{10}$ quantum dots using e-beam lithography. Dots with 150 nm radii and 700 nm period are induced in a natural Si quantum well by the gates. Smaller dots are expected to reduce the effects of nearly degenerate valley states and spin-orbit coupling on the electron spin coherence. However, the small number of spins makes signal recovery extremely challenging. We have implemented a broadband cryogenic HEMT low-noise-amplifier and a high-speed single-pole double-throw switch operating at liquid helium temperatures. The switch and preamp have improved our signal to noise by an order of magnitude, allowing for smaller samples and shorter measurement times. We will describe these improvements and the data they have enabled.

²supported by the ARO

3:42PM J26.00005 Quantum theory of dynamic nuclear polarization in quantum dots, SOPHIA ECONOMOU, Naval Research Laboratory, EDWIN BARNES, Condensed Matter Theory Center, University of Maryland — Nuclear spins play a major role in the dynamics of spin qubits in III-V semiconductor quantum dots. Although the hyperfine interaction between nuclear and electron (or hole) spins is typically viewed as the leading source of decoherence in these qubits, understanding how to experimentally control the nuclear spin polarization can not only ameliorate this problem, but in fact turn the nuclear spins into a valuable resource for quantum computing. Beyond extending decoherence times, control of this polarization can enable universal quantum computer operation as shown in singlet-triplet qubits and, in addition, offers the possibility of repurposing the nuclear spins into a robust quantum memory. In [1], we took a first step toward taking advantage of this resource by developing a general, fully quantum theory of non-unitary electron-nuclear spin dynamics with a periodic train of delta-function pulses as the control. We extend this approach to other types of controls and further expand on the predictions and physical insights that emerge from the theory. [1] Edwin Barnes and Sophia E. Economou, Phys. Rev. Lett. 107, 047601 (2011)

3:54PM J26.00006 Enhanced spin-flip transport in a quantum dot spin-valve with uniform hyperfine coupling, STEFANO CHESI, WILLIAM A. COISH, McGill University — We study the transport current and nuclear spin polarization dynamics in a quantum dot spin-valve, for which a strong enhancement of the spin-flip electron tunneling rates can be realized in the limit of uniform hyperfine interaction. We extend the analogy of transport to superradiance, directly applicable to a spin valve with half-metal leads and a maximally polarized nuclear system, to the more general situation of ferromagnetic contacts and a nuclear system initially fully dephased and partially polarized, as naturally realized at finite bias under stationary conditions. An analytic treatment of the dynamics in terms of simple rate equations becomes possible for very fast/slow nuclear dephasing. We recover these limiting results, as well as analyze the crossover regime, from a general master equation for the nuclear dynamics. We also present strategies to approach the limit of uniform hyperfine interaction in realistic heterostructures.

4:06PM J26.00007 Single Electron Spin Resonance in a Si-MOS Double Quantum Dot¹, XIAOJIE HAO, MING XIAO, HONGWEN JIANG, Department of Physics and Astronomy, University of California at Los Angeles, RUSKOV RUSKOV, CHARLES TAHAL, Laboratory for Physical Sciences, USA — Pauli spin blockade is used as a means to detect the flip of spins in a silicon metal-oxide-semiconductor (MOS) based double quantum dot. Microwave driven electron spin resonance (ESR) signals, with a linewidth as narrow as 1.5 G, has been observed only in a narrow range of magnetic fields. ESR spectroscopy in the magnetic field - microwave frequency plane shows an unexpected level anti-crossing, with an energy gap of about 50 MHz. The spectral line gives an estimation of the lower bound for inhomogeneous phase decoherence time $T_8$ of about a couple of hundred ns for individual spins in the nano-structured system with a Si/SiO2 interface. We explain the anti-crossing gap as due to spin-orbit mixing with higher states, which is also responsible for the narrow-window visibility of the ESR signal in Si based double quantum dots.

¹The work is supported by the U.S. Department of Defense and by ARO (w911NF-11-1-0028).
4:18PM J26.00008 Theory of Spin Relaxation in Two-Electron Laterally Coupled GaAs and Si Quantum Dots¹. MARTIN RAITH, University of Regensburg, PETER STANO, University of Basel, JAROSLAV FABIAN, University of Regensburg

We present quantitative results of the phonon-induced spin relaxation in two-electron lateral double quantum dots for a wide range of tuning parameters. Both spin-orbit coupling and hyperfine coupling are taken into account. Our analysis of GaAs [1] and silicon [2] based dots includes the variation of the electric field (detuning), the exchange coupling, and the magnetic field strength and orientation. The focus is on experimentally important regimes. We find that even in strong magnetic fields, the hyperfine coupling can dominate the relaxation rate of the un-polarized triplet in a detuned double dot. Where the spin-orbit coupling dominates, the rate is strongly anisotropic and its maxima and minima are generated by an in-plane magnetic field either parallel or perpendicular to the dots’ alignment dependent on specifics, such as spectral (anti-)crossings (spin hot spots), or the detuning strength. For all regimes, we give qualitative explanations of our observations. We emphasize the differences between GaAs and Si based dots. By understanding the spin lifetimes ($T_1$), this work marks a crucial step toward the realization of two-electron semiconductor qubits for quantum information processing.


¹This work is supported by the DFG under grant SPP 1285.

4:30PM J26.00009 Anomalous electron spin decoherence in an optically pumped quantum dot. XIAOFENG SHI, L.J. SHAM, Department of Physics, University of California San Diego, La Jolla, CA 92093-0319, USA — We study the nuclear-spin-fluctuation induced spin decoherence of an electron (SDE) in an optically pumped quantum dot. The SDE is computed in terms of the steady distribution of the nuclear field (SDNF) formed through the hyperfine interaction (HI) with two different nuclear species in the dot. A feedback loop between the optically driven electron spin and the nuclear spin ensemble determines the SDNF [W. Yang and L. J. Sham, Phy. Rev. B 85, 235319(2012)]. Different from that work and others reviewed therein, where a bilinear HI, $\alpha S_I \gamma$, between the electron (or hole) spin $S$ and the nuclear spin I is used, we use an effective nonlinear interaction of the form $S_I I_I I_I$, derived from the Fermi-contact HI. Our feedback loop forms a multi-peak SDNF in which the SDE shows remarkable collapses and revivals in nanosecond time scale. Such an anomalous SDE results from a quantum interference effect of the electron Larmor precession in a multi-peak effective magnetic field. In the presence of a bilinear HI that suppresses the nuclear spin fluctuation, the non-Markovian SDE persists whenever there are finite Fermi contact interactions between two or more kinds of nuclei and the electron in the quantum dot.

³This work is supported by NSF(PHY 1104446) and the US Army Research Office MURI award W911NF0910406.

4:42PM J26.00010 Mechanisms for Electric Field Control of Single Spin Relaxation in Double Quantum Dots¹. V. SRINIVASA, Joint Quantum Institute, University of Maryland and NIST, K.C. NOWACK, M. SHAFFIEI, L.M.K. VANDERSYPEN, Kavli Institute of Nanoscience, TU Delft, J.M. TAYLOR, Joint Quantum Institute, University of Maryland and NIST — We theoretically investigate electrically-tunable spin-flip transitions for a single electron confined within a double quantum dot. In the presence of spin-orbit and hyperfine interactions, the rate at which phonon-induced spin relaxation occurs depends non-monotonically on the detuning between the dots. We analyze this detuning dependence for both direct decay to the ground state and indirect decay via an intermediate excited state of the double dot. A description in terms of a simple toy model captures characteristic features of the relaxation rate recently measured for GaAs double quantum dots. Our results suggest that spin-orbit mediated relaxation via phonons serves as the dominant mechanism through which the electron spin-flip rate in these systems varies with detuning.

¹Support from DARPA MTO and IARPA is gratefully acknowledged.

4:54PM J26.00011 Enhanced hyperfine-induced spin dephasing in a magnetic field gradient. FELIX BEAUDOIN, WILLIAM A. COISH, McGill University — Magnetic field gradients are important for single-site addressability and electric-dipole spin resonance of electrons in quantum dots or in donor impurities. We show that these advantages are offset by a potential reduction in coherence time. Although the magnetic field appears uniform to the electron, it provides a non-uniform field for the nuclear-spin bath. This leads to a finite bath correlation time, preventing the full recovery of electron-spin coherence. We apply our model to single electron spins in quantum dots and single donor impurities, singlet-triplet spin qubits, and consider both free-induction decay and spin-echo. This mechanism can dominate over known dephasing sources due to nuclear dipole-dipole interactions and hyperfine flip-flops. This result is especially important for systems requiring large magnetic field gradients, including spin qubits coupled to superconducting stripline resonators.

³We acknowledge FRQNT, INTRIQ, NSERC and CIFAR for funding.

5:06PM J26.00012 Spin Qubit Relaxation in a Moving Quantum Dot¹. PEIHAO HUANG, XUEDONG HU, State Univ of NY - Buffalo — Long-range quantum communication for spin qubits is a significant open problem in the scale-up of spin qubit architectures. Among the many spin information transfer proposals, directly moving the electrons themselves is attractive because of its conceptual simplicity and its similarity to the conventional charge-coupled devices. Here we focus on electron spin decoherence when the quantum dot is in motion. Specifically, we study a spin decoherence mechanism for a moving but confined electron due to the spin-orbit interaction and an environmental random electric potential. We find that at the lowest order, the magnetic fluctuations experienced by the spin have only components transverse to the total magnetic field, so that the motion induced spin decoherence is a pure longitudinal relaxation channel. Our calculated spin relaxation time ranges from as fast as sub µs in GaAs to above ms in Si. Our results also clearly indicates how to reduce the decoherence effects of electron motion.

¹We thank support by US ARO and NSF.

Tuesday, March 19, 2013 5:45PM - 6:45PM — Session K25 GQI: GQI Business Meeting

5:45PM K25.00001 GQI BUSINESS MEETING —

Wednesday, March 20, 2013 8:00AM - 11:00AM — Session M26 GQI: Semiconductor Qubits - RF Measurement and Hybridization

The University of Sydney
8:00AM M26.00001 Circuit quantum electrodynamics with a spin qubit1. KARL PETERSSON, Princeton University — Electron spins in quantum dots have been proposed as the building blocks of a quantum information processor. While both fast one and two qubit operations have been demonstrated, coupling distant spins remains a daunting challenge. In contrast, circuit quantum electrodynamics (cQED) has enabled superconducting qubits to be readily coupled over large distances via a superconducting microwave cavity. I will present our recent work aimed at integrating spin qubits with the cQED architecture. Our approach is to use spin qubits formed in strong spin-orbit materials such as InAs nanowires to enable a large effective coupling of the spin to the microwave cavity field. For an InAs nanowire double quantum dot coupled to the superconducting microwave cavity we achieve a charge-cavity coupling rate of 30 MHz. Combining this large charge-cavity coupling rate with electrically driven spin qubit rotations we demonstrate that the cQED architecture can be used as a sensitive probe of spin dynamics. In another experiment, we can apply a source-drain bias to drive current through the double quantum dot and observe gain in the cavity transmission. We additionally measure photon emission from the cavity without any input field applied. Our results suggest that long-range spin coupling via superconducting microwave cavities is feasible and present new avenues for exploring quantum optics on a chip.

1Research was performed in collaboration with Will McFaul, Michael Schroer, Minkyung Jung, Jake Taylor, Andrew Houck and Jason Petta. We acknowledge support from the Sloan and Packard Foundations, Army Research Office, and DARPA QNEST.

8:36AM M26.00002 Measuring the Charge Parity of an InAs Double Quantum Dot2, M.D. SCHROER, M. JUNG, K.D. PETERSSON, J.R. PETTA, Princeton University — We have fabricated tunable, few electron InAs nanowire double quantum dots (DQDs) which support rapid electrically driven single spin rotations. However, the measurement of nanowire DQDs presents an outstanding problem, typically relying on transport through the sample due to the lack of a local quantum point contact charge detector. We demonstrate a non-invasive charge sensing method based on a radio frequency measurement of the sample's complex admittance, which yields a fast and sensitive determination of the charge state. We show that this measurement is also sensitive to the spin state of the DQD, allowing a simple determination of the total charge parity in the sample.

2Supported by the Sloan and Packard Foundations, ARO, DARPA, and the NSF.

8:48AM M26.00003 Photon emission from a cavity-coupled double quantum dot3, Y.-Y. LIU, K.D. PETERSSON, J.R. PETTA, Princeton University, J.M. TAYLOR, Joint Quantum Institute and NIST — Circuit quantum electrodynamics (cQED) allows strong coupling between a microwave photon and a superconducting qubit. We recently demonstrated coupling of a double quantum dot (DQD) spin qubit to a high quality factor cavity in the cQED architecture, with a charge-cavity coupling rate of 30 MHz. Combining this large charge-cavity coupling rate with electrically driven spin qubit rotations we demonstrate that the cQED architecture can be used as a sensitive probe of single spin dynamics. In another experiment, we can apply a source-drain bias to drive current through the double quantum dot and observe gain in the cavity transmission. We additionally measure photon emission from the cavity without any input field applied. Our results suggest that long-range spin coupling via superconducting microwave cavities is feasible and present new avenues for exploring quantum optics on a chip.

3Supported by the Sloan and Packard Foundations, ARO, DARPA, and the NSF.

9:00AM M26.00004 Superconducting coplanar waveguide resonators for electron spin resonance applications4, A.J. SIGILLITO, R.M. JOCK, A.M. TYRYSHKIN, Princeton University, H. MALISSA, The University of Utah, S.A. LYON, Princeton University — Superconducting coplanar waveguide (CPW) resonators are a promising alternative to conventional volume resonators for electron spin resonance (ESR) experiments where the sample volume and thus the number of spins is small. However, the magnetic fields required for ESR could present a problem for Nb superconducting resonators, which can be driven normal. Very thin Nb films (50 nm) and careful alignment of the resonators parallel to the magnetic field avoid driving the Nb normal, but flux trapping can still be an issue. Trapped flux reduces the resonator Q-factor, can lead to resonant frequency instability, and can lead to magnetic field inhomogeneities. At temperatures of 1.9 K and in a magnetic field 0.32 T, we have tested X-band resonators fabricated directly on the surface of a silicon sample. Q-factors in excess of 15,000 have been obtained. A thin layer of GE varnish applied directly to the resonator has been used to glue a sapphire wafer to its surface, and we still find Q-factors of 16,000 or more in the 0.32 T field. ESR applications of these resonators will be discussed.

4Supported in part by the ARO.

9:12AM M26.00005 Microwave Measurements Electrons on Helium with Superconducting Coplanar Waveguide Resonators, GE YANG, Department of Physics, University of Chicago, ANDREAS FRAGNER, Applied Physics Department, Yale University, BING LI, Department of Physics, University of Chicago, ROB SCHOELKOPF, Applied Physics Department, Yale University, DAVID I. SCHUSTER, Department of Physics, University of Chicago, ELECTRONS ON HELIUM COLLABORATION — Electrons on helium is a unique two-dimensional electron gas system formed at the interface of a quantum liquid (superfluid helium) and vacuum. The motional and spin states of single-electron quantum dots defined on such systems have been proposed for hybrid quantum computing [1,2]. Traditional AC transport experiments of electrons on helium are conducted at kilohertz frequencies. Here, we will present microwave measurements of electrons trapped in a 5GHz superconducting coplanar waveguide resonator with 1 MHz bandwidth. The effect of trapping parameters on the resonance, and experimental progress towards a single trapped electron regime will also be discussed.


9:24AM M26.00006 Photon mediated interaction between distant quantum dot circuits, TAKIS KONTOS, MATTHIEU DELBEQ, LAURE BRUHAT, JÉRÉMIE VIENNOT, SUBHADEEP DATTA, AUDREY COTTET, CNRS/ENS — Cavity QED allows one to study the interaction between light and matter at the most elementary level, by using for instance Rydberg atoms coupled to cavity photons. Recently, it has become possible to perform similar experiments on-chip, by using artificial two-level systems made from superconducting circuits instead of atoms. This circuit-QED offers unexplored potentialities, since other degrees of freedom than those of superconducting circuits could be used, and in particular, those of quantum dots. Such a hybrid circuit QED would allow one to study a large variety of situations not accessible with standard cavity QED, owing to the versatility of nanofabricated circuits. Here, we couple two quantum dot circuits to a single mode of the electromagnetic field in a microwave cavity. Our quantum dots are separated by 200 times their own size, with no direct tunnel and electrostatic couplings between them. We demonstrate their interaction mediated by the cavity photons. This could be used to scale up quantum bit architectures based on quantum dot circuits, and simulate on-chip photon-mediated interactions between strongly correlated electrons.
9:36AM M26.00007 Phonon-Mediated Population Inversion in a Driven Double Quantum Dot1, XANTHE CROOT, JAMES COLLESS, ANDREW DOHERTY, ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Sydney, Australia, TOM STACE, ARC Centre of Excellence for Engineered Quantum Systems, School of Mathematics and Physics, University of Queensland, Brisbane, QLD 4072, Australia., SEAN BARRETT, Blackett Laboratory and Institute for Mathematical Sciences, Imperial College London, London SW7 2PG, United Kingdom, HONG LU, ART GOSSARD, Materials Department, University of California, Santa Barbara, California 93106, USA., — We investigate phonon-assisted tunneling (PAT) in a double quantum dot (DQD) and show that the population inversion of a qubit can be obtained by using microwave excitation. We demonstrate that this approach can be used to perform single-shot spin readout in a silicon quantum dot.

We acknowledge funding from the U.S. Intelligence Advanced Research Projects Activity (IARPA), through the U.S. Army Research Office and the Australian Research Council Centre of Excellence Scheme (Grant No. EQUS CE110001013).

9:48AM M26.00008 Dispersive Readout of a Few-Electron Double Quantum Dot with Fast rf Gate-Sensors1, ALICE MAHONEY, JAMES COLLESS, JOHN HORNIBROOK, ANDREW DOHERTY, DAVID REILLY, ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, NSW 2006, Australia., — We report the dispersive charge-state readout of a double quantum dot in the few-electron regime using the in situ gate electrodes as sensitive detectors. We benchmark this gate-sensing technique against the well-established quantum point contact (QPC) charge detector and find comparable performance with a bandwidth of ~ 10 MHz and an equivalent charge sensitivity of ~ 6.3 × 10^-3 e/√Hz. Dispersive gate-sensing alleviates the burden of separate charge detectors for quantum dot systems and promises to enable readout of qubits in scaled-up arrays.

We acknowledge funding from the U.S. Intelligence Advanced Research Projects Activity (IARPA), through the U.S. Army Research Office and the Australian Research Council Centre of Excellence Scheme (Grant No. EQUS CE110001013).

10:00AM M26.00009 Spectroscopy of a GaAs Double Dot Qubit with Dispersive Readout1, JAMES COLLESS, ALICE MAHONEY, XANTHE CROOT, JOHN HORNIBROOK, ANDREW DOHERTY, ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, NSW 2006, Australia., TOM STACE, ARC Centre of Excellence for Engineered Quantum Systems, School of Mathematics and Physics, University of Queensland, Brisbane, QLD 4072, Australia., HONG LU, ART GOSSARD, Materials Department, University of California, Santa Barbara, California 93106, USA., — We report microwave spectroscopy of a GaAs double dot qubit device using the dispersive gate sensor (DGS) readout technique. In contrast to charge-sensing methods based on quantum point contacts (QPCs) or single-electron transistors (SETs), the DGS detection method senses the tunneling of charge between states that are near degenerate in energy. Microwave excitation applied to the surface gates enables this readout approach to resolve low energy spectroscopic features not apparent in transport or standard charge-sensing measurements. We discuss the origin of these features and the use of this technique for characterizing semiconductor qubit systems.

We acknowledge funding from the U.S. Intelligence Advanced Research Projects Activity (IARPA), through the U.S. Army Research Office and the Australian Research Council Centre of Excellence Scheme (Grant No. EQUS CE110001013).

10:12AM M26.00010 Radio frequency charge sensing in a Si double quantum dot device1, C. PAYETTE, K. WANG, Y. DOVZHENKO, J.R. PETTA, Department of Physics, Princeton University. — Coherent spin manipulation has recently been demonstrated in a variety of silicon based devices.1 We fabricate accumulation mode double quantum dot devices and use radio frequency reflectometry to perform fast charge sensing in the few-electron regime. Our devices employ a nearby single quantum dot as a charge sensor. Charge transitions in the double quantum dot are driven by applying microwave radiation to the surface gates. We observe a ~ 60% relative change in the charge sensor conductance when the qubit is driven in a resonant condition. Further development of these techniques may enable us to perform single-shot spin readout in a silicon quantum dot.

Supported by the United States Department of Defense. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressly or implied, of the United States Government.


10:24AM M26.00011 Transport and Charge Manipulation in a Single Electron Silicon Double Quantum Dot1, K. WANG, C. PAYETTE, Y. DOVZHENKO, J.R. PETTA, Princeton University. — Silicon is one of the most promising candidates for ultra-coherent qubits due to its relatively early position in periodical table and the absence of nuclear spin in its naturally abundant isotope. Here we demonstrate a reliable recipe that enables us to reproducibly fabricate an accumulation mode few electron double quantum dot (DQD). We demonstrate tunable interdot tunnel coupling at single electron occupancy in the device. The charge state of the qubit is monitored by measuring the amplitude of the radio frequency signal that is reflected from a resonant circuit coupled to a charge sensor. By applying microwave radiation to the depletion gates, we probe the energy level structure of the DQD using photon-assisted tunneling (PAT). We apply bursts of microwave radiation and monitor the dependence of the PAT peak height on the burst period to extract the charge relaxation time, T₁. By experimentally tuning the charge qubit Hamiltonian, we measure the tunnel coupling and detuning dependence of T₁.

Supported by the United States Department of Defense. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressly or implied, of the United States Government.

10:36AM M26.00012 Progress towards microwave readout of a silicon double quantum dot1, A.R. SCHMIDT, E. HENRY, QNL, UC Berkeley, M. HOUSE, UCLA, Y. T. WANG, UC Berkeley, C.C. LO, University College London, UC Berkeley, H. LI, L. GREENMAN, UC Berkeley, H. PAN, M. XIAO, UCLA, K.B. WHALEY, UC Berkeley, H.-W. JIANG, UCLA, E. YABLONOVITCH, J. BOKOR, I. SIDDIQI, UC Berkeley. — Microwave resonators coupled to quantum systems have been used for fast dispersive measurement in several 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 a semiconductor qubit in silicon through coupling to a superconducting microwave resonator. We report progress on a novel design of a lateral

1This work is supported by the DARPA QuEST program.
10:48AM M26.00013 Fabrication and measurement of an RF-QPC in an undoped Si/SiGe heterostructure - ROBERT MOHR, DANIEL ENDERICH, JONATHAN PRANCE, LEON MAURER, DANIEL WARD, DONALD SAVAGE, MAX LAGALLY, ROBERT MCDERMOTT, SUSAN COPPERSMITH, MARK ERIKSSON, University of Wisconsin - Madison — We perform radio-frequency reflectometry measurements on a quantum point contact fabricated in an undoped accumulation-mode Si/SiGe heterostructure. This device is a promising candidate for high-bandwidth charge sensing in Si/SiGe, and it provides the capability for fast qubit readout in this material. We show operation of the device with a well-defined resonance that can be modulated by a nearby gate. We will discuss design challenges that are particular to accumulation-mode structures and how they can be resolved.

Wednesday, March 20, 2013 8:00AM - 11:00AM –
Session M27 GQL: Focus Session: Quantum Error Correction and Decoherence Control | 329 -
Kenneth Brown, Georgia Institute of Technology

8:00AM M27.00001 Dynamical quantum error correction: recent achievements and prospects1, LORENA VIOLA, Dartmouth College — Precisely controlling the dynamics of real-world open quantum systems is a central challenge across quantum science and technology, with implications ranging from quantum physics and chemistry to fault-tolerant quantum computation. Dynamical quantum error correction strategies based on open-loop time-dependent modulation of the system dynamics provide a general perturbative framework for boosting physical-layer fidelities in the non-Markovian regime. I will describe recent progress in designing dynamical error correction schemes able to incorporate various system and control constraints encountered in realistic scenarios. In particular, I will show how to employ dynamical decoupling methods to achieve high-fidelity quantum storage for long times, while minimizing access latency and sequencng complexity, and how to synthesize dynamically corrected quantum gates for simultaneously canceling non-Markovian decoherence and control errors, while accommodating internal always-on dynamics and limited control. In the process, I will make contact with current qubit devices to the extent possible and point to remaining challenges and directions for further explorations.

8:36AM M27.00002 Quantum Control and Fault-tolerance - GERARDO PAZ SILVA, JASON DOMINY, DANIEL LIDAR, University of Southern California — Quantum control (QC) and the methods of fault-tolerant quantum computing (FTQC) are two of the cornerstones on which the hope for a quantum computer rests. However QC methods do not generally scale well with the size of the system, and it is not known how their performance is hindered when integration with FTQC methods, especially considering these demand a large system size overhead, is attempted under realistic noise models. Here we study this problem using dynamical decoupling in the bang-bang limit as a toy model, with a non-Markovian noise where interactions decay with distance, and show that there exists a regime of the norm of the relevant Hamiltonians, in which dynamical decoupling protected gates provide an advantage over the bare gate implementation. This is a first step towards showing that QC protocols designed for a small set of qubits can be extended to larger sets without a significant loss of performance, as long as the noise model behaves reasonably well.

8:48AM M27.00003 Preserving electron spin coherence by dynamical decoupling based on Nitrogen-Vacancy center in diamond - JIANGFENG DU, University of Science and Technology of China — To exploit the quantum coherence of electron spins in solids in future technologies such as quantum manipulations, it’s first vital to overcome the problem of spin decoherence due to their coupling with the noisy environment. Dynamical decoupling is a particularly promising strategy for combating decoherence. I will briefly introduce the roadmap for dynamical decoupling and show our experimental research on the field in detail. We first applied the optimal dynamical decoupling scheme [1] on electron spins of ensemble sample [2]. Based on the technology, the dynamical decoupling sequence was used to observe the anomalous coherence effect and of single electron spin based on nitrogen-vacancy defect center in diamond [3]. For application, combined the dynamical decoupling together with quantum metrology protocol, the phase estimation was enhanced [4]. Instead of pulsed model, continuous dynamical decoupling was realized in our experiment and applied to protect quantum gate [5]. The next step, we will apply multi flip pulses to enhance the magnetic field sensitivity of NV center towards to the micro-scale magnetic resonance and single molecular imaging. [1] G. S. Uhrig, Phys. Rev. Lett. 98, 100504 (2007) [2] J. Du, et al., Nature 461, 1265 (2009) [3] P. Huang, et al., Nature Communications, 2, 570 (2011) [4] X. Rong, et al., Europhys. Lett. 95, 60005 (2011) [5] X. Xu, et al., Phys. Rev. Lett. 109, 070502 (2012)

9:00AM M27.00004 Improving quantum gate fidelities by using a qubit to measure microwave pulse distortions - SIMON GUSTAVSSON, OLGER ZWIER, JONAS BYLANDER, FEI YAN, Massachusetts Institute of Technology, Cambridge, MA 02139, FUMIKI YOSHIIHARA, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan, YASUNOBU NAKAMURA, Research Center for Advanced Science and Technology (RCAST), The University of Tokyo, Komaba, Meguro-ku, Tokyo 153-8904, Japan, TERRY ORLANDO, Massachusetts Institute of Technology, Cambridge, MA 02139, WILLIAM OLIVER, MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420, USA — We present a new method for determining pulse imperfections and improving the single-qubit gate fidelity in a superconducting qubit. By applying consecutive positive and negative π pulses, we amplify the qubit evolution due to microwave pulse distortions, which causes the qubit state to rotate around an axis perpendicular to the intended rotation axis. Measuring these rotations as a function of pulse period allows us to reconstruct the shape of the microwave pulse arriving at the sample. Using the extracted response to predistort the input signal, we are able to improve the pulse shapes and to reach an average single-qubit gate fidelity higher than 99.8%.

9:12AM M27.00005 ABSTRACT WITHDRAWN —

9:24AM M27.00006 Accurate quantum Z rotations with less magic - ANDREW LANDAHL, Sandia National Laboratories, CHRIS CESARE, University of New Mexico — We present quantum protocols for executing arbitrarily accurate π/2k rotations of a qubit about its Z axis. Unlike reduced instruction set computing (RISC) protocols which use a two-step process of synthesizing high-fidelity “magic” states from which \( T = Z(\pi/4) \) gates can be teleported and then compiling a sequence of adaptive stabilizer operations and \( T \) gates to approximate \( Z(\pi/2^k) \), our complex instruction set computing (CISC) protocol distills magic states for the \( Z(\pi/2^k) \) gates directly. Replacing this two-step process with a single step results in substantial reductions in the number of gates needed. The key to our construction is a family of shortened quantum Reed-Muller codes of length \( 2^{k+1}-1 \), whose distillation threshold shrinks with \( k \) but is greater than 0.85% for \( k \leq 6 \). AJL and CC were supported in part 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 Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.
9:36AM M27.00007 Fault-tolerant, nondestructive measurement of logical operators and quantum teleportation in large stabilizer codes. TODD BRUN. University of Southern California — Fault-tolerant quantum computation seeks to perform large calculations by protecting quantum information against decoherence using quantum error-correcting codes. Such schemes have been widely studied, but the resources needed to actually perform a fault-tolerant computation are daunting. In principle, it may be possible to reduce this overhead by using large block codes with significantly higher rates. Logical gates can be done in such a scheme by teleporting the logical qubits between code blocks. Logical teleportation can be done fault-tolerantly by measuring a particular set of logical operators. This measurement involves preparing an entangled ancillary state and doing a transversal circuit between the codeword and the ancilla. We study this procedure, and show that a wide range of such measurement protocols exist. There is a trade-off between the size of the ancilla and the robustness against errors; for a large codeword, it may be fruitful to use a larger ancilla that has greater error-correcting power.

10:12AM M27.00008 Quantum “hyperbicycle” low-stabilizer-weight finite-rate error correction codes1, LEONID P. PRYADKO, ALEXEY KOVALEV, University of California, Riverside — We construct a large family of finite-rate quantum error correcting codes (QECCs) which interpolate between the hypergraph-product [1] and generalized bicycle codes [2]. The construction allows for the lower and upper bounds on the distance which generally scale as a square root of the block size; in several important cases the two bounds coincide. The constructed QECCs include several new classes of codes with low stabilizer weights; they can offer an advantage compared to the toric codes.

1This research was supported in part by the U.S. Army Research Office under Grant No. W911NF-11-1-0027, and by the NSF under Grant No. 1018935.

10:24AM M27.00009 Error correction with quantum low-density parity check codes1, ALEXEY KOVALEV, LEONID PRYADKO, University of California, Riverside — We study quantum low-density parity check (LDPC) codes and their fault tolerance. We show that any family of quantum LDPC codes where each syndrome measurement involves a limited number of qubits, and each qubit is involved in a limited number of measurements (as well as any similarly-limited family of classical LDPC codes), where distance scales as a positive power of the number of physical qubits, has a finite error probability threshold. We conclude that for sufficiently large quantum computers, finite-rate quantum LDPC codes can offer an advantage over the toric codes. Error correction in the presence of errors in syndrome measurements is also addressed. We discuss possible realizations of decoders and their error thresholds, e.g. in relation to LDPC versions of the quantum hypergraph-product codes [1] and their generalizations [2].


10:36AM M27.00010 Relative performance of ancilla verification and decoding in the [[7,1,3]] Steane code1, ALI ABU-NADA, BENJAMIN FORTESCUE, MARK BYRD, Southern Illinois University at Carbondale, SOUTHERN ILLINOIS UNIVERSITY AT CARBONDALE TEAM — We present numerical simulation results comparing the logical error rates for the fault-tolerant [[7,1,3]] Steane code using standard ancilla verifications techniques vs. the newer method of ancilla decoding, as described in [1]. We simulate a realistic QEC procedure in which failed ancilla creation requires storing the data until a new ancilla can be created; we expect the decoding method, which avoids the need for such storage, to be advantageous when the failure probability is sufficiently high. For the [[7,1,3]] code, we analyze the effect of both different syndrome extraction techniques and of different classes of physical error (initialization, measurement, hold etc.) on the relative performance of these two methods.


1Authors gratefully acknowledge support from the Intelligence Advanced Research Projects Activity (IARPA) via Department of Interior National Business Center contract number D11PC20168.

10:48AM M27.00011 Quantum Error Correction with Mixed State Ancilla Qubits1, MIKIO NAKAHARA, YASUSHI KONDO, CHIARA BAGNASCO, Department of Physics, Kinki University — It is commonly assumed that ancilla qubits must be in a pure state for successful quantum error correction. We show in our talk that they can initially be in any mixed state if the error operator acts simultaneously on all the physical qubits (fully correlated noise). In particular, they can be in the uniformly mixed state, which makes implementation of our scheme extremely cheap. We also note that 1-qubit gate operations can be implemented easily within the codeword. We experimentally demonstrated our scheme by using a liquid state NMR quantum computer. The encoded state has an interesting nature in terms of quantum discord, which is purely quantum correlations between the data qubit and the ancilla qubits.

1Work partially supported MEXT and JSPS, Japan.


11:15AM N1.00001 Entanglement and entanglement storage in dipolar coupled diamond defects. JOERG WRACHTRUP, University of Stuttgart — The generation of robust entangled states is one of the key steps in quantum science. Although diamond defects are highly versatile quantum bits mutual entanglement has not been demonstrated so far. The talk will describe the engineering of strongly coupled defect centers as well as their characteristic features. Entanglement generation as well as different means of tomography will be outlined. Correlated photon emission form coupled defect center pairs is analyzed. Robust storage of electron spin entanglement into nuclear spins resulting in entanglement storage lifetime of ms is demonstrated and roads towards efficient generation of strongly coupled defect arrays will be discussed.
we perceive objective classical reality, and supports Bohr’s intuition that quantum phenomena acquire classical reality only when communicated.

decoherence, this separation shows that accessible information is maximized for the quasi-classical pointer observable. Other observables are accessible only via

between a quantum system and its environment. First, it relies on a natural separation of accessible information and quantum information about a system. Under

MICHAEL ZWOLAK, Oregon State University, WOJCIECH ZUREK, Los Alamos National Laboratory — We prove an anti-symmetry property relating accessible

computing tasks and the implementation of an elementary quantum repeater.

by using the electron spin as an ancilla [2,3]. Entanglement of remote quantum registers will enable deterministic quantum teleportation, distributed quantum

in different bases and correlating the results. These results open the door to a range of exciting opportunities. For instance, the remote entanglement can be

of a scheme based on quantum measurements: we perform a joint measurement on photons emitted by the NV centers that are entangled with the electron

polarize, manipulate and readout with high fidelity individual nuclear spins. A promising approach to overcome this limitation consists in utilizing an ancillary

spins at room temperature.

quantum information processing (QIP) including active feedback in quantum error correction protocols and tests of quantum correlations with solid-state single

11:51 AM N1.00002 Mobile quantum sensing with spins in optically trapped nanodiamonds1.

DAVID D. AWSCHALOM2, Center for Spintronics and Quantum Computation, University of California, Santa Barbara, California 93106 — The nitrogen-vacancy (NV) color center in diamond has emerged as a powerful, optically addressable, spin-based probe of electromagnetic fields and temperature. For nanoscale sensing applications, the NV center’s atom-like nature enables the close-range interactions necessary for both high spatial resolution and the detection of fields generated by proximal nuclei, electrons, or molecules. Using a custom-designed optical tweezers apparatus, we demonstrate three-dimensional position control of nanodiamonds in solution with simultaneous optical measurement of electron spin resonance (ESR[1]). Despite the motion and random orientation of NV centers suspended in optical tweezers, we observe distinct peaks in the ESR spectra from the ground-state spin transitions. Accounting for the random dynamics of the trapped nanodiamonds, we model the ESR spectra observed in an applied magnetic field and estimate the dc magnetic sensitivity based on the ESR line shapes to be ~50 μT/√Hz. We utilize the optically trapped nanodiamonds to characterize the magnetic field generated by current-carrying wires and ferromagnetic structures in microfluidic circuits. These measurements provide a pathway to spin-based sensing in fluidic environments and biophysical systems that are inaccessible to existing scanning probe techniques, such as the interiors of living cells.

1This work is supported by AFOSR and DARPA.

2In collaboration with Viva R. Horowitz, Benjamin J. Alemán, Paolo Andrich, David J. Christle, and Andrew N. Cleland.

212:27PM N1.00003 Quantum optical networks with diamond nanophotonics , NATHALIE DE LEON, Harvard University Department of Physics — Scalable quantum optical networks require identical single photons from multiple quantum bits and high collection efficiency of these single photons. Nitrogen vacancy (NV) centers in diamond are a promising candidate for quantum information processing because they have quantum mechanical degrees of freedom that can be addressed optically and, as solid-state structures, can potentially be easily integrated into nanophotonic networks. In particular, they have a zero-phonon line (ZPL), which acts as an atom-like cycling transition that can be used for coherent optical manipulation. However, the ZPL only accounts for 3-5% of the total emission, and it is difficult to generate a high density of NV centers with stable ZPL. I will present progress toward gaining both spectral and spatial control over NV emission by coupling NV centers to nanophotonic devices. In particular, we have fabricated high quality factor (Q), small mode volume (V) photonic crystal cavities directly out of diamond, and have deterministically placed them around stable NV centers to enhance the spontaneous emission at the cavity resonance by a factor of ~100. This emission is guided efficiently into a single optical mode, enabling integration with other photonic elements, as well as networks of cavities, each with their own optically addressable qubit. These nanophotonic elements in diamond will provide a building block for a variety of applications in quantum information processing, such as entanglement of distant NV centers and single photon transistors.

1:03PM N1.00004 Single-shot readout of multiple nuclear spin qubits in diamond under ambient conditions , VINCENT JACQUES, Laboratoire de Photonique Quantique et Moléculaire, Ecole Normale Supérieure de Cachan and CNRS UMR 8537, 94235 Cachan, France — Nuclear spins are attractive candidates for solid-state quantum information storage and processing owing to their extremely long coherence time. However, since this appealing property results from a high level of isolation from the environment, it remains a challenging task to polarize, manipulate and readout with high fidelity individual nuclear spins. A promising approach to overcome this limitation consists in utilizing an ancillary single electronic spin to detect and control remote nuclear spins coupled by hyperfine interaction. In this talk, I will show how the electronic spin of a single Nitrogen-Vacancy (NV) defect in diamond can be used as a robust platform to observe the real-time evolution of surrounding single nuclear spins under ambient conditions. Using a diamond sample with a natural abundance of 13C isotopes, we first demonstrate high fidelity initialization and single-shot readout of an individual 13C nuclear spin. By including the intrinsic 14N nuclear spin of the NV defect in the quantum register, we then report the simultaneous observation of quantum jumps linked to both nuclear spin species, providing an efficient initialization of the two qubits. These results open up new avenues for diamond-based quantum information processing (QIP) including active feedback in quantum error correction protocols and tests of quantum correlations with solid-state spins at room temperature.

1:39PM N1.00005 Quantum entanglement between diamond spin qubits separated by 3 meters , RONALD HANSON, Kavli Institute of Nanoscience, Delft University of Technology — Entanglement of spatially separated objects is one of the most intriguing phenomena that can occur in physics. This can lead “spooky action at a distance” where measurement of one object instantaneously affects the state of the other object. Besides being of fundamental interest, entanglement is also a valuable resource in quantum information technology enabling secure quantum communication networks and distributed quantum computing. Here we present our most recent results towards the realization of scalable quantum networks with solid-state qubits. We have entangled two spin qubits in diamond, each associated with a nitrogen vacancy center in diamond [1]. The two diamonds reside in separate setups three meters apart from each other. Without direct interaction between the two spins to mediate the entanglement, we make use of a scheme based on quantum measurements: we perform a joint measurement on photons emitted by the NV centers that are entangled with the electron spins. The detection of the photons projects the spins into an entangled state. We verify the generated entanglement by single-shot readout of the spin qubits in different bases and correlating the results. These results open the door to a range of exciting opportunities. For instance, the remote entanglement can be extended to nuclear spins near the NV center. Our recent experiments demonstrate robust methods for initializing, controlling and entangling nuclear spins by using the electron spin as an ancilla [2,3]. Entanglement of remote quantum registers will enable deterministic quantum teleportation, distributed quantum computing tasks and the implementation of an elementary quantum repeater.


Wednesday, March 20, 2013 11:15AM - 2:15PM –

Session N19: Open Quantum Systems and Decoherence 321 - Daniel Lidar, University of Southern California

11:15AM N19.00001 Complementarity of information and the emergence of the classical world.

MICHAEL ZWOLAK, Oregon State University, WOJCIECH ZUREK, Los Alamos National Laboratory — We prove an anti-symmetry property relating accessible information to a system through some auxiliary system F and the quantum discord with respect to a complementary system F’. In Quantum Darwinism, where fragments of the environment relay information to observers – this relation allows us to understand some fundamental properties regarding correlations between a quantum system and its environment. First, it relies on a natural separation of accessible information and quantum information about a system. Under decoherence, this separation shows that accessible information is maximized for the quasi-classical pointer observable. Other observables are accessible only via correlations with the pointer observable. Second, It shows that objective information becomes accessible to many observers only when quantum information is relegated to correlations with the global environment, and, therefore, locally inaccessible. The resulting complementarity explains why, in a quantum Universe, we perceive objective classical reality, and supports Bohr’s intuition that quantum phenomena acquire classical reality only when communicated.
11:27AM N19.00002 Quantum Decoherence with Bath Size: Dynamics, Randomness, and Connectivity¹. MARK NOVOTNY, Mississippi State U., FENGPING JIN, KRISTEL MICHIELEN, Jülich Supercomputing Centre, Germany, SEJI MIYASHITA, U. Tokyo, Japan, HANS DE RAEDT, U. Groningen, Netherlands — The decoherence of a quantum system $S$ coupled to a quantum environment $E$ is considered, where $S + E$ is a closed quantum system. For typical states $X$ of the Hilbert space, i.e. for states chosen randomly from the Hilbert space unit hypersphere, we derive a scaling relation for the sum of the off-diagonal elements of the reduced density matrix $\rho_S$ of $S$. This sum is a measure of the decoherence of $S$, and decreases as $D_{E}^{1/2}$ as the dimension of the environment Hilbert space $D_E$ increases. We present long-time calculations of the time dependent Schrödinger equation (TDSE) of spin $1/2$ particles comprising $S + E$ in order to test this scaling. The Hamiltonian has uniform or random Heisenberg couplings of a spin chain for $S + E$. Factors that affect the approach to the predicted scaling relation for the Heisenberg $d = 1$ ring include how quickly and successfully the dynamics drives an initial configuration to an $X$ state, and this depends on the randomness of the coupling strengths in the Hamiltonian and the addition of other connections either within $E$ or between $S$ and $E$.

¹NSF DMR-1206233

11:39AM N19.00003 Open Quantum Walks: Microscopic Derivation and Generalised Master Equation². FRANCESCO PETRUCCIONE, ILYA SINAYSKIY, University of KwaZulu-Natal and National Institute for Theoretical Physics, QUANTUM RESEARCH GROUP TEAM — Recently, a formalism for discrete time open quantum walks was introduced [S. Attal et al., J. Stat. Phys., 147 (2012) 832; S. Attal, F. Petruccione, I. Sinayskiy, Phys. Lett. A, 376 (2012) 1545]. This formalism is exclusively based on the non-unitary dynamics induced by the environment. This approach rests upon the implementation of appropriate completely positive maps. Open quantum walks include the classical random walk and through a realization procedure a connection to the Hadamard quantum walk is established. Open quantum walks allow for an unravelling in terms of quantum trajectories. It was shown [I. Sinayskiy and F. Petruccione, QIP 11 (2012) 1301] that open quantum walks can perform universal quantum computation and can be used for quantum state engineering. Here, we present the microscopic derivation of open quantum walks. A walk on a graph is considered and transitions between vertices are mediated by the interaction of the walker with a shared bosonic environment. The reduced dynamics of the walker is shown to be described in terms of a generalised Markovian master equation. The time discretization of the master equation gives raise to an open quantum walk. Based on the class of microscopic models considered here possible physical implementations are discussed.

²This work is based upon research supported by the South African Research Chair Initiative of the Department of Science and Technology and the National Research Foundation.

11:51AM N19.00004 Efficient simulation of stochastically-driven quantum systems. MOHAN SAROVAR, MATTHEW GRACE, Sandia National Laboratories, Livermore CA, USA — The simulation of noisy quantum systems is critical for accurate modeling of many experiments, including those implementing quantum information tasks. The expansion of a stochastic equation for the coupled evolution of a quantum system and an Ornstein-Uhlenbeck process into a hierarchy of coupled differential equations is a useful technique that simplifies the simulation of stochastically-driven quantum systems. We expand the applicability of this technique by completely characterizing the class of diffusive Markov processes for which a useful hierarchy of equations can be derived. The expansion of this technique enables the examination of quantum systems driven by non-Gaussian stochastic processes with bounded range. We present an application of this extended technique by simulating Stark-tuned Forster resonance transfer in Rydberg atoms with non-perturbative position fluctuations.

The work was supported by the Sandia National Laboratories Directed Research and Development Program. Sandia National Laboratories is a multi-program laboratory managed and 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-AC04-94AL85000.

12:03PM N19.00005 Realizing a lattice-based quantum simulator using circuit quantum electrodynamics. DEVIN UNDERWOOD, WILL SHANKS, Princeton University, ANDY LI, Northwestern University, JAMES RAFTERY, DARIUS SADRI, Princeton University, JENS KOCH, Northwestern University, ANDREW HOUCK, Princeton University — Recent experimental progress in circuit quantum electrodynamics (CQED) has triggered extensive theoretical research on using these systems to implement a CQED lattice-based quantum simulator for non-equilibrium physics. CQED systems are inherently open due to unavoidable photon loss and the ease of replenishing photons through driving. The focus of this research is to experimentally realize proposals focused on building lattice-based simulators, where each lattice site contains a single CQED element. Results will be presented on a kagome lattice of 49 niobium coplanar waveguide resonators, each coupled a single aluminum transmon qubit.

12:15PM N19.00006 Decoherence and Thermalisation dynamics in many-body systems¹. DEREK LEE, Imperial College London, UK, SAM GENWAY, University of Nottingham, UK, ANDREW HO, Royal Holloway University of London, UK — An isolated quantum system prepared in a pure state will evolve coherently in time. However, local observables of the system can appear thermalised in the sense that the reduced density matrix of a small part of the system approaches the form expected from a thermal Gibbs distribution. This eigenstate thermalisation hypothesis has been demonstrated numerically. We explore the dynamics of how the system approaches this thermalised state. Our previous numerical work on the Hubbard model [Phys. Rev. Lett. 105, 260402 (2010)] has found two dynamical regimes with exponential and Gaussian decay towards the thermal state respectively. We discuss how this can be understood analytically in a generic theory. We will explore the impact of symmetry laws on the dynamics.

¹Funded by UK Engineering and Physical Sciences Research Council.

12:27PM N19.00007 Wigner distribution functions for complex dynamical systems: a path integral approach. DRIES SELS, WIM MAGNUS, FONS BROSENS, University of Antwerp — Starting from Feynman’s Lagrangian description of quantum mechanics, we propose a method to construct explicitly the propagator for the Wigner distribution function of a single system. For general quadratic Lagrangians, only the classical phase space trajectory is found to contribute to the propagator. Inspired by Feynman’s and Vernon’s influence functional theory we extend the method to calculate the propagator for the reduced Wigner function of a system of interest coupled to an external system. Explicit expressions are obtained when the external system consists of a set of independent harmonic oscillators.
12:39PM N19.00008 Chain representations of Open Quantum Systems and Lieb-Robinson like bounds for the dynamics, MISCHA WOODS, Imperial College — This talk is concerned with the mapping of the Hamiltonian of open quantum systems onto chain representations, which forms the basis for a rigorous theory of the interaction of a system with its environment. This mapping progresses as an interaction which gives rise to a sequence of residual spectral densities of the system. The rigorous mathematical properties of this mapping have been unknown so far. Here we develop the theory of secondary measures to derive an analytic expression for the sequence solely in terms of the initial measure and its associated orthogonal polynomials of the first and second kind. These mappings can be thought of as a way to nonlocal Hamiltonian to a local Hamiltonian. In the latter, a Lieb-Robinson like bound for the dynamics of the open quantum system makes sense. We develop analytical bounds on the error to observables of the system as a function of time when the semi-infinite chain is truncated at some finite length. The fact that this is possible shows that there is a finite “Speed of sound” in these chain representations. This has many implications of the simulatability of open quantum systems of this type and demonstrates that a truncated chain can faithfully reproduce the dynamics at shorter times. These results make a significant and mathematically rigorous contribution to the understanding of the theory of open quantum systems; and pave the way towards the efficient simulation of these systems, which within the standard methods, is often an intractable problem.

12:51PM N19.00009 Understanding the role of counter-rotating terms of Rabi Model under dissipation, RESUL ERYIGIT, FERDI ALTINTAS, Department of Physics, Abant Izzet Baysal University, Bolu, Turkey. — Rabi Hamiltonian is one of the most complete quantum mechanical models that describe the interaction of a qubit with a quantized field which became more relevant with the recent developments in the circuit QED technologies that made possible to obtain strong coupling in the field-qubit interactions. In the dissipative regime, the standart Lindblandian quantum optical master equation with Rabi Hamiltonian leads to unphysical effects such as an increase of total excitation number in the qubit-field system with increasing cavity decay rate. Recently, a new Liouville superoperator describing the loses of the system have been derived [F. Beaudoin, J.M.Gambetta, A. Blais, Phys. Rev. A 84, 043832 (2011)] at the ultrastrong coupling regime. In this study, by using the new dissipators for cavity loses, we have investigated the role of counter-rotating terms on the dynamics of entanglement and quantum discord at ultrastrong coupling regime and provided a comprehensible picture for the role of counter-rotating terms on quantum correlations. Contrary to the standart dissipators case, the steady-state of the system is found to contain non-zero entanglement.

1:03PM N19.00010 Classical memoryless noise-induced maximally discordant mixed separable steady states, ARZU KURT, FERDI ALTINTAS, RESUL ERYIGIT, Department of Physics, Abant Izzet Baysal University, Bolu, Turkey. — Noise is, generally, detrimental to quantum correlations. For some initial states, it has been shown that back-action of the environment or the memory in environment-system interactions can create and/or sustain some of the quantum correlations in the system. In the present study, we have investigated the dynamics of quantum discord and entanglement for two qubits subject to independent global transverse and/or longitudinal memoryless noisy classical fields and have shown that a classical memoryless noise can lead to maximally discordant mixed separable states. Moreover, two independent noises in the system are found both the steady state randomness and quantum discord in the absence of entanglement for some initial states.

1:15PM N19.00011 Decoherence effects of a charge detector on a nearby quantum dot, DAVID RUIZ-TJERINA, Ohio University, EDSON VERNEK, Universidade Federal de Uberlândia, GEORGE MARTINS, Oakland University, SERGIO ULLOA, Ohio University and Freie Universität — We study the effects of a charge detector, implemented by a quantum point-contact (QPC), on the Kondo state of an adjacent spin-1/2 quantum dot (QD). The Coulomb interaction between electrons traversing the QPC and those within the QD contribute to charge fluctuations and decoherence of the Kondo state in the QD, which can be detected through conductance measurements. Modeling the QPC as two current leads coupled through a localized level near resonance with the Fermi level of the leads, one can explore different transport regimes of the detector: Coulomb blockade, ballistic resonant-transport, and a Kondo screening state (associated with the “0.7 anomaly”). Transitions between different states are achieved by tuning the capacitive coupling $u$, or the local gates in the QPC. The transitions are studied using Varma–Yafet variational techniques, providing interesting insights into the different regimes. We employ numerical renormalization-group calculations to accurately evaluate the spectral densities and conductance behavior of the coupled QPC–QD system. We report the dependence of the Kondo temperatures of both subsystems on the capacitive coupling strength $u$, and describe the phases’ signatures in the local spectral densities and the conductance profile of the QPC.

1 Supported by NSF MWN/CIAM, NSF PIRE and CONAcYTI.

1:27PM N19.00012 Full Counting Statistics of Photons Emitted by a Double Quantum Dot, CANRAN XU, MAXIM VAVILOV, University of Wisconsin — We analyze the full counting statistics of photons emitted by a double quantum dot (DQD) to a high-quality microwave resonator due to the dipole coupling. We show that at the frequency matching condition $\omega_0 = \Delta E/\hbar$ for the energy splitting $\Delta E$ of the DQD and the resonator frequency $\omega_0$, photon statistics exhibits both a sub-Poissonian distribution and anti-bunching. In the ideal case, when the system decoherence stems only from photo-detection process, the photon noise is reduced to nearly one-half of the noise for the Poisson distribution. The photon distribution remains sub-Poissonian even at moderate decoherence in the DQD, but eventually become super-Poissonian in the regime of strong decoherence of the DQD.

1 Supported by NSF-DMR grants 0955500 and 1105178.

1:51PM N19.00014 Dephasing by a Zero Temperature Detector and the Friedel Sum Rule, BERND ROSENOW, University of Leipzig, YULIA GEFEN, Weizmann Institute of Science — Detecting the passage of an interfering particle through one of the interferometer’s arms, known as “which path” measurement, gives rise to interference visibility degradation (dephasing). Here we consider a detector at equilibrium [1]. At finite temperature dephasing is caused by thermal fluctuations of the detector. More interestingly, in the zero temperature limit, equilibrium quantum fluctuations of the detector give rise to dephasing of the out-of-equilibrium interferometer. This dephasing is a manifestation of an orthogonality catastrophe which differs qualitatively from Anderson’s. Its magnitude is directly related to the Friedel sum rule.


2:03PM N19.00015 Quantum dynamics of a spin chain in the presence of engineered collective noise, CHRISTOPHER ZEITLER, LAUREL E. ANDERSON, LORENA VIOLA, CHANDRASEKHAR RAMANATHAN, Dartmouth College — We experimentally and theoretically investigate the effect of engineered collective noise on the quantum dynamics of a spin chain evolving under the double-quantum Hamiltonian. This Hamiltonian is related by a similarity transformation to the isotropic XX Hamiltonian, and is experimentally accessible in solid-state NMR using coherent averaging techniques. In the absence of noise, a localized magnetic moment is observed to move down the chain at a constant velocity. We show that this transport is disrupted by the presence of collective z-noise, and that the magnetic moment becomes localized at the initial site as the strength of the noise increases. The relevance to quantum information transport in spin chains is also discussed.
11:15AM N26.00001 Noise of Quantum Channels can Generate Quantum Entanglement from Classical Correlation1, LASZLO GYONGYOSI, Budapest University of Technology and Economics, Hungarian Academy of Sciences, SANDOR IMRE, Budapest University of Technology and Economics — Transmission of quantum entanglement will play a crucial role in future networks and long-distance quantum communications. Quantum Key Distribution, the working mechanism of quantum repeaters and the various quantum communication protocols are all based on quantum entanglement. To share entanglement between distant points, high fidelity quantum channels are needed. In practice, these communication links are noisy, which makes it impossible or extremely difficult and expensive to distribute entanglement. In this work we first show that quantum entanglement can be generated by a fundamentally new idea, exploiting the most natural effect of the communication channels: the noise itself of the link. We prove that the noise transformation of communication links that are not able to transmit quantum entanglement can be used to generate entanglement from classically correlated, unentangled input. We call this new phenomenon the Correlation Conversion property (CC-property) of communication channels. Our results have serious implications and fundamental consequences for the future of quantum communications, and for the development of global-scale quantum communication networks.

1The results discussed above are supported by the grant TAMOP-4.2.1/B-09/1/KMR-2010-0002, 4.2.2.B-10/1-2010-0009 and COST Action MP1006.

11:27AM N26.00002 Measuring Entanglement Entropy of a Generic Many-Body System with a Quantum Switch1, DMITRY ABANIN, EUGENE DEMLER, Harvard University — Entanglement entropy has become an important theoretical concept in condensed matter physics because it provides a unique tool for characterizing quantum mechanical many-body phases and new kinds of quantum order. However, the experimental measurement of entanglement entropy in a many-body system is widely believed to be unfeasible, owing to the nonlocal character of this quantity. Here, we propose a general method to measure the entanglement entropy. The method is based on a quantum switch (a two-level system) coupled to a composite system consisting of several copies of the original many-body system. The state of the switch controls how different parts of the composite system connect to each other. We show that, by studying the dynamics of the quantum switch only, the Rényi entanglement entropy of the many-body system can be extracted. We propose a possible design of the quantum switch, which can be realized in cold atomic systems. Our work provides a route towards testing the scaling of entanglement in critical systems as well as a method for a direct experimental detection of topological order.

1The work supported by Harvard-MIT CUA, NSF Grant No. DMR-07-05472, DARPA OLE program, AFOSR Quantum Simulation MURI, and ARO-MURI on Atomtronics

11:39AM N26.00003 Postion-momentum duality in the entanglement spectrum of free fermions, CHING HUA LEE, XIAO-LIANG QI, Stanford University — The entanglement spectrum (ES) provides a valuable way of studying the topological properties of a system, i.e. those of exotic phases where no usual topological order parameter exists. In this talk, I shall discuss a framework where the partitionings of various spaces, i.e. real, momentum and spin space are treated on equal footing. This relies on an equivalence of the eigenvalue spectra of certain combinations of projection operators. For instance, the ES remains invariant if we mathematically interchange the real-space projector with the occupied band projector. One can go a step further and conclude that exchanging the physical roles of real-space and momentum space projectors lead to two different systems with identical ES. Such reinterpretations allow one to extend well-known results involving real-space cuts in critical systems to those with simultaneous momentum-space cuts. The results for gapped systems are even more interesting, with the real-space ES of a generic band insulator shown to be identical to that of two different layers or spins in a specific fermion liquid state. This framework also allows one to view the Wannier polarization spectrum as the infinite temperature limit of the ES of a certain system originally defined at zero temperature.

11:51AM N26.00004 Characterizing disordered fermion systems using the momentum-space entanglement spectrum, IAN MONDRAGON-SHEM, MAYUKH KHAN, TAYLOR HUGHES, University of Illinois, Urbana-Champaign — We show that momentum-space entanglement can reveal the existence of robust extended states in disordered fermion systems. This approach represents a novel alternative to the more conventional position-space entanglement used in condensed matter settings. We illustrate this proposal by using explicit 1D models with spatially correlated disorder that exhibit phases which avoid complete Anderson localization. The momentum space entanglement spectrum clearly reveals the location of delocalized states in the energy spectrum and can be used as a signature of the phase transition between a delocalized and localized phase. We further discuss possible applications to 2D systems that exhibit topological properties which arise from the existence of robust bulk extended states in their energy spectrum.

12:03PM N26.00005 Geometric entanglement for the toric code, color code and quantum double models, TZU-CHIEH WEI, C.N. Yang Institute for Theoretical Physics, Stony Brook University, ROMAN ORUS, Max-Planck-Institut für Quantenoptik, OLIVER BUERSCHAPER, Perimeter Institute for Theoretical Physics, MAARTEN VAN DEN NEST, Max-Planck-Institut für Quantenoptik — We use the geometric entanglement to characterize ground states in the toric code, color code and quantum double models. We find that the entanglement in all these cases scales with the system size plus a constant term. Such a constant contribution has a topological origin, characterized previously by the entanglement entropy. In particular, the constant term in the color code is twice that in the toric code, a result consistent with a recent study that the color code is equivalent to two copies of the toric code.

12:15PM N26.00006 Log divergence in finite-size quantum Riemann metric, TIAGO SOUZA, MICHAEL KOLODUBETZ, ANATOLI POLKOVNIKOV, Boston University — We study the geometric tensor, an object that describes distances between quantum states within a ground state manifold. Traditionally, it has been studied for changes in external parameters, e.g., magnetic field, at fixed system size. Here, instead, we treat the system size as a tunable parameter and analyze the distance between wave functions at different system sizes. For some simple fermion models, we find that the geometric tensor diverges logarithmically with system size in the thermodynamic limit, similar to the entanglement entropy in a CFT. We discuss similar calculations for the XY model, and comment on the relationship to RG.
Entanglement Entropy of the composite fermion non-Fermi liquid state at $\nu = 1/2$, JUNPING SHAO, Binghamton University, EUN-AH KIM, Cornell University — There has been much interest in entanglement entropy as a measure to theoretically probe strongly correlated states that do not involve broken symmetries. In particular, one may hope entanglement entropy can offer a quantitative characteristic of Non-Fermi liquids which are otherwise defined based on “what they are not part of.” Swingle and Senthil [1] conjectured that the entanglement entropy of non-Fermi liquids will be at most of order L$^{d-1} \log L$ for a region of linear size L. However, to date, there is no explicit calculation of entanglement entropy for non-Fermi liquids (though there are calculations for spin-liquids with spinon fermi surface). Here we perform a Monte Carlo calculation of the entanglement entropy for the best established example of strongly correlated non-Fermi liquid: gapless state at $\nu = 1/2$. We use a composite fermion many body wavefunction in a toroidal geometry and use the swap operator to calculate the second Renyi entropy. We discuss the resulting scaling behavior in the context of the Swingle-Senthil conjecture.


Renyi Entropy of the Interacting Fermi Liquid, JEREMY MCMINIS, NORM TUBMAN, University of Illinois — Entanglement properties, including the Renyi $\alpha$-entropies and scaling laws, are becoming increasingly important in condensed matter physics. In this work we use variational quantum Monte Carlo to compute the Renyi $\alpha$-entropies, their scaling laws, and the relationship between different $\alpha$-entropies for one of the most important phases in condensed matter, the interacting Fermi liquid. Contrary to recent theoretical predictions, we find that interactions increase the prefactor for the $\alpha$-entropy scaling laws for all particle interaction strengths and forms.

12:51PM N26.00009 Multipartition of Spatially Entangled Systems with Sine Square Deformation, ISAO MARUYAMA, Osaka university — We propose a method to decouple quantum systems without disturbing the Fermi sea, extending the sine-square deformation (SSD)[1,2] toward more general cases. This multipartition operation opens a way to real-time manipulation for separating the gapless Fermi liquid system spatially into several decoupled systems without losing quantum entanglement among them. As a demonstration of entanglement preservation, by solving the time-dependent Schrödinger equation numerically, we show that our method works well in entanglement dynamics of non-interacting tight-binding models on a one dimensional zigzag chain and a two dimensional square lattice. [1] A. Gendiar, et. al., Prog. Theo. Phys. 122. 953 (2009) [2] IM, et.al., Phys. Rev. B. 84. 165132 (2011) and references therein.

1:03PM N26.00010 Entanglement in fermionic superlattices, RAIMUNDO DOS SANTOS, TIAGO MENDES-SANTOS, THEREZEA PAIVA, Universidade Federal do Rio de Janeiro — We discuss how entanglement of strongly correlated fermions is influenced by a superlattice structure, by considering a one-dimensional Hubbard superlattice, made up of a repeated pattern of $L_0$: repulsive sites followed by $L_1$: free sites. Lanczos diagonalization of lattices up to 24 sites are used to calculate the von Neumann entropy and the negativity. The breakdown of particle-hole symmetry broadens the maxima of the entropy in the underdoped region, while the entanglement in the overdoped region is crucially influenced by the nature of the magnetic state, with dips at densities corresponding to repulsive layer singlets and to $\nu = \pi$ (in units of inverse unit cell length, $L_U+L_0$) spin-density waves; at these special densities the system is either a Mott insulator or a ‘compressible insulator’. We have also found that sites in the repulsive layer (for $L_U \geq 2$) are monogamically entangled with each other.

1:15PM N26.00011 Thermal Reduced Density Matrices in Fermion and Spin Ladder Systems, XIAO CHEN, EDUARDO FRADKIN, University of Illinois at Urbana-Champaign — A recent numerical study [1] found that the reduced density matrix of a spin 1/2 system on a two-leg ladder is the same as the spectrum of a spin 1/2 chain at a finite temperature determined by the spin gap of the ladder. We investigate this interesting result by considering two-leg ladders of free fermions and spin systems with a gapped ground state using several controlled approximations. We calculate the entanglement entropy for the cut made between the chains. In the fermionic system we find the explicit form of the reduced density matrix of one of the chains and determine the entanglement spectrum explicitly. In the case of the spin system, we consider both the strong coupling limit by using perturbation theory and weak coupling limit by using replica trick method. The calculation shows that, 1) the Von Neumann entropy equals to the thermal entropy of one chain, 2) the Renyi entropy is equivalent to the free energy of one chain, and 3) the coupling constant (gap) plays the role of effective temperature. This result can be generalized to other coupled critical systems with a bulk gap. This work was supported in part by the NSF grant DMR-1064319 at the University of Illinois [1] D. Poilblanc, Phys. Rev. Lett. 105, 077202 (2010).

1:27PM N26.00012 Entanglement measures and the quantum to classical mapping, JESKO SIRKER, TU Kaiserslautern — A quantum model can be mapped to a classical model in one higher dimension. Here we introduce a finite-temperature correlation measure based on a reduced density matrix $\rho_A$ obtained by cutting the classical system along the imaginary time (inverse temperature) axis. We show that the von-Neumann entropy $S_{\text{cut}}$ of $\rho_A$ shares many properties with the mutual information, yet is based on a simpler geometry and is thus easier to calculate. For one-dimensional quantum systems in the thermodynamic limit we prove that $S_{\text{cut}}$ is non-extensive for all temperatures T. For the integrable transverse Ising and XXZ models we demonstrate that the entanglement spectra of $\rho_A$ in the limit $T \to 0$ are described by free-fermion Hamiltonians and reduce to those of the regular reduced density matrix $\rho_A$—obtained by a spatial interval of an imaginary-time cut—up to degeneracies.

1:39PM N26.00013 Entanglement Entropy and Spectra of the One-dimensional Kugel-Khomskii Model, REX LUNDGREN, VICTOR CHUA, GREGORY FIEITE, University of Texas at Austin — We study the quantum entanglement of the spin and orbital degrees of freedom in the one-dimensional Kugel-Khomskii model, which includes both gapless and gapped phases, using analytical techniques and exact diagonalization with up to 16 sites. We compute the entanglement entropy, and the entanglement spectra using a variety of partitions or “cuts” of the Hilbert space, including two distinct real-space cuts and a momentum-space cut. Our results show the Kugel-Khomskii model possesses a number of new features not previously encountered in studies of the entanglement spectra. Notably, we find robust gaps in the entanglement spectra for both gapped and gapless phases with the orbital partition, and show these are not connected to each other. We observe the counting of the low-lying entanglement eigenvalues shows that the “virtual edge” picture which equates the low-energy Hamiltonian of a virtual edge, here one gapless leg of a two-leg ladder, to the “low-energy” entanglement Hamiltonian breaks down for this model, even though the equivalence has been shown to hold for similar cut in a large class of closely related models.
1:51PM N26.00014 Understanding the entanglement entropy and spectra of 2D quantum systems through arrays of coupled 1D chains, ANDREW JAMES, ROBERT KONIK, Brookhaven National Laboratory — We study the entanglement entropy and spectra of a coupled array of N one dimensional quantum Ising chains in their continuum limit. Employing a DMRG algorithm specifically adapted to the study of coupled, continuum systems, we are able to study large arrays of chains (up to N=200) both in their gapped phase and in the approach to criticality. Away from criticality the entanglement entropy obeys an area law. Close to criticality the entanglement entropy continues to obey the area law but possesses an additive piece scaling as $c_f \log(N)/6$ with $c_f \approx 1$. We also study the entanglement spectra of the coupled chains. Away from criticality in the disordered phase the low lying portion of the entanglement spectra appears similar to that of a single gapped quantum Ising chain. As the critical point is approached the entanglement gap closes. A finite size scaling analysis shows that the entanglement gap and the energy gap vanish at the same value of interchain coupling.

2:03PM N26.00015 Entanglement spectrum and entangled modes of random XX spin chains, MOHAMMAD POURANVARI, KUN YANG, Florida State University — We study in this work the ground state entanglement properties of finite XX spin-$1/2$ chains in with random couplings, using Jordan-Wigner transformation. We divide system into two parts and study reduced density matrices (RDMs) of its subsystems. Due to the free-fermion nature of the problem, the RDMs take the form of that of a free fermion thermal ensemble. Finding spectrum of the corresponding entanglement Hamiltonian and corresponding eigenvectors, and comparing them with real space renormalization group (RSRG) treatment, we establish the validity of the RSRG approach for entanglement in the limit of strong disorder, but also find its limitations when disorder is weak. In the latter case our work provides a way to visualize the effective spins that form long distance singlet pairs.

Wednesday, March 20, 2013 2:30PM - 5:30PM –

Session R10 GQI DCMP: Invited Session: New Platforms for Non-Abelian Statistics Majoranas and Beyond 309 - Kirill Shengel, University of California, Riverside

2:30PM R10.00001 Coulomb-assisted braiding of Majorana fermions in a Josephson junction array, CARLO BEENAKKER, Leiden University, Institut-Lorentz — We show how to exchange (braid) Majorana fermions in a network of superconducting nanowires by control over Coulomb interactions rather than tunneling. Even though Majorana fermions are charge-neutral quasiparticles (equal to their own antiparticles), they have an effective long-range interaction through the even-odd electron number dependence of the superconducting ground state. The flux through a split Josephson junction controls this interaction via the ratio of Josephson and charging energies, with exponential sensitivity. By switching the interaction on and off in neighboring segments of a Josephson junction array, the non-Abelian braiding statistics can be realized without the need to control tunnel couplings by gate electrodes. This is a solution to the problem how to operate on topological qubits when gate voltages are screened by the superconductor.

3:06PM R10.00002 Zero-bias peaks and splitting in an Al–InAs nanowire topological superconductor as signature of Majorana fermions, MOTY HEIBLUM, Weizmann Institute of Science — Majorana fermions are the only fermionic particles that are expected to be their own antiparticles. While elementary particles of the Majorana type were not identified yet, quasi-particles with Majorana like properties, born from interacting electrons in the solid, were predicted to exist. Here, we present thorough experimental studies, backed by numerical simulations, of a system composed of an aluminum superconductor in proximity to an indium arsenide nanowire, with the latter possessing strong spin-orbit coupling and Zeeman splitting. Induced one-dimensional topological superconductor, supporting Majorana fermions at both ends, is expected to form. We concentrate on the characteristics of a distinct zero bias conductance peak (ZBP) and its splitting in energy — both appearing only with a small magnetic field applied along the wire. The ZBP was found to be robustly tied to the Fermi energy over a wide range of system parameters. While not providing a definite proof of a Majorana state, the presented data and the simulations support its existence.

3:42PM R10.00003 Exotic non-Abelian anyons from conventional fractional quantum Hall states, DAVID CLARKE, Caltech — Non-Abelian anyons are widely sought after for the exotic fundamental physics they harbor as well as for quantum computing applications. There now exist numerous blueprints for stabilizing the simplest type of non-Abelian anyon, defects binding Majorana fermion zero modes, by judiciously interfacing widely available materials. Following this line of attack, we introduce a device fabricated from conventional fractional quantum Hall states and s-wave superconductors. We show that a new type of zero mode is bound at the interface between the quantum Hall state and the superconductor. These zero mode operators have parafermionic rather than fermionic commutation relations, implying a topologically protected ground state degeneracy larger than that of Majorana fermions. We discuss how these modes might be experimentally identified (and distinguished from Majoranas) using Josephson measurements.

4:18PM R10.00004 Fractionalizing Majorana Fermions: Non-Abelian Statistics on the Edges of Abelian Quantum Hall States, NETANEL LINDNER, California Institute of Technology — We study the non-Abelian statistics characterizing systems in which the edges of fractional quantum Hall states are gapped by proximity coupling to superconductors and ferromagnets. We show that as more superconductor-ferromagnet interfaces are introduced, the ground state degeneracy grows with a quantum dimension of a square root of an even integer, corresponding to a new family of non-Abelian anyons. Topologically protected braiding of two anyons can be achieved by a sequence of adiabatic manipulations of the system. We show that the unitary transformations resulting from these braiding operations realize a richer set of representations of the braid group than those realized by non-Abelian anyons based on Majorana fermions. We discuss implications of these braiding operations to topological quantum computation, and consider possible realizations of these ideas in experimentally accessible solid state systems.

4:54PM R10.00005 Genons, twist defects, and projective non-Abelian statistics, MAISSAM BARKESHLI, Stanford University — An intense focus in the condensed matter community currently is the search for Majorana fermions in solid state systems. Defects which localize Majorana zero modes obey the simplest kind of non-Abelian statistics, and are of interest partially for the goal of achieving topological quantum computing. In this talk, I will present recent advances in our understanding of how to synthesize a much more general class of non-Abelian defects using conventional topological states. After discussing the new theoretical foundations, I will present an experimental proposal using only conventional bilayer fractional quantum Hall states and a simple geometry of top and bottom gates. I will also discuss how these ideas can be used to perform universal topological quantum computing (TQC) using non-Abelian states that by themselves are not universal for TQC.
2:30PM R26.00001 Distinct Quantum States Can Be Compatible with a Single State of Reality

PETER LEWIS, DAVID JENNINGS, Imperial College, London; JONATHAN BARRETT, University of Oxford; TERRY RUDOLPH, Imperial College, London — Perhaps the quantum state represents information available to some agent or experimenter about reality, and not reality directly. This view is attractive because if quantum states represent only information, then wave function collapse is possibly no more mysterious than a Bayesian update of a probability distribution given new data. Several other “puzzling” features of quantum theory also follow naturally given this view. In order to explore this idea rigorously, we consider models for quantum systems with probabilities for measurement outcomes determined by some underlying physical state of the system, where the underlying state is not necessarily described by quantum theory. In our model, quantum states correspond to probability distributions over the underlying states so that the Born rule is recovered. More specifically, we consider models for quantum systems where several quantum states are consistent with a single underlying state—i.e., probability distributions for distinct quantum states overlap. Recent work shows that such a model is impossible (e.g., the PBR theorem [Nat. Phys. 8, p.474]). Significantly, our example demonstrates that non-trivial assumptions (beyond those required for a well-defined realistic model) are necessary for the PBR theorem and those like it.

This work was supported by the Engineering and Physical Sciences Research Council, Leverhulme Foundation and The Royal Commission for the Exhibition of 1851

2:42PM R26.00002 ABSTRACT WITHDRAWN —

2:54PM R26.00003 Our Current Concept of Locality May Be Incomplete

ARMIN NIKKHAH SHIRAZI, University of Michigan, Ann Arbor — The predictions of Bell’s inequalities, and their subsequent experimental verification in the form of correlations between space-like separated events have led to the prevailing current view that “nature is non-local.” Here we examine the possibility that our current concept of locality may at present not be sufficiently differentiated, and that by using ‘nature’ synonymously with ‘spacetime’ we may have missed an implication of special relativity which by rendering a more complete conception of locality permits such quantum correlations without either hidden variables or violations of locality.

3:06PM R26.00004 No Drama Quantum Theory?

ANDREY AKHMETELI, LTASolid Inc. — Is it possible to offer a “no drama” quantum theory? Something as simple (in principle) as classical electrodynamics - a theory described by a system of partial differential equations (PDE) in 3+1 dimensions, but reproducing unitary evolution of a quantum field theory in the Fock space? The following results suggest an affirmative answer: 1. The scalar field can be algebraically eliminated from scalar electrodynamics; the resulting equations describe independent evolution of the electromagnetic field (EMF). 2. After introduction of a complex 4-potential (producing the same EMF as the standard real 4-potential), the spinor field can be algebraically eliminated from spinor electrodynamics; the resulting equations describe independent evolution of EMF. 3. The resulting theories for EMF can be embedded into quantum field theories. Another fundamental result: in a general case, the Dirac equation is equivalent to a 4th order PDE for just one component, which can be made real by a gauge transform. Issues related to the Bell theorem are discussed. A. Akhmeteli, Int’l Journal of Quantum Information, Vol. 9, Suppl., 17-26 (2011) A. Akhmeteli, Journal of Mathematical Physics, Vol. 52, 082303 (2011) A. Akhmeteli, quant-ph/1111.4630 A. Akhmeteli, J. Phys.: Conf. Ser., Vol. 361, 012037 (2012)

3:18PM R26.00005 A realist, “local,” “hidden variable” model of quantum mechanics without observers

WILLIAM SULIS, McMaster University and University of Waterloo — The violation of Bell type inequalities hinges upon the non-Kolmogorov nature of quantum probability structures. I show that a Process theory based, game theoretic formulation of quantum mechanics admits non-Kolmogorov probability structures. This formulation is realist, discrete and local at the level of space-time events while having nonlocal properties at the process level. These nonlocal effects respect relativistic constraints. Solutions to the Schrodinger equation arise through sinc interpolation of local samples generated by local path integral calculations based upon local information. Nonrelativistic quantum mechanics emerges in the continuum limit with perfect information transfer. This model avoids Kochen-Specker type restrictions and violates Bell and Leggett-Garg type inequalities. This formulation will be illustrated with a model of the classical two slit experiment.


WAYNE HUANG, HERMAN BATELAAN, University of Nebraska-Lincoln — Since the early development of Quantum Mechanics, the discrete atomic spectra have been considered as the defining feature of Quantum Mechanics. However, when the classical electromagnetic zero-point radiation is introduced as a modification to Classical Mechanics, our simulation shows that a linear classical harmonic oscillator, when excited by a laser pulse, can exhibit an integer spaced energy spectrum just as its quantum counterpart. This finding may be surprising given the use of a fully classical theory, and it may help us identify the true quantum features in physical systems such as harmonic oscillator and ultimately atoms.

3:42PM R26.00007 Normalized spacings between zeros of Riemann zeta function follow normalized Maxwell-Boltzmann distribution

SIVAVASH SOHRAB, Northwestern University — Through Planck relation ε = hν normalized spacings between energy levels of oscillators are related to those between frequencies expressed as Gauss clock calculator or Hensel p-adic numbers. Energy-level spacings are related to spacings between “stationary states” and through Euler golden key to zeros of Riemann zeta function. The latter are shown to follow normalized Maxwell-Boltzmann (NMB) distribution function,

$$\rho_\beta = \frac{1}{(8\pi\beta)}\frac{1}{(2/\sqrt{\pi}\beta)}x_\beta^2 e^{-[(2/\sqrt{\pi})^2 x_\beta]^2}$$

hence providing physical explanations of Montgomery-Odlyzko law and Hilbert-Polya conjecture. Position of the critical line is found to coincide with that of stationary states. Normalized spacing between eigenvalues of GUE of an Adele space constructed by superposition of infinite NMB distribution functions will coincide with spacing of zeros of Riemann zeta function according to the theory of noncommutative geometry of Connes.
with the best previously known protocol.

of stabilizer codes with an encoding rate

\[ \frac{1}{3} \]

software states known as “magic states” and substantially increases the space and time overheads. To reduce the distillation overhead we propose a new family

\[ \frac{\pi}{2\epsilon} \]

measurements. On the other hand, implementation of encoded non-Clifford gates such as the

\[ \gamma \]

the output accuracy and

\[ \gamma = \log_2(3) \approx 1.6 \]

Our techniques lead to a two-fold overhead reduction for distilling magic states with accuracy

\[ \epsilon \sim 10^{-12} \]

compared with the best previously known protocol.

\[ 1 \]

2:30PM R27.00001 Magic state distillation with low overhead, SERGEY BRAVYI, IBM Watson Research Center — Most of error correcting codes used in fault-tolerant quantum computing permit an efficient implementation of high-fidelity encoded Clifford gates and Pauli measurements. On the other hand, implementation of encoded non-Clifford gates such as the \( \pi/8 \)-rotation \( T \) usually requires distillation of certain quantum software states known as “magic states” and substantially increases the space and time overheads. To reduce the distillation overhead we propose a new family of stabilizer codes with an encoding rate \( 1/3 \) that permit a transversal implementation of the \( T \)-gate on all logical qubits. The new codes are used to construct protocols for distilling high-quality magic states by Clifford group gates and Pauli measurements. The distillation overhead scales as \( O(\log^7(1/\epsilon)) \), where \( \epsilon \) is the output accuracy and \( \gamma = \log_2(3) \approx 1.6 \). Our techniques lead to a two-fold overhead reduction for distilling magic states with accuracy \( \epsilon \sim 10^{-12} \) compared with the best previously known protocol.

\[ 1 \]

2:30PM R26.00008 Shape Invariance in Deformation Quantization\(^1\), CONSTANTIN RASINARIU, Columbia College Chicago — Shape invariance is a powerful solvability condition, that allows for complete knowledge of the energy spectrum, and eigenfunctions of a system. After a short introduction into the deformation quantization formalism, this work explores the implications of the supersymmetric quantum mechanics and shape invariance techniques to the phase space formalism. We show that shape invariance induces a new set of relations between the Wigner functions of a system, that allows for their direct calculation, once we know one of them. The simple harmonic oscillator and the Morse potential are presented as examples.

\[ 1 \]

would like to acknowledge a sabbatical leave and grant from Columbia College Chicago that made this work possible.

4:06PM R26.00009 Entangled states associated with N-qubit GHZ paradoxes, MORDECAI WAEGELL, P.K. ARAVIND, Worcester Polytechnic Institute — Many workers have generalized the original GHZ paradox by replacing the qubits in it by qudits and the three observers by an arbitrary number of observers. We point out that if one stays with qubits but allows an arbitrary number of observers, a large number of paradoxes are possible. Some of the paradoxes come in families that extend upwards to all numbers of qubits. The entangled states connected within these paradoxes come in a wide variety. We survey the different types of entangled states that occur and also discuss some of their applications.

4:18PM R26.00010 Logical difficulty from combining counterfactuals in the GHZ-Bell theorems, LOUIS SICA, Chapman University, Orange, CA — Since it depends on predictions of single sets of measurements on three particles, the Greenberger, Horne, Zeilinger (GHZ) theorem eliminates the sampling loophole encountered by the Bell theorem that requires a large number of observations to obtain a relatively small number of useful joint measurements. In evading this problem, the GHZ theorem is believed to have confirmed Bell’s historic conclusion that local hidden variables are inconsistent with the results of quantum mechanics. The GHZ theorem depends on predicting the results of sets of measurements of which only one may be performed, i.e., counterfactuals. In the present paper, the non-commutative aspects of these unperformed measurement sequences are critically examined. Three classical examples and the logic of the GHZ construction are analyzed to demonstrate that combined counterfactual results of non-commuting operations may be logically absurd, and in general are logically inconsistent with performed measurement sequences that take non-commutation into account. The Bell theorem is also revisited in the light of this result. It is concluded that negative conclusions regarding local hidden variables do not follow from the GHZ and Bell theorems as historically reasoned.

4:30PM R26.00011 Observation of a Fast Evolution in a Parity-time-symmetric System\(^2\), CHAO ZHENG, LIANG HAO, G. LU LONG, Tsinghua University — In the parity-time-symmetric (PT-symmetric) Hamiltonian theory, the optimal evolution time can be reduced drastically and can even be zero. In this letter, we report our experimental simulation of the fast evolution of a PT-symmetric Hamiltonian in a nuclear magnetic resonance quantum system. The experimental results demonstrate that the PT-symmetric Hamiltonian system can indeed evolve much faster than the quantum system, and the evolution time can be arbitrarily close to zero.

\[ 2 \]

China National Natural Science Foundation

4:42PM R26.00012 Second law of thermodynamics for random walk of quantum particle in-apresence of detectors, IVAN SADOVSKYY, Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA, GORDEY LESOVIK, L.D. Landau Institute for Theoretical Physics RAS, 117940 Moscow, Russia — We test H-theorem for a several models of particle random walk. We study interaction with a reservoir/detectors and its influence on entropy and found entropy growing in the time for some models and behaving non-monotonically for the others. We discuss the details of the system-reservoir interaction (such as presence of the interference in the system and number of interactions with detector parts) and their impact on the monotonicity of entropy.

4:54PM R26.00013 Analogy between optical interferometry and integer factorization inspires novel mathematical results, GABRIEL SEIDEN, Weizmann Institute of Science — Prime factorization of integers is an outstanding problem in arithmetic with important consequences in a variety of fields, most notably cryptography. We explore the intriguing relationship between prime factorization and optical interferometry with the aim of obtaining novel analytic expressions for number-theoretic functions directly related to prime factorization [1]. [1] G. Seiden, Phys. Rev. A 85, 043842 (2012)

5:06PM R26.00014 Glimpses of the quantal algebra in early papers on quantum mechanics, SAMIR LIPOVACA, None — A closer reading of early papers on quantum mechanics reveals that the quantal algebra lies hidden beneath the surface. We will show from the standpoint of the quantal algebra that, in essence, Heisenberg came across the symmetric product of the quantal algebra in his remarkable 1925 paper, Born and Jordan limited a general Hamiltonian function to a linear form of the terms containing the symmetric product of the quantal algebra, and Dirac found that the most general operation \( d/dv \) is the Leibnitz identity of the quantal algebra.

Wednesday, March 20, 2013 2:30PM - 5:30PM –

Session R27 GQI: Focus Session: Quantum Error Correction and Decoherence Control II

329 -

Andrew Landahl, Sandia National Laboratories

2:30PM R27.00001 Magic state distillation with low overhead, SERGEY BRAVYI, IBM Watson Research Center — Most of error correcting codes used in fault-tolerant quantum computing permit an efficient implementation of high-fidelity encoded Clifford gates and Pauli measurements. On the other hand, implementation of encoded non-Clifford gates such as the \( \pi/8 \)-rotation \( T \) usually requires distillation of certain quantum software states known as “magic states” and substantially increases the space and time overheads. To reduce the distillation overhead we propose a new family of stabilizer codes with an encoding rate \( 1/3 \) that permit a transversal implementation of the \( T \)-gate on all logical qubits. The new codes are used to construct protocols for distilling high-quality magic states by Clifford group gates and Pauli measurements. The distillation overhead scales as \( O(\log^7(1/\epsilon)) \), where \( \epsilon \) is the output accuracy and \( \gamma = \log_2(3) \approx 1.6 \). Our techniques lead to a two-fold overhead reduction for distilling magic states with accuracy \( \epsilon \sim 10^{-12} \) compared with the best previously known protocol.
We develop a procedure for distilling magic states used in universal quantum computing which requires substantially fewer resources than prior schemes. Our distillation circuit is based on a family of concatenated quantum codes with a transversal Hadamard operation which can distill the eigenstate of the Hadamard operator. A crucial result of this design is that low-fidelity magic states can be consumed to purify high-fidelity magic states to even higher fidelity, which we call “multilevel distillation.” We show numerically that there exist multilevel protocols such that the average number of magic states consumed to distill from error rate $\epsilon_{in} = 0.01$ to $\epsilon_{out}$ in the range $10^{-5}$ to $10^{-10}$ is about $14\log_{2}(1/\epsilon_{out}) - 40$. The efficiency of multilevel distillation dominates all other reported protocols when distilling Hadamard magic states from initial infidelity 0.01 to any final infidelity below $10^{-7}$. These methods are an important advance for magic-state distillation circuits in high-performance quantum computing.

3:18PM R27.00003 ABSTRACT WITHDRAWN

3:30PM R27.00004 Direct-to-Toffoli Magic-state Distillation

— In recently proposed quantum computing architectures, approximately 90% of the required resources are consumed during the distillation of single-qubit magic-states for use in performing Toffoli gates. In this talk I describe how the overhead for magic-state distillation can be reduced by merging distillation with the implementation of Toffoli gates. The resulting routines distill single-qubit magic-states directly to Toffoli ancillae, each of which can be used without further magic to perform a Toffoli gate.

3:42PM R27.00005 Magic state distillation protocols with noisy Clifford gates

— A promising approach to universal fault-tolerant quantum computation is to implement the non-universal group of Clifford gates, and to achieve universality by adding the ability to prepare high-fidelity copies of certain “magic states.” By applying state distillation protocols, many noisy copies of a magic state ancilla can be purified into a smaller number of clean copies which are arbitrarily close to the perfect state, using only Clifford operations. In practice, the Clifford gates themselves will be noisy, which can limit the efficiency of state distillation and put a floor on the achievable fidelity with the desired state. Recently, a number of new state distillation protocols have been proposed that have the potential to reduce the required resource overhead. I analyze these protocols and explore the tradeoffs between these different approaches to magic state distillation when noisy Clifford gates are taken into account.

3:54PM R27.00006 Simulating Anyon Interference to Measure the Levin-Wen Plaquette Operator

— In a recent paper, Koenig et al. [1] have used the Levin-Wen model for Fibonacci anyons as a non-Abelian surface code for fault-tolerant quantum computation. In this talk, we develop a methodology to connect logical error rates of a Fibonacci anyon surface code with the ground states of the Levin-Wen model for Fibonacci anyons and a non-Abelian surface code for fault-tolerant quantum computation [2]. To do this, it will be necessary to repeatedly measure the vertex and plaquette operators of the model to check for errors. Recently, two of us have constructed quantum circuits for performing such measurements [3]. Here we present an alternate measurement scheme based on simulating an interference experiment. This “experiment” can be thought of, roughly, as first inserting a pair of Fibonacci anyons with trivial total topological charge onto one edge of a plaquette, “braiding” one anyon all the way around the plaquette while the other remains fixed, and then either measuring the total topological charge of the two anyons or manipulating their state in a specific way. We construct explicit quantum circuits which can be used to simulate these processes and show how they can be used to measure the Levin-Wen plaquette operator on a quantum computer.

4:06PM R27.00007 Optimal control in presence of decoherence and measurement imperfections: Pure state preparation problem

— Quantum control is a key component in the mathematical toolbox for designing fault-tolerant quantum processors. It becomes important to find optimal control protocols for realistic experimental conditions. In this talk, I focus on quantum feedback control for preparing pure states as ideal resources for quantum computation and communication. I discuss how the optimal protocols under experimental imperfections can be different from the ones found under theoretical simplifications. The problem of our study is motivated by superconducting circuit QED proposals for quantum computation.

4:42PM R27.00008 Surface code with decoherence: An analysis of three superconducting architectures

— We consider a realistic, multi-parameter error model and develop a methodology to connect logical error rates of a surface code architecture with single qubit coherence time (T1 or T2) for any realistic set of intrinsic parameters, such as state preparation, gate, and readout errors. The amplitude and phase damping are mapped to a diagonal Pauli depolarization channel via the Pauli twirl approximation. Three existing superconducting architectures are chosen and a numerical Monte Carlo simulation is performed to obtain the logical error rates. A leading order analytic model is also constructed that estimates the scaling behavior of logical error rates below threshold for small distances. Our results suggest that large-scale fault-tolerant quantum computation should be possible with existing state-of-the-art superconducting devices.

4:54PM R27.00009 Surface Code Threshold in the Presence of Correlated Errors

— We study the fidelity of the surface code in the presence of correlated errors induced by the coupling of physical qubits to a bosonic environment. By mapping the time evolution of the system after one quantum error correction cycle onto a statistical spin model, we show that the existence of an error threshold is related to the appearance of an order-disorder phase transition in the statistical model in the thermodynamic limit. This allows us to relate the error threshold to bath parameters and to the spatial range of the correlated errors.

References

1. Supported in part by IARPA under contract D11PC20165, by NSF under Grant No. PHY-0803371, by DOE under Grant No. DE-FG03-92-ER40701, and by NSA/ARO under Grant No. W911NF-09-1-0442.


3. This work was supported by IARPA under ARO Grant No. W911NF-10-1-0334.

4. E.N. was partially supported by INCT-IQ and CNPq (Brazil) and E.M. was supported in part by ONR and NSF (USA).
5:06PM R27.00010 Surface code fidelity decay in the presence of a bosonic bath , PEJMAN JOUZDANI, EDUARDO MUCCIOLI, University of Central Florida, EDUARDO NOVAIS, Universidade Federal do ABC (Brazil) — The surface code is a promising quantum computing environment that provides topological protection against errors, ensuring that the distance of the code grows as the physical sizes of the system increases. It has been recently proposed that a surface code in contact with a bosonic bath experiences an effective evolution that induces an constrained Ising-like interaction between qubits. As the coupling to the bosonic bath increases, the system may undergo a transition where the fidelity decays substantially after one quantum error correction cycle even for non-error syndromes. We investigate the manifestation of such a transition by evaluating numerically the fidelity of a surface code qubit system with the proposed Ising interaction. We carry out exact calculations for small systems and perform a finite-size scaling analysis using a cluster mean-field approach. We find a significant change in the fidelity at coupling constant values compatible with the mean-field transition point. Calculations performed with complex coupling constants yield the same behavior for the fidelity.

5:18PM R27.00011 Fast decoder for local quantum codes using Groebner basis1 , JEONGWAN HAAH, California Institute of Technology — Based on arXiv:1204.1063. A local translation-invariant quantum code has a description in terms of Laurent polynomials. As an application of this observation, we present a fast decoding algorithm for translation-invariant local quantum codes in any spatial dimensions using the straightforward division algorithm for multivariate polynomials. The running time is $O(n \log n)$ on average, or $O(n^2 \log n)$ on worst cases, where $n$ is the number of physical qubits. The algorithm improves a subroutine of the renormalization-group decoder by Bravyi and Haah (arXiv:1112.3252) in the translation-invariant case.

1This work is supported in part by the Institute for Quantum Information and Matter, an NSF Physics Frontier Center, and the Korea Foundation for Advanced Studies.

Thursday, March 21, 2013 8:00AM - 11:00AM — Session T10 GQI DCMP: Invited Session: Superconducting Qubits 309 - Matthias Steffen, IBM

8:00AM T10.00001 A strand of a surface code fabric with superconducting qubits1 , JERRY CHOW, IBM T.J. Watson Research Center — Quantum error correction will be a necessary component towards realizing scalable quantum computers with physical qubits. Theoretically, it is possible to perform arbitrarily long computations so long as the error rate is below a threshold value. The two-dimensional surface code permits relatively high fault-tolerant thresholds at the ~1% level, and only requires a lattice network of qubits with nearest-neighbor interactions. I will discuss our implementation of a sub-section of the larger fabric using three transmon qubits and two linking microwave resonators. We demonstrate high-fidelity control over the sub-section surface code strand, verified via quantum process tomography and randomized benchmarking experiments. Our fixed-frequency qubit approach relies on the two-qubit cross-resonance microwave driving interaction, which is now one of many microwave-based entangling gate protocols. I will also discuss the prospects to scale to surface code plaquette level experiments.

1We acknowledge support from IARPA under contract W911NF-10-1-0324

8:36AM T10.00002 Recent progress of the fluxonium qubit1 , MICHEL DEVORET, Applied Physics Department, Yale University — Superconducting artificial atoms are all based on the purely dispersive non-linearity of a Josephson tunnel junction, which provides anharmonicity for a microwave oscillator mode. In the fluxonium qubit [1], the microwave oscillator crucially involves a superinductor, built with a linear array of several tens of "large" Josephson junctions. As the flux threading the loop formed by the superinductor and the tunnel junction is swept from zero to half a flux quantum, the g-e transition frequency varies between a sweet spot around 10GHz and another sweet spot at a few hundreds of MHz. By optimizing the fabrication and parameters of this superinductor [2], we have eliminated spurious phase slips through the array, and ensured that its self-resonance frequency lies above the frequency of the qubit. The improved relaxation times of this multi-junction circuit are promising for the design of a novel mesoscopic artificial atom, in which large anharmonicity, long coherence times and fast coupling rate to a cavity bus would all be compatible.


1Work supported by IARPA, ARO, NSF and YINQE.

9:12AM T10.00003 Are materials good enough for a superconducting quantum computer? , JOHN MARTINIS, UC Santa Barbara — Recent developments of surface codes now place superconducting quantum computing at an important crossroad, where “proof of concept” experiments involving small numbers of qubits can be transitioned to more challenging and systematic approaches that could actually lead to building a quantum computer. Although the integrated circuit nature of these qubits helps with the design of a complex architecture and control system, it also presents a serious challenge for coherence since the quantum wavefunctions are in contact with a variety of materials defects. I will review both logic gate design and recent developments in coherence in superconducting qubits, and argue that state-of-the-art devices are now near the fault tolerant threshold. Future progress looks promising for fidelity ten times better than threshold, as needed for scalable quantum error correction and computation.

9:48AM T10.00004 Overhead considerations of surface codes , AUSTIN FOWLER, The University of Melbourne — How big would a commercially relevant superconducting quantum computer making use of the surface code need to be? What is the simplest experiment required to conclusively demonstrate that arbitrarily reliable quantum computation is technologically feasible? In this talk, we discuss the current state-of-the-art of the surface code and answer these two questions according to the latest available results. We describe ongoing research to bring down the overhead associated with quantum computation.

10:24AM T10.00005 Scaling up with superconducting qubits , ALEXANDRE BLAIS, Université de Sherbrooke — There have been significant developments in the field of superconducting qubits since the first observation, almost 15 years ago, of coherent oscillations in a superconducting electrical circuit. One key number could summarize this progress: the coherence time. Indeed, this quantity has increased by about 5 orders of magnitude since the first experiments. Characterizing this progress with a single number is, however, too simplistic. It does not capture the many improvements that the field has witnessed and, in the same way, hides many of the challenges that lie ahead. Indeed, with many ingredients having to come together and work just right, quantum computation is about more than long coherence times. A much better (yet incomplete) measure is the error rate of single- and two-qubit logical gates. Recent experiments show this rate approaching the level required for fault-tolerant quantum computation, a requirement for a scalable quantum computer architecture. In parallel, much effort has been invested in using superconducting qubits as artificial atoms to explore quantum optics with microwaves and in unconventional parameter ranges. With an emphasis on theoretical work, in this talk I will present an overview of the recent achievements in the field and present some challenges that will have to be overcome.
We have fabricated and tested an Al/AlO$_x$/Al SQUID phase qubit using a tunable cavity. The qubit is on a sapphire substrate. The qubit is a capacitively coupled superconducting microwave resonator and a transmon qubit fabricated on a separate chip and mounted to a three-dimensional cryogenic translation stage. The qubit-resonator system reached the strong coupling regime with a coupling strength in excess of 180 MHz, while qubit and resonator linewidths were roughly 0.4 and 10 MHz respectively. We map out the coupling strength in the plane of the resonator and find good agreement with finite element simulation. Such a scannable qubit could be used as a part of a local probe of a large array of microwave cavities and superconducting qubits.

This work was supported by the MEXT Kakenhi “Quantum Cybernetics”, the JSPS through its FIRST Program, and the NICT Commissioned Research.

Acknowledgement: LPS, JQI, and CNAM

This work was supported by the MEXT Kakenhi “Quantum Cybernetics”, the JSPS through its FIRST Program, and the NICT Commissioned Research.

Acknowledgement: LPS, JQI, and CNAM
9:24AM T25.00008 Quantum Superinductor with Tunable Nonlinearity1, MATTHEW BELL, IVAN SADOVSKY, LEV IOFFE, Rutgers University, ALEXEI KITAEG, Caltech, MICHAEL GERSHENSON, Rutgers University — We report on the realization of a superinductor, a dissipationless element whose microwave impedance greatly exceeds the resistance quantum $R_Q$. The design of the superinductor, implemented as a ladder of nanoscale Josephson junctions, enables tuning of the inductance and its nonlinearity by a weak magnetic field. The Rabi decay time of the superinductor-based qubit exceeds 1 $\mu$s. The high kinetic inductance and strong nonlinearity offer new types of functionality, including the development of qubits protected from both flux and charge noises, fault tolerant quantum computing, and high-impedance isolation for electrical current standards based on Bloch oscillations.

1This work was supported by DARPA (HR0011-09-1-0009), NSF (DMR 1006265), and ARO (W911NF-09-1-0395).

9:36AM T25.00009 Long-lived, radiation-suppressed superconducting quantum bit in a planar geometry, MARTIN SANDBERG, MICHAEL VISSERS, national institute of standards and technology, THOMAS OHKI, Raytheon BBN technologies, JIANSONG GOA, JOSE AUENTADO, national institute of standards and technology, MARTIN WEIDE, Karlsruhe institute of technology, Germany, DAVID PAPPAS, national institute of standards and technology — We present a superconducting qubit design that is fabricated in a 2D geometry over a superconducting ground plane to enhance the lifetime. The qubit is coupled to a microstrip resonator for readout. The circuit is fabricated on a silicon substrate using low loss, stoichiometric titanium nitride for capacitor pads and small, shadow-evaporated aluminum/aluminum-oxide junctions. We observe qubit relaxation and coherence times ($T_1$ and $T_2^*$) of 117 $\pm$ 0.2 $\mu$s and 8.7 $\pm$ 0.3 $\mu$s, respectively. Calculations show that the proximity of the superconducting plane suppresses the otherwise high radiation loss of the qubit. A significant increase in $T_1$ is projected for a reduced qubit-to-superconducting plane separation.

9:48AM T25.00010 Towards Tunable Transitions in 2-D Transmons, Z.K. KEANE, Laboratory for Physical Sciences, College Park, MD, B. SURI, S. NOVIKOV, Laboratory for Physical Sciences, College Park, MD; Department of Physics, University of Maryland, J.E. ROBINSON, Laboratory for Physical Sciences, College Park, MD, F.C. WELSTOOD, Department of Physics, University of Maryland, B.S. PALMER, Laboratory for Physical Sciences, College Park, MD — We have developed a design for a tunable transmon qubit with an on-chip flux bias. The transmon is fabricated with two sub-micron Al/AIO$_3$/Al tunnel junctions and coupled to a superconducting planar lumped-element resonator. A coplanar transmission line provides flux coupling and tuning of the qubit’s transition energies. We will discuss the design and fabrication strategy and present preliminary measurements of coherence and tunability in these devices.

10:00AM T25.00011 Tuning qubit interactions with asymmetric transmons, MATTHEW WARE, DANIELA F. BOGORIN, J.D. STRAND, B.L.T. PLOURDE, Syracuse University — Superconducting transmon qubits have been used in numerous key experiments in the field of quantum information processing. We are exploring a variation of this circuit, the asymmetric transmon, where the two Josephson junctions making up the qubit have substantially different critical currents. This results in a second sweet spot with respect to magnetic flux at half-integer flux-quantum bias points. The corresponding reduction in energy-modulation depth makes the qubit less sensitive to dephasing due to flux noise for bias points away from the sweet spots. At the same time, the tunability of the qubit energy allows for novel qubit-cavity processes, including flux-driven sideband transitions, as well as adjustable interactions between multiple qubits.

10:12AM T25.00012 Investigation of Single and Coupled Flux Qubit Energy Spectra Using Tunneling Spectroscopy, ANTHONY PRZYBYSZ, TREVOR LANTING, ANDREW BERKLEY, RICHARD HARRIS, ANATOLY SMIRNOV, MOHAMMAD AMIN, D-Wave Systems Inc., NEIL DICKSON, Side Effects Software Inc., EMILE HOSKINSON, FABIO ALTMARE, ANDREW WILSON, ELENA TOLKACHEVA, PAUL BUNYK, MARK JOHNSON, GEORDIE ROSE, D-Wave Systems Inc. — We present the results of our investigation of the energy levels of systems of flux qubits using tunneling spectroscopy. Tunneling spectroscopy is a technique by which we use macroscopic resonant tunneling processes of a neighboring qubit to probe the energy spectrum of a system of flux qubits. We used this technique to measure the energy gap of a single qubit near its degeneracy point where it is in a superposition of left and right circulating current states. Furthermore, we applied this technique to systems of up to 8 coupled qubits that were biased at degeneracy and observed energy spectra that agree with theoretical predictions based on independently determined device parameters.

10:24AM T25.00013 Phase versus flux coupling between resonator and superconducting flux qubit 1, J.S. BIRENBAUM, S.R. O’KELLEY, S.M. ANTON, UC Berkeley, C.D. NUGROHO, V. ORLYANCHIK, A.H. DOVE, Z.R. YOSCOVITS, G.A. OLSON, D.J. VAN HARLINGEN, J. ECKSTEIN, University of Illinois at Urbana-Champaign, D.A. BRAJE, R.C. JOHNSON, W.D. OLIVER, MIT Lincoln Laboratory, JOHN CLARKE, UC Berkeley — The dispersive coupling of qubits to microwave resonators has become widely used for qubit readout. Recent advances in coupling qubits to 3D resonators have demonstrated the importance of the nature of the qubit-resonator coupling in determining the qubit relaxation and decoherence times, $T_1$ and $T_2^*$. We study the effect of phase versus flux coupling on flux qubits coupled to planar resonators. Using an aluminum shadow evaporation technique we fabricate a low-loss planar resonator, consisting of a meandering inductor and interdigitated capacitor, and a flux qubit, all in a single processing step. Whereas the qubit and resonator are always flux coupled via a geometric mutual inductance, a phase coupling can be added by including a shared trace between the qubit and resonator. This technique allows us to control both the magnitude and nature of the qubit-resonator coupling without significantly affecting either the qubit or resonator design. We characterize the dependence of the qubit parameters $T_1$, $T_2^*$, and spin echo time $T_{echo}$ on the resonator coupling parameters to gain insight into possible sources of decoherence and loss.

1This work was supported by ARO, IARPA, and the US Government.

10:36AM T25.00014 Solid-state quantum metamaterials, RICHARD WILSON, MARK EVERITT, SERGEY SAVELIEV, ALEXANDRE ZAGOSKIN, Department of Physics, Loughborough University — Quantum metamaterials provide a promising potential test bed for probing the quantum-classical transition. We propose a scalable and feasible architecture for a solid-state quantum metamaterial. This consists of an ensemble of superconducting flux qubits inductively coupled to a superconducting transmission line. We make use of fully quantum mechanical models which account for decoherence, input and readout to study the behaviour of prototypical 1D and 2D quantum metamaterials. In addition to demonstrating some of the novel phenomena that arise in these systems, such as “quantum birefringence,” we will also discuss potential applications.

10:48AM T25.00015 Development of superconducting transmission-line metamaterials, HAOZHI WANG, FRANCISCO ROUXINOL, B.L.T. PLOURDE, Syracuse University — In recent years, various metamaterials have received substantial attention for their ability to exhibit simultaneous negative permittivity and permeability. Such systems are commonly referred to as left-handed materials and display a variety of counterintuitive properties. We are investigating one-dimensional metamaterials consisting of superconducting circuit elements that operate in the microwave regime. In this talk, we will discuss our efforts to develop a superconducting left-handed transmission line (LHTL) coupled to a coplanar waveguide resonator (right-handed line –RHTL) to create a composite transmission line. Such a structure is predicted to exhibit an intriguing mode structure and we will discuss possible schemes for coupling superconducting qubits to these metamaterials.
6:00AM T26.00001 LeRoy Apker Award Lecture: Coherent control of a semiconductor charge qubit1, YULIYA DOVZHENKO, Department of Physics, Princeton University, New Jersey, 08544 — A charge qubit is formed in a GaAs double quantum dot containing one electron. The two basis states of the qubit correspond to the electron residing in either the left or the right dot. In order to drive coherent rotations of the qubit state, 100 psec timescale voltage pulses are applied to the depletion gates forming the double dot. The resulting charge state is detected by a nearby quantum point contact charge sensor. In contrast with previous work, where a single non-adiabatic pulse was applied for quantum control2, we apply multiple pulses working towards dynamic decoupling3. Data for Ramsey and charge echo pulse sequences are obtained and compared with numerical simulations of the charge qubit evolution4. Coherent multi-pulse control of a semiconductor charge qubit demonstrated in this experiment is an essential requirement for future work in understanding charge noise in semiconductor qubits and improving the fidelity of spin qubit operations.

1In collaboration with J. Stehlik, K. D. Petersson, and J. R. Petta. Supported by the Sloan and Packard Foundations, DARPA, and the NSF.

8:36AM T26.00002 Spectroscopy of a many-electron InAs spin-orbit qubit1, J. STEHLIK, M.D. SCHROER, K.D. PETERSSON, M. JUNG, J.R. PETTA, Department of Physics, Princeton University, Princeton, NJ 08544, USA — The ability to perform arbitrary single spin rotations is a crucial ingredient for solid state quantum computation using electron spins. However, achieving rapid and selective single spin rotations has been challenging. Strong spin-orbit materials are very promising in this regard, as the spin-orbit interaction can turn a periodic electric driving field into an effective oscillating magnetic field through a process called electric dipole spin resonance (EDSR). In this work we explore EDSR in an InAs nanowire spin-orbit qubit. The qubit is implemented using a many-electron double quantum dot (DQD) and is configured in Pauli-blockade, where electron transport is highly sensitive to processes that rotate spin. We use EDSR to probe the detailed level structure of the DQD. We find a strong current response in several regions of the parameter space, raising the prospects for fast spin rotations.

1Research supported by the Sloan and Packard Foundations, the NSF, and the Army Research Office.

8:48AM T26.00003 Pulse-gated quantum dot hybrid qubit1, S.N. COPPERSMITH, TECK SENG KOH, JOHN KING GAMBLE, M.A. ERIKSSON, MARK FRIESEN, Department of Physics, University of Wisconsin-Madison — A quantum dot hybrid qubit formed from three electrons in a double quantum dot has the potential for great speed, due to presence of level crossings where the qubit becomes charge-like. Here, we show how to exploit the level crossings to implement fast pulsed gating. We develop one- and two-qubit dc quantum gates that are simpler than the previously proposed ac gates [1]. We obtain closed-form solutions for the control sequences and show that the gates are fast (sub-nanosecond) and can achieve high fidelities.

1Work supported by ARO (W911NF-08-1-0482) and NSF (DMR-0805045, PHY-1104660), and the National Science Foundation Graduate Research Fellowship (DGE-0718123).

9:00AM T26.00004 Enhanced Coherence and High Figure of Merit in a Silicon Charge qubit1, ZHAN SHI, CHRISTIE SIMMONS1, DANIEL WARD, JONATHAN FRANCE2, TECK SENG KOH, JOHN GAMBLE, XIAN WU, DONALD SAVAGE, MAX LAGALLY, MARK FRIESEN, SUSAN COPPERSMITH, MARK ERIKSSON, University of Wisconsin-Madison — Coherent manipulation of a charge qubit is an essential step in the use of pulsed gate voltages [1] to manipulate a quantum dot hybrid spin qubit [2]. Here, we demonstrate coherent manipulation of a charge qubit in Si/SiGe double quantum dot. We perform Larmor oscillations (x-rotations on the Bloch sphere) between the (2,1) and (1,2) charge states, measuring a T2* time of 2.1 ns at the charge degeneracy point. We find an increased coherence time (3.7 ns) and higher figure of merit (37) away from the charge degeneracy point, arising from a second charge anti-crossing involving a low lying excited state in the right dot — the desired structure for a hybrid spin qubit. We also observe Ramsey fringes (z-rotations on the Bloch sphere) and measure a T2* of 179 ps at detunings away from any protective energy level structures.

1Now work at Massachusetts Institute of Technology
2Now work at Lancaster University, UK

9:12AM T26.00005 Multi-electron double quantum dot spin qubits, ERIK NIELSEN, Sandia National Laboratories, JASON KESTNER, University of Maryland, Baltimore County, EDWIN BARNES, SANKAR DAS SARMA, University of Maryland — Double quantum dot (DQD) spin qubits in a solid state environment typically consist of two electron spins confined to a DQD potential. We analyze the viability and potential advantages of DQD qubits which use greater than two electrons, and present results for six-electron qubits using full configuration interaction methods. The principal results of this work are that such six electron DQDs can retain an isolated low-energy qubit space that is more robust to charge noise due to screening.

Sandia National Laboratories is a multi-program laboratory managed and 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-AC04-94AL85000.
9:24AM T26.00006 Charge noise and dynamical decoupling in singlet-triplet spin qubits1. GUY RAMON, Santa Clara University — We consider theoretically the effects of an ensemble of fluctuating charges on the coherence of a singlet-triplet qubit in gate-defined double quantum dots. We predict a crossover behavior of the system between non-Gaussian noise and 1/f spectrum, going from mesoscopic single-qubit devices to multi-qubit larger devices. With increasing size of the fluctuator ensemble we find a narrowed distribution of qubit dephasing times that result from random sets of fluctuators. At the same time the noise becomes Markovian with a characteristic Gaussian spectrum and it is dominated by a large collection of weakly-coupled fluctuators. The efficiency of dynamical decoupling pulse sequences in the qubit is examined as a function of the qubit's working position and the fluctuator ensemble size. Analytical solutions for qubit dephasing in the limits of weak and strong qubit-fluctuator coupling shed light on the distinct dynamics at different parameter regimes.

1Supported by Research Corporation

9:36AM T26.00007 Relaxation in quantum dots due to evanescent-wave Johnson noise from a metallic backgate1, LUKE LANGJSJOEN, AMRIT POULDE, MAXIM VAVILOV, ROBERT JOYNT, University of Wisconsin - Madison — This talk will present a study of decay of coherence in charge and spin qubits due to evanescent-wave Johnson noise (EWJN) in a laterally coupled double quantum dot and single quantum dot, respectively. The high density of evanescent modes in the vicinity of metallic gates causes energy relaxation and a loss of phase coherence of electrons trapped in quantum dots. These energy relaxation rates are derived, and EWJN is shown to be a dominant source of decoherence for spin qubits held at low magnetic fields. Previous studies in this field approximated the charge or spin qubit as a point dipole. Ignoring the finite size of the quantum dot in this way leads to a spurious divergence in the relaxation rate as the qubit approaches the metal. Our approach goes beyond the dipole approximation and remedies this unphysical divergence by taking into account the finite size of the quantum dot.

1This work was supported by ARO and LPS grant no. W911NF-11-1-0030 and NSF grant DMR 0955500.

9:48AM T26.00008 Charge noise and spin noise in a semiconductor qubit. RICHARD WARBURTON, ANDREAS KUHLMANN, JULIEN HOUEL, Department of Physics, University of Basel, Switzerland, ARNE LUDWIG, ANDREAS WIECK, Ruhr University Bochum, Germany — Developing semiconductor spin qubits involves dealing with noise. Spin noise arising from the fluctuating nuclear spins results in electron spin dephasing and decoherence. Charge noise also results in dephasing and decoherence via the spin-orbit interaction and the electric field dependence of the g-factors. We have used resonance fluorescence from a single optically-active quantum dot as a local, minimally-invasive probe of the noise. Our technique is sensitive to 4 decades of noise over 6 decades of frequency. We present a method which allows us to distinguish between charge noise (a fluctuating electrostatic potential) and spin noise (a fluctuating effective magnetic field): we show how the two noise sources result in different optical signatures. The charge noise dominates at low frequencies, the spin noise at higher frequencies. The charge noise spectrum following neither a Lorentzian nor a 1/f-behaviour can be understood by considering an ensemble of 2-level fluctuators located close to the quantum dot. Crucially, both sources of noise decrease rapidly with increasing frequency. The consequences for the quantum dot are profound: at high frequencies (above 10 kHz) the noise is sufficiently small that we achieve ideal optical linewidths (the Fourier transform limit).

10:00AM T26.00009 Leakage-current lineshapes from inelastic cotunneling in the Pauli spin blockade regime2. FARZAD QASSEMI, Inst for Quantum Computing, University of Waterloo, Waterloo, Canada, BILL COISH, Department of Physics, McGill University, Montreal, Canada — We find the leakage current through a double quantum dot in the Pauli spin blockade regime accounting for inelastic (spin-flip) cotunneling processes. Taking the energy-dependence of this spin-flip mechanism into account allows for an accurate description of the current as a function of applied magnetic fields, gate voltages, and an inter-dot tunnel coupling. In the presence of an additional local dephasing process or nonuniform magnetic field, we obtain a simple closed-form analytical expression for the leakage current giving the full dependence on an applied magnetic field and energy detuning. This work is important for understanding the nature of leakage, especially in systems where other spin-flip mechanisms (due, e.g., to hyperfine coupling to nuclear spins or spin-orbit coupling) are weak, including silicon and carbon-nanotube or graphene quantum dots.


2We acknowledges funding from the CIFAR JFA, NSERC, FQRNT, and INTRIQ.

10:12AM T26.00010 Reweighting of charge occupation in charge stability diagrams due to finite temperature effect and asymmetric tunnel rates in a silicon MOS double quantum dot1. KHOI NGUYEN, MICHAEL LILLY, NATHANIEL BISHOP, ERIK NIELSEN, RAJIB RAHMAN2, JOEL WENDT, JASON DOMINGUEZ, TAMMY PLUYM, JEFF STEVENS, GREG TEN EYCCK, MALCOLM CARROLL, Sandia National Laboratories, Albuquerque, NM 87185 — The combination of asymmetric tunnel rates and finite temperature can shift the average charge occupation within a double quantum dot (DQD) stability diagram. DQD charge sensing shows the transitions in electron occupation dependence on gate bias. Applied source-drain bias further introduces shifts in the charge transition lines including the formation of bias triangles. In some material systems, tunnel barrier uniformity can be difficult to achieve. Asymmetry in tunnel barriers can lead to vanishingly small transitions in regions. Finite temperature effects with asymmetric barriers further leads to kinks in the stability diagram. In this talk we present measurements of DQDs with asymmetric barriers and compare them to simulation of stability diagrams using a capacitance network including the rate equation and temperature dependent tunneling. The model provides quantitative insight about finite temperature effects as well as the vanishing charge transition lines that is not readily available in the literature.

1Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s NNSA under contract DE-AC04-94AL85000.

2Now at Purdue University

10:24AM T26.00011 Integration of on-chip FET switches with dopantless Si/SiGe quantum dot structures for high throughput testing, DANIEL WARD, DONALD SAVAGE, MAX LAGALLY, SUSAN COPPERSMITH, MARK ERIKSSON, University of Wisconsin-Madison — In the last few years, significant research on dopantless Si/SiGe planar quantum dot structures has occurred. One of the limiting factors is that typically only a single double-dot structure can be cooled down in a dilution refrigerator at time due to the limited number of electrical connections available. We report on our recent work to create samples with four sets of double-dots on a single chip that can all be tested in a single cool down through the introduction of on-chip FET switches. In our samples the four double-dot structures have their depletion gates and ohmic contacts connected in parallel, minimizing the number of connections. We energize accumulation gates for the device under test such that the other dot structures do not contribute to the measurements. Our double-dot structures require five accumulation gates, which limits scaling due to limited fringe wiring capacity. To alleviate this problem and to test integration approaches for cryogenic quantum dot devices we fabricated a series of on-chip FET switches to form a multiplexer for the accumulation gates. Using the multiplexer we can wire up four double-dot structures using just 23 connections instead of the 34 required without it. As more devices are added the scaling benefits increase exponentially.
10:36AM T26.00012 Electron transport on ultra thin helium, MAIKA TAKITA, E.Y. HUANG, S.A. LYON, Department of Electrical Engineering, Princeton University — Electrons floating on the surface of superfluid helium have been suggested as promising mobile spin qubits, and they have shown extremely efficient transport above micron-sized helium-filled channels. While the calculated spin decoherence and relaxation times on helium are long, no experimental measurements have been made. Efficient thermalization of the spins is necessary for ESR measurements of their coherence, and a lack of thermalization has hindered these experiments. Bringing electrons onto a thin helium film above a metallic layer will speed spin relaxation due to Johnson noise current in the metal. At the same time, higher electron densities can be supported by thin helium films. Ideally, the electrons could be thermalized on the thin helium film coating a metal surface, and then moved to a helium-filled channel for electrical measurements of their density and the spin measurements. However, roughness of the metal surface severely limits the electron mobility. Preliminary work show that electrons can be transported from one channel, across a helium-coated metal layer, and to the neighboring channel, by creating a smooth transition from the channel to the thin film.

1Present address: Carnegie Mellon University

10:48AM T26.00013 Implementation and test of an Levitov’s n-electron coherent source, D. CHRISTIAN GLATTLI, JULIE DUBOIS, THIBAUT JULLIEN, PREDEN ROULLEAU, FABIEN PORTIER, P. ROCHE, Service de l’Etat Condense CEA Saclay — Injecting a controlled number of electrons in a quantum conductor opens the way to new quantum experiment. It is known that a voltage biased contact applied on a single mode quantum conductor, such as a perfectly transmitting Quantum Point Contact (QPC), continuously injects single electrons at a rate eV/h. Here we consider the injection of n electrons using a short time voltage pulse with \( \int eV(t) dt = nh \). When the voltage pulse has a Lorentzian shape, L. Levitov et al. [1] have shown that the n-electron injection is free of extra neutral electron-hole pairs and is a minimal excitation state. We present the first realization of Levitov’s proposal. Using periodic voltage pulses applied on a contact of a 2DEG, a coherent train of n-electrons is send to a QPC which acts as an electron beam splitter. By measuring the shot noise resulting from the partitioning of all excitations we demonstrate that Lorentzian pulses are minimal excitation states. This is complemented by energy domain study of the excitations using shot noise spectroscopy and by a time-domain study using shot noise in a Hong-Ou-Mandel like n-electron collision experiment.


Thursday, March 21, 2013 8:00AM - 11:00AM — Session T27 GQI: Focus Session: Superselection and Quantum Reference Frames 329 - Ian Durham, Saint Anselm College

8:00AM T27.00001 Quantum frameness for charge-parity-time inversion symmetry, BARRY SANDERS, University of Calgary — Physical laws are invariant under simultaneous charge-parity-time (CPT) inversion, which is due to relativistic Lorentz covariance and the linearity of quantum mechanics. We show that CPT-superselection can be circumvented by employing a system that possesses CPT frameness, and we construct such resources in two cases: for massive spin-zero particles and for Dirac-spinors. In the case of spin-zero particles, we explicitly construct and quantify all resourceful pure states. Our approach is to treat CPT inversion unitarily by considering the aggregate action of the CPT transformation, rather than sequentially composing a unitary and two anti-unitary transformations, thereby overcoming a major drawback of circumventing time-inversion symmetry alone using an anti-unitary transformation [G. Gour, P. S. Turner and B. C. Sanders, J. Math. Phys. 50, 102105 (2009)]. We discuss an explicit example using pionic communication to overcome CPT superselection.

1Supported by AITF, NSERC and CIFAR
2Collaboration with Michael Skotiniotis, Borzumehr Toloui, and Ian Durham

8:36AM T27.00002 The capacity to transmit classical information via black holes, CHRISTOPH ADAMI, Michigan State University, GREG VER STEEG, University of Southern California — One of the most vexing problems in theoretical physics is the relationship between quantum mechanics and gravity. According to an argument originally by Hawking, a black hole must destroy any information that is incident on it because the only radiation that a black hole releases during its evaporation (the Hawking radiation) is precisely thermal. Surprisingly, this claim has never been investigated within a quantum information-theoretic framework, where the black hole is treated as a quantum channel to transmit classical information. We calculate the capacity of the quantum black hole channel to transmit classical information (the Holevo capacity) within curved-space quantum field theory, and show that the information carried by late-time particles sent into a black hole can be recovered with arbitrary accuracy, from the signature left behind by the stimulated emission of radiation that must accompany any absorption event. We also show that this stimulated emission turns the black hole into an almost-optimal quantum cloning machine, where the violation of the no-cloning theorem is ensured by the noise provided by the Hawking radiation. Thus, rather than threatening the consistency of theoretical physics, Hawking radiation manages to save it instead.

8:48AM T27.00003 Constructing holographic spacetimes using entanglement renormalization, BRIAN SWINGLE, Harvard — We elaborate on our earlier proposal connecting entanglement renormalization and holographic duality in which we argued that a tensor network can be reinterpreted as a kind of skeleton for an emergent holographic space. Here we address the question of the large N limit where on the holographic side the gravity theory becomes classical and a non-fluctuating smooth spacetime description emerges. We show how a number of features of holographic duality in the large N limit emerge naturally from entanglement renormalization, including a classical spacetime generated by entanglement, a sparse spectrum of operator dimensions, and phase transitions in mutual information. We also address questions related to bulk locality below the AdS radius, holographic duals of weakly coupled large N theories, Fermi surfaces in holography, and the holographic interpretation of branching MERA. Some of our considerations are inspired by the idea of quantum expanders which are generalized quantum transformations that add a definite amount of entropy to most states. Since we identify entanglement with geometry, we thus argue that classical spacetime may be built from quantum expanders (or something like them).

1BGS is supported by the Simons Foundation
9:00AM T27.00004 Quantifying asymmetry of quantum states using entanglement,
BORZU TOLoui, Departments of Physics and Astronomy, Haverford College — For open systems, symmetric dynamics do not always lead to conservation laws. We show that, for a dynamic symmetry associated with a compact Lie group, one can derive new selection rules from entanglement theory. These selection rules apply to both closed and open systems as well as reversible and irreversible time evolutions. Our approach is based on an embedding of the system’s Hilbert space into a tensor product of two Hilbert spaces allowing for the symmetric dynamics to be simulated with local operations. The entanglement of the embedded states determines which transformations are forbidden because of the symmetry. In fact, every bipartite entanglement monotone can be used to quantify the asymmetry of the initial states. Moreover, where the dynamics is reversible, each of these monotones becomes a new conserved quantity.

This research has been supported by the Institute for Quantum Information Science (IQIS) at the University of Calgary, Alberta Innovates, NSERC, General Dynamics Canada, and MITACS.

Joint work with Gilad Gour.

9:36AM T27.00005 How hard is it to decide if a quantum state is separable or entangled?
MARK WILDE, PATRICK HAYDEN, KEVIN MILNER, McGill University — Suppose that a physical process, described as a sequence of local interactions that can be executed in a reasonable amount of time, generates a quantum state shared between two parties. We might then wonder, does this physical process produce a quantum state that is separable or entangled? Here, we give evidence that it is computationally hard to decide the answer to this question, even if one has access to the power of quantum computation. In order to address this question, we begin by demonstrating a two-message quantum interactive proof system that can decide the answer to a promise version of this problem. We then prove that this promise problem is hard for the class “quantum statistical zero knowledge” (QSZK) by demonstrating a polynomial-time reduction from the QSZK-complete promise problem “quantum state distinguishability” to our quantum separability problem. Finally, we consider a variant of this question, in which a given physical process accepts a quantum state as input, and the question is to decide if there is an input to this process which makes its output separable across some bipartite cut. We prove that this latter problem is a complete promise problem for the class QIP of problems admitting quantum interactive proof systems.

9:48AM T27.00006 Operator extension of strong subadditivity of entropy
ISAAC KIM, California Institute of Technology — We prove an operator inequality that extends strong subadditivity of entropy: after taking a trace, the operator inequality becomes the strong subadditivity of entropy.

10:00AM T27.00007 Measuring Entanglement via SICs and 2-designs
MATTWEN GRAYDON, University of Waterloo, Perimeter Institute for Theoretical Physics, Institute for Quantum Computing, MARCUS APPLEBY, Perimeter Institute for Theoretical Physics — We consider measuring entanglement via the classical quadratic Rényi entropy of joint probability distributions over the measurement outcomes associated with tensor products of elements of local positive operator valued measures (POVMs). We examine the case of pure $d \times d$ bipartite quantum states and identical local POVMs. In this case, we prove that if the local POVMs are rank 1, then the classical quadratic Rényi entropy of such a distribution (denoted by $H$) is independent of the underlying Schmidt bases if and only if the local POVMs are equivalent to spherical 2-designs. We also prove that if the local POVMs admit a cardinality equal to the composite Hilbert space dimension, then $H$ is independent of the underlying Schmidt bases if and only if the local POVMs are symmetric informationally complete POVMs of arbitrary rank. We show that different degrees of entanglement correspond to distinct spheres within the corresponding joint probability simplexes. Furthermore, we derive a separability criterion for mixed isotropic quantum states in terms of probabilities for outcomes of generalized quantum measurements constructed from tensor products of elements of local POVMs formed from spherical 2-designs.

This work was supported in part by the U. S. Office of Naval Research (Grant No. N00014-09-1-0247), by the Government of Canada through NSERC, and by the John Templeton Foundation.

10:12AM T27.00008 Do emergent entangled coherent Glauber states violate the no-signaling theorems of quantum theory?
JACK SARFATTI, ISEP — Quantum information theory assumes entanglement cannot be used as a direct stand-alone-communication channel with a light speed limited retarded signal key to unlock the message encrypted in the correlation pattern. This pre-supposes orthogonal base states for the entangled subsystems. Macro-quantum coherent Glauber states emerge as ground/vacuum states in spontaneous quantum interactive proof systems without a light speed limited retarded signal key to unlock the message encrypted in the correlation pattern. This of generalized quantum measurements constructed from tensor products of elements of local POVMs formed from spherical 2-designs.

Emergent spontaneous symmetry breakdown violates the probability interpretation of orthodox quantum theory. It represents an extension of quantum theory in the same way that gravity required an extension of special relativity limiting it to coincident local inertial frames.

10:24AM T27.00009 Entanglement witnesses for many qubit systems
JUSTYNA ZWOLAK, Oregon State University, DARIUSZ CHRUŚCINSKI, Nicolaus Copernicus University — Entanglement is one of the essential features of quantum physics and is fundamental to future quantum technologies. The characterization of entanglement has been shown to be equivalent to the characterization of positive, but not completely positive, maps (PnCP) over matrix algebras. In the cases of $2 \times 2$ and $2 \times 3$ dimensional spaces there exist complete characterization of the separability problem (due to the celebrated Peres-Horodecki criterion). However, for increasingly higher dimensions this task becomes more and more difficult. There has been a considerable effort devoted to constructing PnCP, but a general procedure is still not known. Recently we were able to generalize the Robertson map in a way that naturally meshes with $2^N$ qubit systems, i.e., its structure respects the $2^{2N}$ growth of the state space. We proved that this map is positive, but not completely positive, indecomposable and optimal, and as such can be used to detect (bipartite) entanglement. We also determined the relation our maps to entanglement breaking channels. We will discuss these new classes of entanglement witnesses.

10:36AM T27.00010 Measurement-Induced Non-locality in an $n$-partite quantum state
PRAMOD JOAG, Professor, Department of Physics, University of Pune, ALI HASSAN, Associate Professor Department of Physics, University of Amran — We generalize the concept of measurement-induced non-locality (MIN) to $n$-partite quantum states. We get exact analytical expressions for MIN in an $n$-partite pure and $n$-qubit mixed state. We obtain the conditions under which MIN equals geometric quantum discord in an $n$-partite pure state and an $n$-qubit mixed state. We obtain an exact (computable) relation between MIN and entanglement (concurrence) for a bipartite pure state.
10:48AM T27.00011 Zitterbewegung in Cold Atoms1, POLIANA PENTEADO, J. CARLOS EGUES, Institute of Physics of São Carlos, University of São Paulo — In condensed matter systems, the coupling between spatial and spin degrees of freedom through the spin-orbit (SO) interaction offers the possibility of manipulating the electron spin via its orbital motion. The proposal by Datta and Das [1,2] of a ‘spin transistor’ for example, highlights the use of the SO interaction to control the electron spin via electrical means. Recently, arrangements of crossed lasers and magnetic fields have been used to trap and cool atoms in optical lattices and also to create light-induced gauge potentials [3], which mimic the SO interactions in real solids. In this work, we investigate the Zitterbewegung in cold atoms by starting from the effective SO Hamiltonian derived in Ref. [4]. Cross-dressed atoms as effective spins can provide a proper setting in which to observe this effect, as the relevant parameter range of SO strengths may be more easily attainable in this context. We find a variety of peculiar Zitterbewegung orbits in real and pseudo-spin spaces, e.g., cycloids and ellipses - all of which obtained with realistic parameters.

1This work is supported by FAPESP, CAPES and CNPq.

8:00AM T41.00001 Surprises in three-mode quantum optomechanics: adiabatic quantum state transfer and entanglement by dissipation , AASHISH CLERK, Department of Physics, McGill University — The canonical quantum optomechanical system involves a single mechanical resonator interacting with photons in a single mode of a resonant cavity. Attention has recently turned to the additional rich physics possible in systems with many interacting vibrational and photonic modes. In this talk, I’ll discuss theoretical work looking at the simplest step in this direction, optomechanical systems with three modes (2 photonic and one mechanical or vice-versa). With appropriate driving, the existence of a “mechanical dark mode” in such systems can allow for efficient quantum state transfer that is resilient against mechanical dissipation, similar to adiabatic population transfer schemes in atomic physics. With an alternate choice of driving, the same system can be used to generate a surprisingly large amount of entanglement. This occurs via a dissipative mechanism where one mode in the system acts as an effective bath for the two modes that are to be entangled.

8:36AM T41.00002 Optomechanical transducer for microwave-to-optical photon conversion1, J. BOCHMANN, A. VAINSENCHER, D.D. AWSCHALOM, A.N. CLELAND, Department of Physics and California Nanosystems Institute, University of California, Santa Barbara — Mechanical resonators with highly confined optical and mechanical modes exhibit strong interaction between phonons and photons. At GHz mechanical frequencies and low temperature, nanomechanical resonators enter the quantum regime and can be interfaced with superconducting quantum circuits [1]. Here, we present the concept of a quantum transducer between microwave and optical photons. In our approach, the piezoelectric effect maps microwave quantum states to nanomechanical excitations which are up-converted to optical photons by optomechanical interaction. The exceptional properties of aluminum nitride allow the required photonic, nanomechanical and piezoelectric functionality to be integrated in one platform. Experimental progress towards this goal will be presented.

1This work is funded through DARPA/DSO.

8:48AM T41.00003 State Transfer between a Mechanical Oscillator and Itinerant Microwave Fields , TAUNO PALOMAKI, JENNIFER HARLOW, JILA, National Institute of Standards and Technology and the University of Colorado, JOHN JOHN TEUFEL, RAYMOND SIMMONDS, National Institute of Standards and Technology, Boulder, KONRAD LEHNERT, JILA, National Institute of Standards and Technology and the University of Colorado — We demonstrate that the state of an itinerant microwave field can be coherently transferred into, stored in, and retrieved from a mechanical oscillator. The mechanical oscillator is coupled to a microwave resonator such that the coupling Hamiltonian is capable of exchanging microwave photons and mechanical phonons by applying a detuned microwave pulse. By shaping the envelope of the detuned microwave pulse, we can ideally capture and release itinerant microwave fields with a particular temporal mode. Crucially, the time to capture and to retrieve the microwave state is shorter than the quantum state lifetime of the mechanical oscillator. Here we demonstrate protocols for optimal transfer and measure their efficiency using coherent states with energy at the single quantum level.

9:00AM T41.00004 Electro-optical transduction via a mechanical membrane , COREY STAMBAUGH, JOHN LAWALL, NIST — Both cavity opto-mechanics and cavity electro-mechanics have been studied as means to achieve ground state cooling of mechanical systems. Recent focus has turned to hybrid systems that attempt to convert photons between microwave and optical frequencies through mechanical transduction. This should allow quantum information stored in an electrical cavity to be transferred optically over longer distances. In this talk we describe our hybrid system, a silicon nitride membrane that is coupled to a piezoelectric element and placed within a high finesse Fabry-Perot cavity. This setup allows us to both sense and perturb the mechanical motion of the membrane. Results regarding the coupling between the different domains and the design strategies to optimize these couplings will be discussed.

9:12AM T41.00005 Dispersive optomechanical coupling between a SiN nanomechanical oscillator and evanescent fields of a silica optical resonator , CHUNHUA DONG, THEIN HTAY OO, VICTOR FIORE, HAILIN WANG, Department of Physics and Oregon Center for Optics University of Oregon, Eugene, Oregon 97403, USA — Tensile stressed SiN nanostrings can feature a picogram effective mass and a mechanical Q-factor exceeding a million. These remarkable nanomechanical oscillators can be dispersively-coupled to an ultra-high finesse optical microresonator via its evanescent field [1]. This composite optomechanical system can potentially lead to a cooperativity that far exceeds that of monolithic optomechanical resonators. Here, we report an experimental study coupling a SiN nanostring to evanescent fields of a whispering gallery mode (WGM) in a silica microsphere. The slight deformation of the microsphere enables us to use free-space optical excitation to probe the optomechanical coupling. The dispersive coupling between a nanostring and the evanescent field of a WGM is generally expected to lead to a red shift in the resonance frequency of the WGM [1]. Our experiments, however, reveal a blue frequency shift of the WGM. Detailed experimental studies and possible physical mechanisms for the blue shift will be presented. 1. G. Anetsberger, et al., Nat. Phys. 5, 909-914 (2009).
9:24AM T41.00006 Cavity optomechanics with silicon nitride sub-wavelength grating membranes. UTKU KEMIKTARAK, MATHIEU DURAND, MICHAEL METCALFE, Joint Quantum Institute, University of Maryland and National Institute of Standards and Technology, JOHN LAWALL, National Institute of Standards and Technology — In the interest of developing a high frequency, low loss, and high reflectivity optomechanical system, we pattern silicon nitride membranes as sub-wavelength diffraction gratings. This allows us to achieve mechanical quality factors reaching $Q = 10^6$, at room temperature, and reflectivities close to $R = 99.8\%$, while simultaneously decreasing the mass of the membrane. We explore the optomechanical interactions, both in the self-oscillation and cooling regimes. In the former regime, we observe a number of mechanical modes competing for self-oscillation and the dynamics of mode competition is determined by the intrinsic damping rates of the mechanical modes and their coupling strengths to the optical mode. In the latter regime, we cool a mechanical mode at 190 kHz from room temperature to below 1 K.

9:36AM T41.00007 Exploiting the nonlinear dynamics of a single-electron shuttle for highly regular current transport. MICHAEL MOECKEL, University of Cambridge, F. MARQUARDT, University of Erlangen, Germany, D. SOUTHWORTH, E. WEIG, University of Munich, Germany — A single-electron shuttle consists of a small metallic island (a quantum dot) resting on a nanomechanical resonator which oscillates between two electrodes. This setup has been suggested as a promising way to deliver single electrons one by one and thereby establish a novel current standard. The precision of charge transport will be determined both by the accuracy of charge quantization in the Coulomb blockade regime and the mechanical frequency. The later is generally affected by several not entirely controllable factors. Among those is the nonlinear dynamics which originates from collisions of the shuttle island with the electrodes at high oscillation amplitudes. Instead of considering this a nuisance, we propose to rather exploit the nonlinearity to fix the oscillation frequency precisely to an external signal via synchronization.

9:48AM T41.00008 Branched comb fingers improve capacitive readout sensitivity to vertical motion in a MEMS sound sensor\(^1\). RICHARD DOWNEY, GAMANI KARUNASIRI, Naval Postgraduate School — A microelectromechanical (MEMS) device that relies on capacitive readout of vertical, out-of-plane displacements can be made more sensitive by replacing the traditional straight comb fingers with a branched design. A branched structure allows for larger capacitors using shorter fingers. When fabrication design rules limit finger length, a branched design can have greater surface area, greater capacitance, and therefore greater sensitivity to vertical displacements. Applying this concept to a MEMS device that relies on capacitive readout of vertical, out-of-plane displacements, we predict and then demonstrate an approximate doubling of signal output.

\(^1\)This work is funded through DARPA/DSO.

10:00AM T41.00009 Optomechanics and integrated photonics and in aluminum nitride\(^1\), A. VAINSENCHER, J. BOCHMANN, D.D. AWSCHALOM, A.N. CLELAND, Department of Physics and California Nanosystems Institute, University of California, Santa Barbara — Integrated photonic devices based on silicon have proven enormously successful, with low loss and high confinement optical and optomechanical devices. We show that aluminum nitride is also an excellent material for photonic integrated circuits, with an extremely wide bandgap and very significantly strong piezoelectric and electro-optic effects. Optical-grade AlN can be deposited on substrates with a CMOS-compatible process. We demonstrate integrated photonic circuits and optomechanical devices based on this novel material. Operating in the optical telecommunications band, we demonstrate ring resonators with ultrahigh optical Q factors as well as one-dimensional optomechanical crystals operating in the resolved sideband regime with localized 4 GHz mechanical modes. This talk will present recent results with the eventual goal of integrating these devices with superconducting quantum bits.

10:12AM T41.00010 Control and measurement of an electro-mechanical system with a phase qubit. FLORENT LECOCQ, JOHN TEUFEL, MICHAEL ALLMAN, KATARINA CICAK, FABIO DA SILVA, ADAM SIROIS, JED WHITTAKER, JOE AUMENTADO, RAY SIMMONDS, NIST Boulder — We discuss a hybrid device that merges an electro-mechanical system with a metastable phase qubit. The phase qubit can act as a single photon source and detector, allowing the preparation and readout of a lumped element electrical resonator, whose capacitance is formed by a mechanically compliant vacuum-gap capacitor. Via radiation pressure induced parametric coupling, we can map the quantum state of the 10 GHz electrical resonator on to the long-lived, ∼10 MHz fundamental mode of the mechanical oscillator. This work opens the way toward the preparation of complex phonon states of mechanical motion. We will discuss current progress with this device.

10:24AM T41.00011 Design and Construction of Cryogenic Optomechanical System. DONGHUN LEE, MITCHELL UNDERWOOD, DAVID MÄSON, Department of Physics, Yale University, ANDREW JAYICH, Department of Physics, UCLA, ANYA KASHKANOVA, Department of Physics, Yale University, JACK HARRIS, Department of Physics and Applied Physics, Yale University — One key challenge to observing quantum phenomena in a macroscopic mechanical oscillator is reaching its ground state. To achieve the low temperatures required for this, we utilize resolved sideband laser cooling of a few hundred kHz mechanical oscillator with high mechanical Q (a Si3N4 membrane) inside a high finesse optical cavity, in addition to cryogenically reducing the bath temperature. Realizing high Q and high finesse cavity optomechanical devices in a cryogenic environment requires overcoming a number of challenges. In this talk, we describe the design and construction of such a device working at a bath temperature of 300 mK (in a 3He refrigerator) and suited for operation at lower temperatures (in a dilution refrigerator). The design incorporates in-situ commercial piezo actuators (manufactured by Janssen Precision Engineering) to couple externally prepared laser light into the cold optical cavity. The design also incorporates filtering cavities to suppress classical laser noise, and acoustic and seismic isolation of the experiment.

10:36AM T41.00012 Two-tone experiments and time domain control in circuit nanoelectromechanics. F. HOCHE, H. HUEBL, Walther-Meissner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany, X. ZHOU, A. SCHLIESSER, T. J. KIRCHENBERG, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland; Max-Planck-Institut für Quantenoptik, Garching, Germany, R. GROSS, Walther-Meissner-Institut, Bayerische Akademie der Wissenschaften and Physik-Department TU München, Garching, Germany — In the field of optomechanics, a light field trapped in an optical resonator dynamically interacts with a mechanical degree of freedom, enabling cooling and amplification of mechanical motion. This concept of light matter interaction can be transferred to the microwave (MW) regime combining superconducting MW circuits with nanometer-sized mechanical beams, establishing the class of circuit nano-electromechanics. Here, two-tone spectroscopy is a tool to access a wider class of phenomena, employing interference of a pump and a probe tone inside the MW cavity. We discuss electromechanically induced transparency and electromechanically induced absorption employing continuous and pulsed excitation. With the latter technique, we access the dynamics of the hybrid system revealing that the switching dynamics of the transmitted light are not limited by the time constant imposed by the mechanical beam, the slowing of light pulses, and the phonon repopulation of a precooled mechanical mode due to thermal decoherence [1,2]. Our experiments provide a key tool towards full quantum control of electromechanical systems, including squeezing, state transfer and entanglement between mechanical and optical degree of freedom. [1] X. Zhou et al. arXiv:1206.6052 [2] F. Hoc et al. arXiv:1209.4470
Gambetta, IBM

We present a scheme to squeeze the even mode of the state of the resonators and consequently reduce the noise in the measurement of the magnetic flux threading the SQUID. We finally analyze the effect of dissipation on the squeezing using the quantum master equation, and show the qualitatively different behavior for the weak and strong damping regimes. Our predictions can be tested using current experimental capabilities.

Thursday, March 21, 2013 11:15AM - 2:15PM –
Session U4 DCMP GQI: Invited Session: Quantum Reservoir Engineering and Feedback Ballroom IV - Steven Girvin, Yale University

11:15AM U4.00001 Cavity-assisted quantum bath engineering1, KATER MURCH, QNL, UC Berkeley — In practice, quantum systems are never completely isolated, but instead interact with degrees of freedom in the surrounding environment, eventually leading to decoherence. Precision measurement techniques such as nuclear magnetic resonance and interferometry, as well as envisioned quantum schemes for computation, simulation, and data encryption, rely on the ability to prepare and preserve delicate quantum superpositions and entanglement. The conventional route to long-lived quantum coherence involves minimizing coupling to a dissipative bath. Paradoxically, it is possible to instead engineer specific couplings to a quantum environment that allow dissipation to actually preserve coherence. I will discuss our recent demonstration of quantum bath engineering for a superconducting qubit coupled to a microwave cavity. By tailoring the spectrum of microwave photon shot noise in the cavity, we create a dissipative environment that autonomously relaxes the qubit to an arbitrarily specified coherent superposition of the ground and excited states. In the presence of background thermal excitations, this mechanism increases the state purity and effectively cools the dressed atom state to a low temperature. We envision that future multi-qubit implementations could enable the preparation of entangled many-body states suitable for quantum simulation and computation.

3This work was supported by the IARPA CSQ program.

11:51AM U4.00002 Quantum measurement in action1, MICHAEL HATRIDGE, Applied Physics, Yale University — A quantum system subject to the infinitely-strong measurement of textbook physics undergoes a discontinuous, random state collapse. However, in practice, measurements often involve a finite-strength, continuous process whose iteration leads to a projective evolution only asymptotically. Moreover, if the observation apparatus is fully efficient informationally, the measured system can remain at all times in a pure state. The stochastic evolution of this pure state is trackable from the measurement record. Thus, an initial superposition of states can be usefully transformed by a partial measurement rather than be entirely destroyed. This striking property has been demonstrated in superconducting qubit experiments in which readout is performed by a microwave signal sent through a cavity dispersively coupled to the qubit, and thereafter processed by an amplifier operating at the quantum limit. Such accurate monitoring of a qubit state is an essential prerequisite for measurement-based feedback control of quantum systems.

1Work supported by: IARPA, ARO and NSF.

12:27PM U4.00003 Quantum feedback control in superconducting qubits: Towards creating and stabilizing entanglement in remote qubits, RAJAMANI VIJAYARAGHAVAN, Tata Institute of Fundamental Research, Mumbai, India — Recent advances in superconducting parametric amplifiers have enabled quantum limited measurements of superconducting qubits, ushering in a new era of measurement based control using quantum feedback. Quantum entanglement is a key aspect of the measurement process. Measurement creates a pointer state which is entangled with the system being measured. Typically, one analyzes the pointer state which in turn determines the state of the original system. I will discuss experiments where we entangle the state of a 3D transmon qubit with a coherent microwave field (the pointer) using the circuit QED architecture. The use of parametric amplifiers to analyze the microwave field enables us to actually observe this entanglement and the resulting strong correlations between the states of the pointer and the qubit. We reconstruct quantum trajectories of the qubit state as it evolves during measurement and show that the final state of the qubit is consistent with the trajectories. Further, we use quantum feedback to actively steer the state of the qubit and demonstrate Rabi oscillations which persist indefinitely [1]. Finally, I will discuss how we can use the pointer states to generate entanglement between remote qubits and stabilize them using feedback. Applications to quantum computing and quantum error correction will also be discussed.


1:03PM U4.00004 Quantum Feedback for preparing and stabilizing photon number states of a field stored in a cavity , MICHEL BRUNE, Laboratoire Kastler Brossel, Paris — The stabilization of complex classical systems requires feedback. A sensor performs measurements of the system's state whose result is fed into a controller, which decides on an action bringing the system closer to a target state. Operating feedback for preparing and stabilizing against decoherence a quantum state is a promising tool for quantum control. It is however much more demanding than its classical counterpart, since a quantum measurement by the sensor changes the measured state. We present the first continuous operation of a closed feedback-loop for preparing and stabilizing photon number states of a microwave field stored in a high Q superconducting cavity. The field is probed by non-resonant Rydberg atoms performing a Quantum Non-Demolition photon counting. The feedback action consists either in the injection of a small coherent field pulse with a controlled amplitude and phase or in the emission and absorption of single photons with individual resonant atoms. The atomic measurement results are fed into a real-time controller, which performs an estimation of the field's state before deciding on the actuator action bringing it closer to the target. We stabilize number states up to 7. We discuss perspectives for the stabilization of mesoscopic quantum superpositions.

1:39PM U4.00005 Experimental quantum error correction with trapped ions , PHILIPP SCHINDLER, University of Innsbruck — The computational potential of a quantum information processor can only be utilized if errors occurring during a quantum computation can be controlled and corrected for. Quantum error correction protocols encode the quantum information of a single qubit in a larger register. Errors are then corrected by a quantum-feedback algorithm that is applied repeatedly. We encode a single logical qubit into three physical qubits and perform multiple rounds of error correction with the aid of high-fidelity gate operations and a reset technique for the auxiliary qubits. Furthermore we demonstrate that the same technique can be used to undo a quantum measurement. Full quantum error correction schemes are able to correct for arbitrary errors and enable universal quantum computation, but they require a significant overhead in the number of qubits. This prevents them to be useful for medium-scale systems used for quantum simulation. Therefore, we develop a quantum feedback scheme to reduce the dominant errors in an open-system quantum simulator. Our scheme requires only a single auxiliary qubit regardless of the system size.

Thursday, March 21, 2013 11:15AM - 2:15PM –
Session U25 GQI: Superconducting Qubits: Qubit-Field Interactions and Qubit Theory 327 - Jay Gambetta, IBM
11:15AM U25.00001 Cavity-Mediated Landau-Zener Interferometry Between Two Superconducting Qubits1

C.M. QUINTANA, K.D. PETERSSON, L.W. MCFAUL, S.J. SRINIVASAN, A.A. HOUCK, J.R. PETTA, Princeton University — Avoided crossings between two energy levels as a function of some external parameter are common to many quantum mechanical systems. In the field of circuit quantum electrodynamics (cQED), the energies of superconducting qubits can be tuned via applied magnetic flux, and a microwave cavity-mediated coupling between two qubits placed in the same resonator leads to an avoided crossing in the system’s energy spectrum when the two singly-excited qubit states become degenerate. We utilize such an avoided crossing between two transmon qubits to explore Landau-Zener transition physics, using nanosecond timescale flux bias pulses to non-adiabatically traverse the avoided crossing. We explore the dynamics of single- and double-passage through the resulting “beam splitter” of two qubit states. In particular, we test the general asymptotic Landau-Zener formula for non-adiabatic transition probabilities and demonstrate the creation of two-transmon entanglement via a single passage through the beam splitter. We also study interference phenomena associated with double passage through the avoided crossing (analogous to an optical interferometer), and explore the dependence of the interference fringes on the level velocity with which the passages are made.

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

11:27AM U25.00002 First-order sideband transitions with flux-driven asymmetric transmons

J.D. STRAND, M.E. WARE, Syracuse University, FELIX BEAUDOIN, McGill University, ALEXANDRE BLAIS, Sherbrooke, T. OHKI, B. JOHNSON, BBN Technologies, B.L.T. POURDEUR, Syracuse University — We present data demonstrating first-order sideband transitions between a qubit and a resonator performed with a digitally synthesized waveform coupled to the qubit loop as a magnetic flux. The resulting first-order sideband transitions are much faster (up to 85 MHz in our measurements) than second-order processes and have the potential to create fast quantum gates. The frequency of the red sideband can also be made quite low, typically a few hundred MHz in our experiment, and at these low frequencies expensive microwave generators are not required, simplifying the control electronics and making the process more scalable. We chose to test this process with asymmetric transmons in which one junction is several times larger than the other. This asymmetry creates a shallow flux modulation curve that is optimum for this flux-driven sideband process.

11:39AM U25.00003 Manipulating Kerr effects in a superconducting cavity via a superconducting qubit

VICTOR V. ALBERT, GERHARD KIRCHMAIR, BRIAN VLASTAKIS, ZAKI LEGHTAS, MAZYAR MIRRAHIMI, S.M. GIRVIN, R.J. SCHOELKOPF, LIANG JIANG, Yale University — Typically, models of qubit-cavity interactions in superconducting circuits have included terms strictly linear in amplitude of the cavity modes. Due to ever-increasing experimental ability to realize larger coupling strengths, induced nonlinearities in the cavity contribute significantly to the dynamics and thus need to be accounted for. Such nonlinearities include interactions between the photon numbers of two cavity modes (cross-Kerr) and between a mode and itself (self-Kerr). Motivated by the recent experimental demonstration of self-Kerr in superconducting cavities, we investigate quantum control of Kerr effects via a dispersive coupled superconducting qubit, which not only enables us to enhance or suppress the Kerr coupling, but also opens the possibility to investigate higher order Kerr effects.

11:51AM U25.00004 Giant Cross Kerr Effect via a Superconducting Artificial Atom

I.-C. HOI, C.M. WILSON, G. JOHANSSON, T. PALOMAKI, Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, Sweden, T.M. STACE, B. FAN, Centre for Engineered Quantum Systems, School of Physical Sciences, University of Queensland, Australia, A. FRISK KOCKUM, L. TORNBERG, P. DELSING, Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, Sweden — We investigate the effective interaction between two microwave fields, mediated by a superconducting artificial atom (transmon qubit) which is strongly coupled to a coplanar transmission line. The interaction between the fields and atom realizes an effective cross Kerr coupling. Using this, we demonstrate average Kerr phase shifts of up to 25 degrees per photon with both coherent microwave fields at the single-photon level. Our results provide an important step towards quantum gates with propagating photons in the microwave regime.

12:03PM U25.00005 Requirements for Electromagnetically Induced Transparency in a Transmon

J.E. ROBINSON, Laboratory for Physical Sciences, College Park, MD, S. NOVIKOV, Z.K. KEANE, B. SURI, Department of Physics, University of Maryland, Laboratory for Physical Sciences, College Park, MD, F.C. WELLSTOOD, Department of Physics, University of Maryland, College Park, MD, B.S. PALMER, Laboratory for Physical Sciences, College Park, MD — In the dressed atom picture, a three-level system can interact with two photons via the AUTLER-Townes (AT) effect, where the system exhibits two peaks separated by the generalized Rabi frequency of the coupling photon. The system can also exhibit electromagnetically induced transparency (EIT), where the first excited state is made transparent to the probe photon by a strong coupling drive. We examine the results from a multi-tone measurement as a transmon qubit coupled to a 3D cavity, which exhibits an AT splitting, as expected from the dressed atom picture, similar to previous results. We will discuss the requirements for a crossover from an AT doublet to an EIT signal, as they relate to the limitations of our device. We will also examine the quantum information implications of realizing EIT in superconducting system.


12:15PM U25.00006 Probing Electromagnetically Induced Transparency in a Transmon

SERGEY NOVIKOV, Dept. of Physics, University of Maryland, J.E. ROBINSON, Laboratory for Physical Sciences, Z.K. KEANE, Dept. of Physics, University of Maryland, Laboratory for Physical Sciences, B. SURI, Dept. of Physics, University of Maryland, F.C. WELLSTOOD, JQI, CNAM, Dept. of Physics, University of Maryland, B.S. PALMER, Laboratory for Physical Sciences — We have designed, fabricated, and measured a transmon made from a single Al/AlOx/Al Josephson-Junction on a sapphire substrate with $\lambda_0 \sim 5 \text{ GHz}$. The transmon was mounted in a 3D microwave cavity (OFHC copper, $f_c \sim 7.5 \text{ GHz}$), similar to other recent experiments. The observed coherence times were $T_1, T_2^\ast \sim 10 \mu\text{s}$ allowing us to investigate the possibility of electromagnetically induced transparency (EIT) and other population trapping effects, such as the AUTLER-Townes (AT) splitting. We will discuss the experiments to look for and distinguish between AT and EIT given the constraints placed by the transmon and the readout limitations imposed by the cavity.


12:27PM U25.00007 cQED Susceptibility of Superconducting Transmons coupled to a Microstrip Resonator Cavat

DAVID PAPPAS, MARTIN SANDBERG, JIANSONG GAO, MICHAEL VISSERS, NIST, ANTON KOCKUM, GORAN JOHANSSON, Chalmers University, NIST COLLABORATION — The light-matter interaction of multi-level transmons strongly coupled to a cavity propagating photons in the microwave regime.

Avoided crossings between two energy levels as a function of some external parameter are common to many quantum mechanical systems. In the field of circuit quantum electrodynamics (cQED), the energies of superconducting qubits can be tuned via applied magnetic flux, and a microwave cavity-mediated coupling between two qubits placed in the same resonator leads to an avoided crossing in the system’s energy spectrum when the two singly-excited qubit states become degenerate. We utilize such an avoided crossing between two transmon qubits to explore Landau-Zener transition physics, using nanosecond timescale flux bias pulses to non-adiabatically traverse the avoided crossing. We explore the dynamics of single- and double-passage through the resulting “beam splitter” of two qubit states. In particular, we test the general asymptotic Landau-Zener formula for non-adiabatic transition probabilities and demonstrate the creation of two-transmon entanglement via a single passage through the beam splitter. We also study interference phenomena associated with double passage through the avoided crossing (analogous to an optical interferometer), and explore the dependence of the interference fringes on the level velocity with which the passages are made.
of the effective hopping matrix elements can be controlled by tuning offset voltages. The circuits could be used for topological quantum computation. We explore the design principles for using these circuits to study many-body physics, for example, explaining how the magnitude and phase of lattice bosons hopping in a magnetic field. For realistic device parameters one can reach the strongly interacting bosonic quantum Hall limit where one will find [2]

A. J. Leggett, Rev. Mod. Phys. 47, 331 (1975)


is by implementing switchable coupling between two microwave resonators. We show experimental progress on two superconducting transmission line resonators, where a superconducting flux qubit mediates a controllable coupling - the Quantum Switch. We show an experimental characterization of such a device and discuss spectroscopic evidence for the switching behavior.

We acknowledge support from the DFG via SFB 631, the German excellence initiative via NIM, and EU projects CQOED, SOLID and PROMISCE, the Basque Foundation for Science, Basque Government IT472-10, and Spanish MICINN FIS2009-12773-C02-01, DZ granted by ARAID

12:51PM U25.00009 Catch-Disperse-Release Readout for Superconducting Qubits1

EYOB A. SETE, ERIC MLINAR, ALEXANDER N. KOROTKOV, University of California, Riverside, ANDREI GALIÀUTDINOV, University of Georgia, Athens, JOHN M. MARTINIS, University of California, Santa Barbara — We analyze a qubit readout scheme for superconducting qubits via controlled capture, dispersion, and release of a microwave field. A tunable coupler is used to decouple the microwave resonator from a transmission line during dispersive interaction with the qubit, thus circumventing the Purcell effect. We show that fast and high-fidelity qubit readout can be achieved for nonlinear dispersive qubit-resonator interaction and for sufficiently adiabatic tuning of the qubit frequency. Interestingly, the Jaynes-Cummings nonlinearity results in quadrature squeezing of the microwave field which leads to a significant decrease in measurement error. The effects of qubit anharmonicity and imperfect quantum efficiency of the microwave amplification on the measurement error are also discussed.

1Supported by IARPA/ARO.

1:03PM U25.00010 Realizing a Deterministic Teleportation Protocol in Superconducting Circuits

LARS STEFFEN, MARKUS OPPLIGER, MATTHIAS BAUR, ARKADY FEDOROV, ANDREAS WALLRAFF, ETH Zurich — Teleportation of a quantum state may be used for distributing entanglement between distant qubits in quantum communication and for realizing universal and fault-tolerant quantum computation. Previously, we have demonstrated the implementation of a teleportation protocol, up to the single-shot measurement step, with superconducting qubits coupled to a microwave resonator [1]. Using full quantum state tomography and calculating the projection of the measured density matrix onto the basis states of two qubits has allowed us to reconstruct the teleported state with an average output state fidelity of 86%. In ongoing experiments we attempt to implement single shot read-out and feedback to perform full deterministic quantum teleportation.


1:15PM U25.00011 Methods for entanglement in circuit QED

FELIX MOTZOI, MOHAN SAROVAR, UC Berkeley, MICHAEL GOERZ, CHRISTIANE KOCH, U. Kassel, BIRGITTA WHALEY, UC Berkeley — We discuss some progress in methods of generating entanglement in superconducting qubit architectures. We focus on the minimal time required to generate a perfect entangler in a given system, specifically by combining simultaneously multiple given forms of coupling. Typically, the different terms will generate different dynamics, and when multiple coupling terms exist, one will have a choice about which local equivalence class to use to generate entanglement. Here, we study the case where we want to simultaneously include the different forms of coupling that will be present in the circuit QED system, such as direct coupling, cavity mediated coupling, or virtual transitions in the multi-qubit space, with similar interaction strengths. No specific gate is targeted, but rather entanglement generation is optimized. Incoherent effects such as measurement/feedback based control can also be included to generate entanglement, even when the qubits are spatially separated (i.e., in different cavities) and no interaction exists.

1:27PM U25.00012 Tuning from coherent interaction to super- and subradiance with artificial atoms in a 1D waveguide

KEVIN LALUMIÈRE, ALEXANDRE BLAIS, Université de Sherbrooke, BARRY C. SANDERS, University of Calgary, ARJAN F. VAN LOO, ARKADY FEDOROV, ANDREAS WALLRAFF, ETH Zurich — Taking advantage of the near ideal spatial mode-matching, strong interaction between light and artificial atoms fabricated in a 1D waveguide has been demonstrated experimentally [1]. Here, we study the situation where multiple and possibly un-identical atoms are fabricated in the same waveguide. We find that atom relaxation and Lamb-shift are modified, leading to collective effects. Depending on the distance between the artificial atoms, or equivalently the phase shift accumulated by light traveling from one atom to another, we find that it is possible to tune between a strong modification of individual atomic relaxation with the formation of sub- and superradiant states, and a strong modification of the Lamb-shift leading to a coherent exchange-type interaction between the atoms. These predictions are based on a master equation derived for an inhomogeneous set of atoms coupled to a transmission line. Comparison with experimental results will be discussed.


1:39PM U25.00013 Quantum dynamics of triplet superconducting circuits

DAVID G. FERGUSON, JENS KOCH, JAMES SAULS, Northwestern University — We generalize the formalism of “circuit quantization” [1] to circuits comprised of spin-triplet superconducting elements. This introduces the dynamics associated with the spin of the Cooper pairs in addition to the phase and charge dynamics. The dynamics of the order parameter for spin-triplet superconductors is encoded in the vector \( \vec{S} \) for the spin-projections of the Cooper pairs, which is coupled to the dynamics of the electronic spin polarization, \( \vec{S} \). At frequencies below the superconducting gap, \( \hbar \omega \ll \Delta \), the classical spin dynamics is described by Leggett’s equations for \( \vec{d} \) and \( \vec{S} \) [2]. Weak spin-orbit coupling \( (\hbar \omega \ll \Delta) \) leads to frequency shifts of the normal-state spin resonance. Quantization of a spin-triplet superconducting circuit is achieved by including the Hamiltonian that generates Leggett’s equations. Analytical and numerical results for the spectra of the quantized Hamiltonians of various circuits are reported. As a case study, we highlight the low energy excitations of two triplet superconductor islands coupled by a Josephson junction.


1Supported by National Science Foundation Grant DMR-1106315.

1:51PM U25.00014 A Vector Potential for Flux Qbits

ELIOT KAPIT, Oxford University, ERICH MUELLER, Cornell University — We design a superconducting circuit, based on three junction flux qubits, in which the motion of magnetic flux mimics the behavior of charged lattice bosons hopping in a magnetic field. For realistic device parameters one can reach the strongly interacting bosonic quantum Hall limit where one will find anyonic excitations. We explore the design principles for using these circuits to study many-body physics, for example, explaining how the magnitude and phase of the effective hopping matrix elements can be controlled by tuning offset voltages. The circuits could be used for topological quantum computation.

2:03PM U25.00015 ABSTRACT WITHDRAWN
Thursday, March 21, 2013 11:15AM - 2:15PM –
Session U26 GQI: Focus Session: Semiconductor Qubits - Impurity Complexes 328 - Kai-Mei Fu,
University of Washington

11:15AM U26.00001 Single-atom spin qubits in silicon1, ANDREW DZURAK, University of New South Wales — Spin qubits in silicon are excellent candidates for scalable quantum information processing (QIP) due to their long coherence times and the enormous investment in silicon MOS technology. Here I discuss qubits based upon single phosphorus (P) dopant atoms in Si [1]. Projective readout of such dopants had proved challenging until single-shot measurement of a single donor electron spin was demonstrated [2] using a single silicon electron transistor (Si-SET) and the process of spin-to-charge conversion. The measurement gave readout fidelities > 90% and spin lifetimes $T_{2e} > 6$ s [2], opening the path to demonstration of electron and nuclear spin qubits in silicon. Integrating an on-chip microwave transmission line enabled single-electron spin resonance (ESR) of the P donor electron. We used this to demonstrate Rabi oscillations of the electron spin qubit, while a Hahn echo sequence revealed electron spin coherence times $T_{2e} > 0.2$ ms [3]. This time is expected to become much longer in isotopically enriched $^{31}$Si devices. We also achieved single-shot readout of the $^{31}$P nuclear spin (with fidelity > 99.6%) by monitoring the two hyperfine-split ESR lines of the P donor system. By applying (local) NMR pulses we demonstrated coherent control of the nuclear spin qubit, giving a coherence time $T_{2e} > 60$ ms.


1Device fabrication was undertaken at the Australian National Fabrication Facility. This work was supported by the Australian Research Council Centre for Quantum Computation and Communication Technology and the U.S. Army Research Office (W911NF-08-1-0527).

T.M. LU, Sandia National Laboratory, N.C. BISHOP, Retired, L.A. TRACY, R. BLUME-KOHOUT, T. PLUYM, J.R. WENDT, J. DOMINGUEZ, M.P. LILLY, M.S. CARROLL, Sandia National Laboratory — We report our measurements of spin life time of an antimony-bound electron in silicon. The device is a double-top-gated silicon quantum dot with antimony atoms implanted near the quantum dot region. A donor charge transition is identified by observing a charge offset in the transport characteristics of the quantum dot. The tunnel rates on/off the donor are first characterized and a three-level pulse sequence is then used to measure the spin populations at different load-and-wait times in the presence of a fixed magnetic field. The spin life time is extracted from the exponential time dependence of the spin populations. A spin life time of 1.27 seconds is observed at $B = 3.25$ T. This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences user facility. The work was supported by the Sandia National Laboratories Directed Research and Development Program. Sandia National Laboratories is a multi-program laboratory managed and 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-AC04-94AL85000.

12:03PM U26.00003 Shuttling electrons on and off As donor atoms in silicon.
A.M. TYRSHKIN, S.A. LYON, Princeton University, C.C. LO, R. LO NARDO, J.I.L. MORTON, University College London, S. SIMMONS, University of Oxford, C.D. WEIS, T. SCHENKEL, Lawrence Berkeley National Laboratory, J. BOKOR, University of California Berkeley, J. MEIJER, D. ROGALLA, Ruhr-Universitat Bochum — Hybrid quantum devices where electron spins are used for state initialization, fast manipulation, long range entanglement and detection, while nuclear spins are used for long term storage promise revolutionary advantages. Here we report our first experiments using a silicon-based device that utilizes electron and nuclear spins of arsenic donors. The device is a large-area, parallel-plate capacitor fabricated on a silicon-on-insulator (SOI) wafer where the SOI layer is implanted with arsenic donors, and a back gate is formed in the silicon below the buried oxide by a high-energy boron implantation. The electrons can be controllably stripped from the donors and then reintroduced to the ionized donors by applying appropriate gate voltages. We use ensemble ESR experiments (X-band, magnetic field of 0.35 T) to track the occupancy of the donors during these operations. Pulsed ESR is used to characterize the spin state of the donor electrons and the effect of applied electric fields below the ionization threshold. The spin state of the arsenic nuclei, and the effect of electron removal and reintroduction on the nuclear state is expected to be observable in pulsed ENDOR experiments. The work is funded by LPS and NSF-MWN.

12:15PM U26.00004 Electronic structure of sub-surface Boron acceptors in silicon for potential qubits.
RAJIB RAHMAN, Purdue University, West Lafayette, IN 47906, USA, JAN MOL, University of New South Wales, Sydney 2052, Australia, GERHARD KLIMECK, Purdue University, West Lafayette, IN 47906, USA, SVEN ROGGE, University of New South Wales, Sydney 2052, Australia — Single acceptors in silicon are investigated as potential qubits. Due to the p-type nature of the valence band (VB), the acceptor states are less susceptible to the hyperfine interaction of the neighboring nuclear spins. The presence of a stronger spin-orbit coupling in the VB also enables the possibility of an all-electric qubit control. Whereas donor qubits exhibit exchange oscillation with separation distance due to conduction band valleys, Boron acceptors are expected to have smoother exchange curves. We investigate the electronic structure of single Boron acceptors in silicon in the presence of electric field, strain, magnetic field, and interfaces. Bulk Boron acceptors have a four-fold degenerate ground state 45 meV above the VB with angular momentum states of $3/2$ and $1/2$. An interface splits this degeneracy, by an electric field, strain or confinement, lifts this degeneracy, resulting in two Kramers doublets. The states within these isolated Kramers doublets be used to store bits of quantum information for several $\mu$s. Strong coupling of spin and momentum in the silicon valence band allows for rapid electrical manipulation of the hole spin. Acceptors in silicon have a four-fold degenerate ground-state, reflecting character of the top of the valence band. Symmetry breaking, by an electric field, strain or confinement, lifts this degeneracy, resulting in two Kramers doublets. The states within these isolated Kramers doublets are protected against decoherence by time reversal symmetry and form the working levels of a hole spin qubit. Here we investigate the effect of the presence of an interface on the ground-state energy splitting of individual sub-surface acceptors, as a function of dopant depth, by means of low temperature scanning tunneling spectroscopy. The depth of individual acceptors is determined by probing the Coulomb potential of the ionized acceptor nuclei. Resonant tunneling through the localized acceptor states provides a direct measure of the excited state spectrum of single dopants.

JAN MOL, JOSEPH SALFI, University of New South Wales, RAJIB RAHMAN, Purdue University, SVEN ROGGE, University of New South Wales — Single dopants in silicon form a particular attractive platform for hosting spin quantum bits (qubits). The effective spin-3/2 states of acceptor-bound holes in silicon can be used to store bits of quantum information for several $\mu$s. Strong coupling of spin and momentum in the silicon valence band allows for rapid electrical manipulation of the hole spin. Acceptors in silicon have a four-fold degenerate ground-state, reflecting character of the top of the valence band. Symmetry breaking, by an electric field, strain or confinement, lifts this degeneracy, resulting in two Kramers doublets. The states within these isolated Kramers doublets are protected against decoherence by time reversal symmetry and form the working levels of a hole spin qubit. Here we investigate the effect of the presence of an interface on the ground-state energy splitting of individual sub-surface acceptors, as a function of dopant depth, by means of low temperature scanning tunneling spectroscopy. The depth of individual acceptors is determined by probing the Coulomb potential of the ionized acceptor nuclei. Resonant tunneling through the localized acceptor states provides a direct measure of the excited state spectrum of single dopants.
12:39PM U26.00006 Towards isolating a single impurity-bound hole  
RUSSELL BARBOUR, TODD KARIN, KAI-MEI FU, University of Washington, YOSHIRO HIRAYAMA, Tohoku University, ARNE LUDWIG, ANDREAS WIECK, Ruhr-Universität Bochum — Single acceptor-bound holes embedded in III-V semiconductor quantum wells could provide an ideal qubit system for scalable quantum information processing and quantum computation. This system combines strong homogenous optical transitions and millisecond long spin coherence times in a fabrication ready material (GaAs). However, single acceptor-bound excitons (A\textsuperscript{X}) have yet to be optically isolated even in the purest bulk GaAs samples. This is primarily due to the high acceptor density (10\textsuperscript{14} cm\textsuperscript{-3}) and exceptional homogeneity. We propose using stimulated emission depletion microscopy (STED) to increase our optical resolution far beyond the diffraction limit in order to spatially isolate a single acceptor-bound exciton. We report the first demonstration of stimulated emission of acceptor-bound excitons at 4.2 K. We resonantly excite the A\textsuperscript{1s}-A\textsuperscript{X} transition and apply a second laser with high power (P\textsuperscript{2}=10mW) resonant with the 2s two-hole transition (THT). We observe a 30 percent reduction in the 1s PL intensity when the STED laser is resonant with the THT's. We will present our two-laser spectroscopy work that explores this coherent system and discuss our progress towards isolating a single acceptor-bound exciton using STED microscopy.

12:51PM U26.00007 Ultrafast coherent optical control of a single diamond spin\textsuperscript{1}  
L.C. BASSETT, F.J. HEREMANS, D.D. AWSCHALOM, Center for Spintronics and Quantum Computation, University of California, Santa Barbara, California 93106, G. BURKARD, Department of Physics, University of Konstanz, D-78457 Konstanz, Germany — As an optically addressable solid-state electronic spin, the nitrogen-vacancy (NV) center in diamond has great promise for applications in quantum information science and metrology. At temperatures below \approx 10 K, the NV center's optical fine structure facilitates coherent coupling between the electronic spin and light, providing the means for all-optical spin control and other applications in quantum optics. Here, using ultrafast optical pump-probe techniques, we investigate the interplay of orbital, vibrational, and spin dynamics on timescales ranging from femtoseconds to nanoseconds. These techniques provide a flexible and powerful probe of orbital dynamics in the NV center's optically excited state, and enable optical spin control with sub-picosecond resolution.

\textsuperscript{1}Work supported by AFOSR, ARO, and DARPA.

1:03PM U26.00008 All-optical quantum dynamical control of an NV center spin in diamond\textsuperscript{1}  
B.B. BUCKLEY, C.G. YALE, D.J. CHRISTLE, F.J. HEREMANS, L.C. BASSET, D.D. AWSCHALOM, Center for Spintronics and Quantum Computation, University of California, Santa Barbara, California 93106, G. BURKARD, Department of Physics, University of Konstanz, D-78457 Konstanz, Germany — The nitrogen-vacancy (NV) center in diamond has emerged as a promising optically addressable qubit candidate, but optical methods are usually used only for spin initialization and readout through the defect's spin-dependent inter-system crossing (ISC) transition. Quantum dynamical control typically requires the application of microwave magnetic fields, limiting possible applications. Here, we demonstrate an all-optical method for unitary, arbitrary-axis spin control of single NV spins below 10 K based on stimulated Raman scattering. Using our recently-demonstrated arbitrary-basis spin initialization and readout, we perform time-domain spin coherence measurements on single NV center spins solely with optical pulses. These techniques enable individual addressing of proximal NV center spins and could be used to probe other previously-inaccessible defect spin systems without ISC spin addressability.

\textsuperscript{1}Work supported by AFOSR, ARO, and DARPA.

1:15PM U26.00009 Experimental control of a nuclear spin quantum register in diamond with decoherence-protected gates  
TIM HUGO TAMINIAU, TOENO VAN DER SAR, Kavli Institute of Nanoscience, Delft, V. V. DOBROVITSKII, Ames Laboratory and Iowa State University, RONALD HANSON, Kavli Institute of Nanoscience, Delft — Nuclear spins are one of the most promising candidates for long-lived quantum bits that store and process quantum information. Individual nuclear spins in diamond have been addressed using the nearby electron spin of a nitrogen vacancy center. However, the relatively fast decoherence of the electron spin limits coherent control to the nearest, strongly coupled, nuclear spins. Here, we employ decoherence-protected gates\textsuperscript{[1]} to access individual spins embedded in a bath of nuclear spins that are weakly coupled to an electron spin\textsuperscript{[2]}. We demonstrate the initialization, control and readout of the nuclear spins and discuss our recent progress in implementing two-qubit entangling operations between nuclear spins. These results greatly extend the number of available quantum bits in diamond and provide a way towards tomography with single nuclear spin sensitivity even in decohering environments.\textsuperscript{[1]} T. van der Sar et al., Nature 484, 82 (2012).\textsuperscript{[2]} T. H. Taminiau et al., Phys. Rev. Lett. 109, 137602 (2012).

1:27PM U26.00010 Entanglement by measurement and Bell inequality violation with spins in diamond  
WOLFGANG PFAFF, TIM TAMINIAU, LUCIO ROBLEDO, HANNES BERNIEN, Kavli Institute of Nanoscience Delft, Delft University of Technology, The Netherlands, MATTTHW MARKHAM, DANIEL TWITCHEN, Element Six, Ltd., Ascot, United Kingdom, RONALD HANSON, Kavli Institute of Nanoscience Delft, Delft University of Technology, The Netherlands — Single spins in diamond have emerged as a promising platform for quantum information processing in the solid state. In particular, individual nuclear spins coupled to nitrogen-vacancy (NV) centers have been recognized as excellent candidates for solid state qubits, because they combine outstanding stability, excellent control by spin resonance techniques, and high-fidelity optical initialization and readout provided by the NV center. Here we report the achievement of a milestone towards quantum computation with spins: The creation of high quality quantum entanglement between two nuclear spins in diamond. This entanglement is an important resource for quantum computation and lies at the heart of many key quantum protocols, such as teleportation and error correction. We show that we can produce entangled states of high fidelity using a projective quantum measurement. Our technique is non-destructive, and thus leaves the quantum information that is required for further computation unharmed. This enables us to demonstrate the violation of Bell’s inequality for the first time with spins in the solid state. Reference: Pfaff et al., Nature Physics, doi:10.1038/nphys2444 (2012).

1:39PM U26.00011 Pulsed ESR of photo-polarized NV centers in diamond at X-band magnetic fields  
BRENDO ROSE, ALEXEI TYRSHKIN, STEPHEN LYON, Princeton U., CHRISTOPH WEIS, THOMAS SCHEKEL, LBNL — Recently nitrogen-vacancy (NV) color centers in diamond have become the focus of many studies aimed towards their use as quantum bits (qubits) in quantum computing applications and as precision magnetic field sensors in scanned imaging applications. The NVs have a ground triplet state (S\textsuperscript{0}=1) with ZFS of 2.88 GHz. It has been previously shown that optical excitation, when shining green light at low magnetic fields (below 100 G), polarizes spins preferentially into the T\textsubscript{D} state. Here we will report an X-band pulsed ESR measurement and demonstrate that the optical spin polarization is more complex at higher magnetic fields (340 G) and can lead to preferential spin polarization into T\textsubscript{+} and T\textsubscript{−} states, instead of T\textsubscript{D}. This effect can be understood from a simple one electron spin Hamiltonian and depends mainly on the relative orientation of the ZFS and external magnetic field. In addition, we observe strong ESEEM effects originating from the central nitrogen nucleus which are most prominent when measuring the T\textsubscript{D} to T\textsubscript{+} transition and when the field is along the ZFS. From the orientation dependence of ESEEM we are able to accurately determine the nitrogen hyperfine and nuclear quadrupole tensors. Spin coherence of 0.8 ms is seen at 10 K, limited by 1 percent of magnetic \textsuperscript{13}C nuclei in our natural diamond sample.
11:15PM U26.00012 Polytype control of spin qubits in silicon carbide\textsuperscript{1}, A.L. FALK, B.B. BUCKLEY, G. CALUSINE, W.F. KOEHL, A. POLITI, D.D. AWSCHALOM, Center for Spintronics and Quantum Computation, University of California, Santa Barbara, California 93106, USA, V.V. DOBROVITSKI, Ames Laboratory and Iowa State University, Ames, Iowa 50011, USA, C.A. ZORMAN, P. X.-L. FENG, Case School of Engineering, Case Western Reserve University, Cleveland, OH 44106, USA — The search for coherently addressable spin states in technologically important materials is a promising direction for solid-state quantum information science. Silicon carbide, a particularly suitable target, is not a single material but a collection of about 250 known polytypes, each with its own set of physical properties and technological applications. We show that in spite of these differences, the 4H-, 6H-, and 3C-SiC polytypes all exhibit optically addressable spins with long coherence times [1]. These results include room temperature spins in all three polytypes and suggest a new method for tuning quantum states using crystal polymorphism. Long spin coherence times allow us to do double electron-electron resonance to measure magnetic dipole interactions between spin ensembles in inequivalent lattice sites of the same crystal. Since such inequivalent spin have distinct optical and spin transition energies, these interactions could lead to dipole-coupled networks of separately addressable spins.

\textsuperscript{1}This work is supported by AFOSR.

Thursday, March 21, 2013 11:15AM - 2:15PM —
Session U27 GQI: Quantum Entanglement: Theory and Experiment 329 - Andrews Doherty, University of Sydney

11:15AM U27.00001 Positivity of Partial Transpose and Separability of Dicke state mixtures . ELIE WOLFE, SUSANNE YELIN, University of Connecticut — We study mixtures of permutation symmetric (Dicke) states, with a special focus on superradiance time evolution. For such systems we develop necessary separability criteria for general N-qubit systems based on the condition of Positive Partial Transpose. We also compose sufficient separability criteria for the specific cases of two and three qubits. Comparing the criteria we prove that, for Dicke state mixtures, the PPT test is always sufficient to imply full separability.

\textsuperscript{1}We gratefully acknowledge financial support from CNPq Brazil and Faep, UEL, Brazil.

11:15AM U26.00013 Defects as qubits in 3C and 4H polymorphs of SiC\textsuperscript{1}, LUKE GORDON, AUDRIUS ALKAUSKAS, WILLIAM F. KOEHL, ANDERSON JANOTTI, DAVID D. AWSCHALOM, CHRIS G. VAN DE WALLE, University of California, Santa Barbara — Using hybrid functional calculations we study defects in SiC that can serve as qubits for quantum computing. We investigate the divacancy in 4H- and 3C-SiC and the N-V center in 3C-SiC, in which the N impurity replacing a C atom is sitting next to a Si vacancy. The calculated excitation and emission energies of the divacancy in 4H-SiC are in excellent agreement with the available experimental data. Most importantly, we predict that the neutral divacancy and the negatively charged NV center in 3C-SiC have all the required characteristics to serve as qubits; in addition, both defects are stable in n-type 3C-SiC, which is in principle easy to fabricate. We calculate luminescence line shapes and Huang-Rhys factors for these defects in 4H and 3C-SiC, and compare with experimental photoluminescence spectra.

\textsuperscript{2}This work has been supported by the NSF.

11:27AM U27.00002 Polynomial invariants to quantify Four-body Correlations\textsuperscript{1}, SANTOSH SHELLY SHARMA\textsuperscript{2}, Depto. de fisica, Universidade Estadual de Londrina, Londrina Pr, Brazil, NARESH KUMAR SHARMA, Depto. de Matematica, Universidade Estadual de Londrina, Londrina Pr, Brazil — Local unitary invariance and notion of negativity fonts are used as the principle tools to construct four qubit polynomial invariants of degree 8, 12, and 24. Determinants of negativity fonts are linked to matrices obtained from state operator through selective partial

\textsuperscript{1}This work has been supported by AFOSR.

11:39AM U27.00003 Numerical Calculations of the Three Tangle for Mixed States , SAUL RODRIQUES, PETER LOVE, Haverford College — We present a steepest descent convex roof optimization algorithm, using the Cayley parametrization of the unitary group, which can be used to calculate the convex roof of any entanglement monotone on mixed states. We use the algorithm to calculate the three tangle on a set of states for which the tangle is known analytically, and show that our results are in good agreement with the analytical calculations. We then randomly generate a set of full-rank three qubit states, of varied mixedness and tangle, calculate the tangle on these states using our convex roof algorithm, and also calculate the lower bound on the three-tangle which has been provided by Etschka and Siewert\textsuperscript{[1]} . We thus provide a profile of the strength of the Etschka-Siewert bound, as a function of mixedness and tangle. [1] “Optimal Witnesses for Three Qubit Entanglement from Greenberger-Horne-Zeilinger Symmetry,” Etschka, C. and Siewert, J., forthcoming, arXiv: 1204.5451

11:51AM U27.00004 Quantum steering ellipsoids: The way to represent two qubits\textsuperscript{1}, SANIA JEVtic, MATTHEW PUSEY, DAVID JENNINGS, TERRY RUDOLPH, Imperial College London — A single qubit state is faithfully represented as a vector in the Bloch sphere. A two qubit state may be faithfully represented as two vectors and a quantum steering ellipsoid (QSE) in the Bloch sphere. When Alice and Bob share a pair of qubits, the QSE is the geometric set of states that Bob can steer Alice’s qubit to when he implements all possible measurements on his qubit. We argue that the QSE is the way one should visualise a two qubit state and show how the correlative properties of the state manifest themselves in this paradigm, in particular we give simple conditions for when the state is entangled, or has discord. We will also present novel features of the two qubit state that are revealed by the QSE formalism, and show that a state corresponding to an ellipsoid with non-zero volume contains a new type of correlation. Such a state is a useful resource in a game where Bob succeeds if he can steer Alice’s qubit to three states with linearly independent Bloch vectors.

\textsuperscript{1}EPSRC, Royal Commission for the Exhibition of 1851
12:03PM U27.00005 Quantum Discord Bounds the Amount of Distributed Entanglement1, MARCO PIANI, Institute for Quantum Computing, University of Waterloo, TAN KOK CHUAN, Centre for Quantum Technologies, National University of Singapore, JEAN MAILLARD, Blackett Laboratory, Imperial College London, KAVAN MODI, Department of Physics, University of Oxford, TOMASZ PATEREK, Nanyang Technological University, Singapore, MAURO PATERNOSTRO, Queen’s University, Belfast — The ability to distribute quantum entanglement is a prerequisite for many fundamental tests of quantum theory and numerous quantum information protocols. Two distant parties can increase the amount of entanglement between them by means of quantum communication encoded in a carrier that is sent from one party to the other. Intriguingly, entanglement can be increased even when the exchanged carrier is not entangled with the parties. However, in light of the defining property of entanglement stating that it cannot increase under classical communication, the carrier must be quantum. Here we show that, in general, the increase of relative entropy of entanglement between two remote parties is bounded by the amount of nonclassical correlations of the carrier with the parties as quantified by the relative entropy of discord. We study implications of this bound, provide new examples of entanglement distribution via unentangled states, and put further limits on this phenomenon.

1 We thank the National Research Foundation and Ministry of Education in Singapore (T. K. Chuan, K. Modi, and T. Paterek), the John Templeton Foundation (K. Modi), the UK EPSRC (M. Paternostro), NSERC, CIFAR, and the Ontario Centres of Excellence (M. Piani)

12:15PM U27.00006 Topological Classification of Types of Quantum Discord Evolutions1, NGA NGUYEN, ROBERT JOYNT, Physics Department, University of Wisconsin-Madison, Madison, WI 53706 — Quantum discord is a type of quantum correlation that has recently attracted extensive attention. One question that is of experimental importance is how quantum correlations such as entanglement and discord are erased by external noise. A general classification of time evolution is seen to depend essentially on the understanding of the topology of the set C of concordant (zero-discord) states. In the 2-qubit case, we show that C is a 9-dimensional simply-connected manifold with boundary that can be embedded in the 15-dimensional space of 2-qubit density matrices. This yields 6 topologically distinct categories for the joint time evolution of entanglement and discord that exhaust all possibilities. We show that these 6 categories can be obtained in one physical model using independent or correlated random telegraph noise sources in the Markovian regime. Transition between these categories is of topological nature and is governed by changing physical parameters or initial conditions.

1 Supported by DRPA-QuEst Grant No. MSN18850.

12:27PM U27.00007 Mutual Preservation of Entanglement, ANDRZEJ VEITIA, University of Columbia — We study a generalized double Jaynes-Cummings (JC) model where two entangled pairs of two-level atoms interact indirectly. We focus on the case where the cavities and the entangled pairs are uncorrelated. We show that there exist initial states of the qubit system so that two entangled pairs are available at all times. In particular, the minimum entanglement in the pairs as a function of the initial state is studied. Finally, we extend our findings to a multi-mode case involving multimode cavity interactions. We use a non-Markovian quantum state diffusion (QSD) equation to obtain the steady-state density matrix for the qubits. We show that the multi-mode model also displays dynamical preservation of entanglement.

12:39PM U27.00008 Quantum geometry and entanglement in the Rabi model, JUSTIN WILSON, VICTOR GALITSKI, University of Maryland at College Park — In composite systems, entanglement can be useful for control since one system’s properties become fundamentally linked with another system’s properties. One way of measuring entanglement is with a quantity called I-concurrence, a generalization of concurrence to systems that have more states than a qubit. We show that I-concurrence can be rewritten in terms of quantum geometric quantities. In particular, we show a dependence on the Hilbert-Schmidt distance measure on the Hilbert space of one of the subsystems. Using this quantity and the recently exactly solved Rabi model, we calculate the entanglement between eigenstates in the Rabi model.

12:51PM U27.00009 Classical Analogs of Quantum Entanglement1, BRIAN LA COUR, The University of Texas at Austin — Quantum computing algorithms rely upon entanglement and context-based measurements, properties that are well exhibited by atomic or photonic systems. In some cases, these properties can be mimicked by cleverly contrived classical systems. We present a notional scheme for such classical analogs and compare their predictions to those of an associated quantum system. Entanglement is verified operationally using quantum tomography, wherein the quantum mixed state is inferred from measurements on a complete orthonormal set of Hermitian observables. Using the Peres-Horodecki criterion for separability, we examine the partial transpose of the estimated density matrix to establish a necessary, and in some cases sufficient, condition for entanglement. Through the use of Monte Carlo simulations, we find that certain classical systems do indeed exhibit a measurably significant level of entanglement.

1 This work was supported by ARL/UT under an internal research and development grant.

1:03PM U27.00010 Robust distant-entanglement generation using coherent multiphoton scattering1, CHING-KIT CHAN, ITAMP, Harvard University, L. J. SHAM, University of California San Diego — The generation and controllability of entanglement between distant quantum states have been the heart of quantum computation and quantum information processing. Existing schemes for solid state qubit entanglement are based on the single-photon spectroscopy that has the merit of a high fidelity entanglement creation, but with a very limited efficiency. This severely restricts the scalability for a qubit network system. Here, we describe a new distant entanglement protocol using coherent multiphoton scattering. The scheme makes use of the postselection of large and distinguishable photon signals, and has both a high success probability and a high entanglement fidelity. Our result shows that the entanglement generation is robust against photon fluctuations, and has an average entanglement duration within the decoherence time in various qubit systems, based on existing experimental parameters.

1 This research was supported by the U.S. Army Research Office MURI award W911NF0910406 and by NSF grant PHY-1104446.

1:15PM U27.00011 Optical control of entangled states in semiconductor quantum wells, MARIO BORUNDA, Oklahoma State University and Harvard University, ESA RASÄNEN, Tampere University of Technology, University of Jyväskyla, and Harvarv University, THOMAS BLASI, Harvard University and Technisch Universitat Munchen, ERIC HELLER, Harvard University — The ability to coherently control arbitrary two-electron states, and to maximize the entanglement, opens up further perspectives in solid-state quantum information. In this talk, we present theory and calculations for coherent high-fidelity quantum control of many-particle states in semiconductor quantum wells. We have shown that coupling a two-electron double quantum dot to a terahertz optical source enables targeted excitations that are one to two orders of magnitude faster and significantly more accurate than those obtained with electric gates. The optical fields subject to realistic physical constraints are obtained through quantum optimal control theory that is applied in conjunction with the numerically exact solution of the time-dependent Schrodinger equation.
Persistent Quantum Beats and Long-Distance Entanglement from Waveguide-Mediated Interactions

Huaixiu Zheng, Harold U. Baranger, Duke University — We study photon-photon correlations and entanglement generation in a one-dimensional waveguide coupled to two qubits with an arbitrary spatial separation [1]. Such a system can be realized by coupling a 1D open transmission line to superconducting qubits. To treat the combination of nonlinear elements and 1D continuum, we develop a novel Green function method. The vacuum-mediated qubit-qubit interactions cause quantum beats to appear in the second-order correlation function. We go beyond the Markovian regime and observe that such quantum beats persist much longer than the qubit lifetime. A high degree of long-distance entanglement can be generated, increasing the potential of waveguide-QED systems for scalable quantum networking.


Measurement of the joint spectrum of entangled photons using rotary dispersion

Daniel Jones, Todd Pittman, University of Maryland, Baltimore County — We report a new method of observing the spectral entanglement of photons generated in spontaneous parametric down-conversion (PDC). In contrast to previous methods based on spatial or temporal dispersion, our method is based on rotary dispersion and polarization measurements. Our experiment utilizes a variation of the Sénarmont compensator in order to rotate the polarization state of the entangled signal and idler photons. By passing the photons through several stages of these “rotators,” we essentially create a Lyot filter in which we can directly correlate an analyzer measurement after the rotators with a specific wavelength, within a resolution defined by the theory. This method is fundamentally different than previous experiments to measure the joint spectrum of PDC photons because of the periodicity of using analyzers as the measurement devices. The periodicity of the analyzers causes a trade-off between the resolution of the device and the maximum bandwidth of the entangled photons that can be measured.

Quantum Dynamics of Photon Condensates

Peter Kirtont, Jonathan Keeling, University of St Andrews — Recent experiments have, for the first time, been able to observe the Bose condensation of a gas of weakly interacting photons. We develop a full out-of-equilibrium quantum mechanical treatment of the dynamics of this system. Our model consists of a series of photon modes coupled to the background dye molecules which we simply treat as two-level systems in which each level is separated into a ladder of rovibration states. We find that the behavior of the photon field is very much like that of a two-level laser in which there is an asymmetry between the effective pump and decay rates induced by the rovibrational states of the dye. This motivates us to use techniques based on those for the inversionless two-level laser. We are able to calculate the coherence properties of the photons as well as giving insights into the thermalization processes which equilibrate the populations of the various photon modes.

Excitations of a driven condensate in a cavity: dynamics of the roton-like mode

Baris Oztop, Manas Kulkarni, Hakan Tureci, Princeton University — Recent experiments have demonstrated the superfluid-superfluid quantum phase transition (PT) of an optically driven Bose-Einstein condensate (BEC), via the observation of a roton-like softening of a mode in the Bogoliubov excitation spectrum [1,2]. This phenomenon is usually studied within two-mode approximation for the BEC which results in Dicke-like effective model. In this system, the long-range interactions between the atoms are mediated by cavity photons and the strength of the interactions is controlled by pump power. In this work, we investigate the effect of including the full spectrum of atomic modes. We find a finite lifetime for the roton-like mode below the threshold that is strongly pump-dependent. The corresponding decay rate and critical exponents for the PT are calculated.


Quantum optomechanics in the strong-driving, strong-coupling regime

Marc-Antoine Lemonde, Wei Chen, Ashish Clerk, McGill University, Ca, Qc — There is considerable interest in trying to develop quantum optomechanical systems where the coupling is appreciable at the level of a single photon and single phonon. Theoretically, such strongly-coupled optomechanical systems have been largely studied using a polaron transformation in the regime of very weak optical driving. We present here a theoretical approach based on the Keldysh technique that describes single-photon strong coupling physics in an optomechanical system in the presence of a strong optical drive. We show that strong driving can be used to dramatically enhance the effects of the single-photon nonlinearity, leading to striking modifications to the usual linearized optomechanical theory. We discuss the resulting strong modifications of the optomechanically-induced transparency (OMIT) spectrum, a quantity easily accessible in experiment.
also demonstrate the emergence of super-splitting, phonon anti-bunching, and phonon blockade through the non-equilibrium density matrix master equation in on-chip, optomechanical crystals. We calculate the parameter regime where the Mott-Superfluid quantum phase transition occurs in realizable devices. We potentially offers advantages in this regime over purely optomechanical systems where the optomechanical coupling is still quite small. First, single phonons to the quantum many-body limit by investigating the physics of phonon-tunnel-coupled arrays of such components. The silicon qubit cavity phoniton system, Ö.O. SOYKAL, University of Maryland, CHARLES TAHAN, Laboratory for Physical Sciences — We previously proposed a nano-mechanical system where


P. Nataf, A. Baksic and C. Ciuti, Phys. Rev. A


3dB, MENNO POOT, HONG TANG, Dept. of Electrical Engineering, Yale University — Parametric squeezing can reduce the uncertainty in one quadrature of the position of a mechanical resonator, even below the standard quantum limit, and it can improve measurement sensitivity. Here we demonstrate squeezing of the thermal motion of a 570 kHz opto-electromechanical resonator made out of high-stress SiN by modulating its spring constant at twice the resonance frequency. Parametric and direct actuation are achieved by applying a.c. voltages between strongly coupled electrodes on the resonator and a fixed one. It is well known that using this method the motion of one quadrature cannot be decreased more than 3 dB below the undriven case before instabilities kick in. However, by measuring the phase-space trajectory of the resonator and adjusting the phase of the parametric drive in real-time we achieve a stationary reduction in both quadratures that is far beyond this limit. Finally, due to the strong coupling between the drive electrodes, the nonlinearity of the resonator can be tuned all the way from a stiffening spring to a softening one.


The support of the U.S. Department of Energy through LANL/LDRD Program for this work is gratefully acknowledged.

11:51AM U41.00004 Quantum many body systems with qubits and phonons in the solid state

Ö.O. SOYKAL, University of Maryland, CHARLES TAHAN, Laboratory for Physical Sciences — We previously proposed a nano-mechanical system where phonons trapped in an acoustic cavity can strongly hybridize with cavity qubit states in silicon (forming a so-called cavity-phonon). Here, we extend the idea to the quantum many-body limit by investigating the physics of phonon-tunnel-coupled arrays of such components. The silicon qubit cavity phoniton system potentially offers advantages in this regime over purely optomechanical systems where the optomechanical coupling is still quite small. First, single phonons in a crystal can have large effective de Broglie wavelengths (microns). Second, as we have previously shown, qubit-phonon coupling can be quite large, easily allowing the system to enter the strong coupling regime and enabling phonon-blockade. Such arrays can be fabricated in semiconductor heterostructures or in on-chip, optomechanical crystals. We calculate the parameter regime where the Mott-Superfluid quantum phase transition occurs in realizable devices. We also demonstrate the emergence of super-splitting, phonon anti-bunching, and phonon blockade through the non-equilibrium density matrix master equation approach in few cavity systems.

12:03PM U41.00005 Quantum Dynamics of Optomechanical Arrays, MAX LUDWIG, University of Erlangen-Nuremberg, FLORIAN MARQUARDT, University of Erlangen-Nuremberg and Max Planck Institute for the Science of Light — Optomechanical system are typically composed of a single mechanical and a single optical mode interacting via radiation pressure. In this talk, we will introduce an array of optomechanical cells, and discuss our theoretical results on the nonlinear quantum dynamics of such a setup. In particular, we have discovered a phase transition between incoherent mechanical oscillations and a collective phase-coherent mechanical state. We describe how quantum fluctuations drive this transition at low temperatures. We will also discuss the prospects of observing these non-equilibrium dynamics in an experimental implementation based on currently available setups.

12:15PM U41.00006 Signatures of nonlinear optomechanics and engineering of nonclassical mechanical steady states, Ö.O. SOYKAL, University of Maryland, CHARLES TAHAN, Laboratory for Physical Sciences — We previously proposed a nano-mechanical system where

The author acknowledges financial support from The Danish Council for Independent Research under the Sapere Aude program.

12:27PM U41.00007 Nonlinear Quantum Relaxation and Generation of Non-classical States in Duffing Oscillators, AURORA VOJE, ALEXANDER CROY, ANDREAS ISACSSON, Chalmers University of Technology — The dissipative quantum dynamics of an anharmonic oscillator is theoretically investigated in the context of carbon-based nano-mechanical systems. In the short-time limit, it is known that macroscopic superposition states appear for such oscillator. Linear and non-linear dissipation leads to decoherence of such non-classical states in the long-time limit. However, as a result of two-vibron losses at zero temperature, the quantum oscillator eventually evolves into a non-classical stationary state — a qubit. In this talk, we will present the relaxation mechanism due to thermal excitations and one-vibron losses is numerically and analytically studied. The possibility of verifying the occurrence of the qubit is discussed and signatures of the non-classicality arising in a ring-down setup are presented. Additionally, the generation of entanglement between two coupled oscillators in presence of strong two-vibron losses is discussed.

12:39PM U41.00008 Parametric feedback squeezing of an opto-electromechanical device below 3dB, MENNO POOT, HONG TANG, Dept. of Electrical Engineering, Yale University — Parametric squeezing can reduce the uncertainty in one quadrature of the position of a mechanical resonator, even below the standard quantum limit, and it can improve measurement sensitivity. Here we demonstrate squeezing of the thermal motion of a 570 kHz opto-electromechanical resonator made out of high-stress SiN by modulating its spring constant at twice the resonance frequency. Parametric and direct actuation are achieved by applying a.c. voltages between strongly coupled electrodes on the resonator and a fixed one. It is well known that using this method the motion of one quadrature cannot be decreased more than 3 dB below the undriven case before instabilities kick in. However, by measuring the phase-space trajectory of the resonator and adjusting the phase of the parametric drive in real-time we achieve a stationary reduction in both quadratures that is far beyond this limit. Finally, due to the strong coupling between the drive electrodes, the nonlinearity of the resonator can be tuned all the way from a stiffening spring to a softening one.

12:51PM U41.00009 Non-classical correlations of scattered photons in a one-dimensional waveguide with multiple atoms, DIBYENDU ROY, Theoretical Division and Center for Nonlinear Studies, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA — We study the scaling of photon-photon correlations mediated by resonant interactions of photons with atoms in a one-dimensional photonic waveguide. Recently a new theoretical approach based on the Bethe-ansatz technique has been developed to study transport in an open quantum impurity. Here we generalize the approach to study multiple atoms. We derive the exact solution of single and two-photon scattering states, and the corresponding photon transmission through the atomic ensemble. We show how various two-photon nonlinear effects, such as spatial attraction and repulsion between photons as well as background fluorescence can be tuned by changing the number of atoms and the coupling between atoms (controlled by the separation). Finally we propose a simple scheme for nonreciprocal optical transmission in the waveguide by placing different atoms. Our fully quantum-mechanical approach provides a better understanding of cascaded optical nonlinearity at the microscopic level.

1:03PM U41.00010 Recent theoretical advances on superradiant phase transitions, ALEXANDRE BAKSIC, PIERRE NATAF, CRISTIANO CIUTI, Laboratoire MFPQ, Université Paris Diderot-Paris 7 and CNRS — The Dicke model describing a single-mode boson field coupled to two-level systems is an important paradigm in quantum optics. In particular, the physics of "superradiant phase transitions" in the ultrastong coupling regime is the subject of a vigorous research activity in both cavity and circuit QED. Recently, we explored the rich physics of two interesting generalizations of the Dicke model: (i) A model describing the coupling of a boson mode to two independent chains A and B of two-level systems [1], where chain A is coupled to one quadrature of the boson field and chain B to the orthogonal quadrature. This original model leads to a quantum phase transition with a double symmetry breaking and a fourfold ground state degeneracy. (ii) A generalized Dicke model with three-level systems [2] including the diamagnetic term. In contrast to the case of two-level atoms for which no-go theorems exist, in the case of three-level system we prove that the Thomas-Reich-Kuhn sum rule does not always prevent a superradiant phase transition.

1:15PM U41.00011 Light-induced phase transition in a quantum spin chain: Breakdown of the Haldane phase by circularly polarized laser

SHINTARO TAKAYOSHI, Department of Applied Physics, University of Tokyo, HIDEO AOKI, Department of Physics, University of Tokyo, TAKASHI OKA, Department of Applied Physics, University of Tokyo — We theoretically propose a new category of non-equilibrium phase transitions in quantum spin systems that can be induced by the magnetic component of strong lasers. As an example, we consider a Haldane chain with single ion anisotropy radiated by circularly polarized light. We study the spin dynamics by combining the numerical infinite-time-evolving block decimation method and an analytical calculation via the Floquet theory, and demonstrate that the laser can magnetize even an antiferromagnet quantum mechanically. It is also shown that the string order is broken by the magnetization, which indicates that a photo-induced breakdown of the Haldane phase has occurred. This phenomenon can be realized using strong THz lasers.

1:27PM U41.00012 Testing Kibble-Zurek mechanism in ion traps

RAMIL NIGMATULLIN, Imperial College London, ADOLFO DEL CAMPO, T4 and Center for Nonlinear Studies, Los Alamos National Laboratory, GABRIELE DE CHIARA, Centre for Theoretical Atomic, Molecular and Optical Physics, Queen’s University Belfast, GIOVANNA MORIGI, Theoretical Physics, University of Saarland, MARTIN PLEINIO, Institute of Theoretical Physics, Ulm University, ALEX RETZKER, The Racah Institute of Physics, Hebrew University of Jerusalem — A quench through a critical point of a second order phase transition results in the formation of topological defects in the system. Kibble-Zurek (KZ) theory predicts the scaling of a number of defects as a function of quench rate. This scaling depends on the critical exponents of the phase transition, and hence the study of the defect density reveals something about the nature of phase transition itself. There are a number of proposals to test KZ theory experimentally. In this talk, we discuss the possibility of studying defect formation in ion traps. A linear ion chain confined in a Paul trap undergoes a continuous phase transition to a zigzag chain when the confining potential is lowered. If the chain is in a ring trap then the zigzag chain can be in a helical configuration with a nonzero winding number. Using molecular dynamics simulations we show that the scaling of the average winding number of the resulting helical chain is consistent with KZ theory.

1:39PM U41.00013 Space-Time Crystals of Trapped Ions

TONGCANG LI, University of California, Berkeley, ZHE-XUAN GONG, University of Michigan, Ann Arbor, ZHANG-QI YIN, Tsinghua University, H. T. QUAN, University of Maryland, College Park, XIAOBO YIN, PENG ZHANG, University of California, Berkeley, L.-M. DUAN, University of Michigan, Ann Arbor, XIANG ZHANG, University of California, Berkeley — Spontaneous symmetry breaking can lead to the formation of time crystals, as well as spatial crystals. Here we propose a space-time crystal of trapped ions and a method to realize it experimentally by confining ions in a ring-shaped trapping potential with a static magnetic field. The ions spontaneously form a spatial ring crystal due to Coulomb repulsion. This ion crystal can rotate persistently at the lowest quantum energy state in magnetic fields with fractional fluxes. The persistent rotation of trapped ions produces the temporal order, leading to the formation of a space-time crystal. We show that these spacetime crystals are robust for direct experimental observation. We also study the effects of finite temperatures on the persistent rotation. The proposed space-time crystals of trapped ions provide a new dimension for exploring many-body physics and emerging properties of matter.

1:51PM U41.00014 Electromagnetic induced transparency and slow light in strongly correlated atomic gases

HSIANG-HUA JEN, BO XIONG, ITE A. YU, DAW-WEI WANG, National Tsing Hua University, PHYSICS DEPARTMENT, NATIONAL TSING HUA UNIVERSITY TEAM, FRONTIER RESEARCH CENTER ON FUNDAMENTAL AND APPLIED SCIENCES OF MATTER,NATIONAL TSING HUA UNIVERSITY TEAM, PHYSICS DIVISION, NATIONAL CENTER FOR THEORETICAL SCIENCES TEAM — We develop the quantum theory for the electromagnetic induced transparency (EIT) and slow light property in ultracold Bose and Fermi gases. It shows a very different property from the classical theory which assumes frozen atomic motion. For example, the speed of light inside the atomic gases can be changed dramatically near the Bose-Einstein condensation temperature, while the properties of the Fermi gas can depend on the EIT effect at zero temperature. This quantum EIT property is mostly manifested in the counter-propagating excitation schemes in either the low-lying Rydberg transition or in D2 transition with a very weak coupling field. Using linear response theory, we further derive an exact and universal form for the EIT spectrum, which applies even in strongly correlated systems of ultracold atoms. We find that the spectrum is closely related to the single particle Green’s function, which is not easily observable in most experimental technique. As an example, we show results of 1D Luttinger liquid, Mott-insulator state, and BCS pairing phase, and compare to the results of standard classical theory. Our theory therefore paves the way to measure strongly correlated physics of ultracold atoms via the state-of-art manipulation of light propagation inside the quantum gases.

2:03PM U41.00015 Orbital Angular Momentum as Manifestation of Photonic Zitterbewegung

BASIL DAVIS, Tulane University — The phenomenon of photonic orbital angular momentum has received considerable attention since its theoretical prediction by Allen et al in 1992. It has been established theoretically and experimentally that laser beams with a Laguerre Gaussian profile possess angular momentum in addition to their intrinsic spin angular momentum. A parallel development has been the renewed interest in zitterbewegung, first predicted for relativistic electrons by Schrodinger. It is now known that zitterbewegung is a property of all particles, regardless of spin, charge or rest mass, since it is basically a quantum mechanical phenomenon. Recently there has arisen an interest in photonic zitterbewegung. This paper shows that photonic orbital angular momentum is one experimentally observable manifestation of photonic zitterbewegung.

Thursday, March 21, 2013 2:30PM - 5:30PM –
Session W3’ GQI: Invited Session: Quantum Foundations Ballroom III - Terry Rudolph, Imperial College London

2:30PM W3.00001 The freedom of choice assumption and its implications

RENATO RENNER, ETH Zurich — The assumption that the parameters of an experiment (e.g., those determining the basis of a quantum measurement) can be chosen freely is implicit to most considerations in physics. One may therefore ask whether it is possible to give a precise meaning to the notion of “free choice” and, if yes, study its implications. One natural approach towards defining free choice, considered already by Bell, is to specify a causal structure on the set of all physically relevant parameters and observables. A parameter may then be considered “free” if it is statistically independent of all other parameters and observations that do not lie in its causal future. Recently, it has been realized that the assumption of free choice, as defined above, has various interesting consequences. In particular, if defined relative to a causal structure compatible with relativity theory, free choice immediately implies completeness of quantum theory. This means that there cannot exist any additional (hidden) parameters that would improve the statistical predictions that quantum theory makes about the outcomes of future measurements. In this talk, I motivate and explain this definition of free choice and give an overview of the most important implications of the free choice assumption.
priori, a hidden communication explanation is not more surprising than nonlocality. We prove that for any contradiction: for example the reference frame in which the cosmic microwave background radiation is isotropic defines such a privileged frame. Hence, a frame in which this faster than light speed is defined. Again, such a universal privileged frame is not in the spirit of relativity, but it is also clearly not in produce correlations that can’t be explained by usual common causes. To define faster than light hidden communication requires a universal privileged reference one could imagine that this communication remains for ever hidden to humans, i.e. that it could not be controlled by humans, only Nature exploits it to measure faster than light speed is defined. Yet, “everything looks as if the two, NICOLAS GISIN, University of Geneva — Experimental violations of Bell inequalities using space-like separated measurements precludes the explanation of quantum correlations through causal influences propagating at subluminal speed. Yet, “everything looks as if the two parties somehow communicate behind the scene.” We investigate the assumption that they do so at a speed faster than light, though finite. Such an assumption doesn’t respect the spirit of Einstein relativity. However, it is not crystal clear that such “communication behind the scene” would contradict relativity. Indeed, one could imagine that this communication remains for ever hidden to humans, i.e. that it could not be controlled by humans, only Nature exploits it to produce correlations that can’t be explained by usual common causes. To define faster than light hidden communication requires a universal privileged reference frame in which this faster than light speed is defined. Again, such a universal privileged frame is not in the spirit of relativity, but it is also clearly not in contradiction: for example the reference frame in which the cosmic microwave background radiation is isotropic defines such a privileged frame. Hence, a priori, a hidden communication explanation is not more surprising than nonlocality. We prove that for any finite speed, such models predict correlations that can be exploited for faster-than-light communication. This superluminal communication doesn’t restrict access to any hidden physical quantities, but only the manipulation of measurement devices at the level of our present-day description of quantum experiments. Indeed, all possible explanations of quantum correlations that satisfy the principle of continuity, which states that everything propagates gradually and continuously through space and time, or in other words, all combination of local common causes and direct causes that reproduce quantum correlations, lead to faster than light communication. Accordingly, either there is superluminal communication or the conclusion that Nature is nonlocal (i.e. discontinuous) is unavoidable [Nature Physics DOI: 10.1038/NPHYS2460 (2012); arXiv:1210.7308].

Three-dimensionality of space and the quantum bit: an information-theoretic approach , MARKUS MUELLER, Perimeter Institute for Theoretical Physics — It is sometimes pointed out as a curiosity that the state space of quantum two-level systems, i.e. the qubit, and actual physical space are both three-dimensional and Euclidean. In this talk, I report on joint work with Lluis Masanes [1], where we attempt an information-theoretic analysis of this relationship, by proving a particular mathematical result: suppose that physics takes place in d spatial dimensions, and that some events happen probabilistically (not assuming quantum theory in any way). Furthermore, suppose there are systems that behave in some sense as “units of direction information,” interacting continuously and reversibly in time. We prove that this uniquely determines spatial dimension d=3 and quantum theory on two qubits (that is, the complex Hilbert space formalism and unitary time evolution). Moreover, we prove that it allows observers to infer local spatial geometry from probability measurements. This applies and generalizes results obtained earlier with further collaborators [2,3].

1 M. P. Mueller and Ll. Masanes, Three-dimensionality of space and the quantum bit: how to derive both from information-theoretic postulates, arXiv:1206.0630

Three-dimensionality of space and the quantum bit: an information-theoretic approach , MARKUS MUELLER, Perimeter Institute for Theoretical Physics — It is sometimes pointed out as a curiosity that the state space of quantum two-level systems, i.e. the qubit, and actual physical space are both three-dimensional and Euclidean. In this talk, I report on joint work with Lluis Masanes [1], where we attempt an information-theoretic analysis of this relationship, by proving a particular mathematical result: suppose that physics takes place in d spatial dimensions, and that some events happen probabilistically (not assuming quantum theory in any way). Furthermore, suppose there are systems that behave in some sense as “units of direction information,” interacting continuously and reversibly in time. We prove that this uniquely determines spatial dimension d=3 and quantum theory on two qubits (that is, the complex Hilbert space formalism and unitary time evolution). Moreover, we prove that it allows observers to infer local spatial geometry from probability measurements. This applies and generalizes results obtained earlier with further collaborators [2,3].

4:42PM W3.00003 Three-dimensionality of space and the quantum bit: an information-theoretic approach , MARKUS MUELLER, Perimeter Institute for Theoretical Physics — It is sometimes pointed out as a curiosity that the state space of quantum two-level systems, i.e. the qubit, and actual physical space are both three-dimensional and Euclidean. In this talk, I report on joint work with Lluis Masanes [1], where we attempt an information-theoretic analysis of this relationship, by proving a particular mathematical result: suppose that physics takes place in d spatial dimensions, and that some events happen probabilistically (not assuming quantum theory in any way). Furthermore, suppose there are systems that behave in some sense as “units of direction information,” interacting continuously and reversibly in time. We prove that this uniquely determines spatial dimension d=3 and quantum theory on two qubits (that is, the complex Hilbert space formalism and unitary time evolution). Moreover, we prove that it allows observers to infer local spatial geometry from probability measurements. This applies and generalizes results obtained earlier with further collaborators [2,3].


4:18PM W3.00004 Quantum correlations with indefinite causal order , CASLAV BRUKNER, Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria — Quantum mechanics differs from classical physics in that no definite values can be attributed to unobserved physical quantities. However, the notion of time and of causal order preserves such an objective status in the theory: all operations are assumed to be ordered such that every operation is either in the future, in the past or space-like separated from any other operation. Consequently, the correlations between operations respect definite causal order: they are either signalling correlations for the time-like or no-signalling correlations for the space-like separated operations. I will present a framework that assumes only that operations in local laboratories are described by quantum mechanics (i.e. are completely-positive maps), but relax the assumption that they are causally connected. Remarkably, we find situations where two operations are neither causally ordered nor in a probabilistic mixture of definite causal orders, i.e. one cannot say that one operation is before or after the other. The correlations between the operations are shown to enable performing a communication task (“causal game”) that is impossible if the operations are ordered according to a fixed background time. I will discuss experimental perspectives for observing such correlations in nature.

4:54PM W3.00005 Realism and the epistemic view of quantum states1 , TERRY RUDOLPH, Imperial College London — The idea that quantum states reflect only an observers knowledge/beliefs/information about the world has a long history, with a wide variety of strong arguments having been proffered in its favour. The challenge for an advocate of this position, however, is to identify what we can deduce is “really going on” out there. There seem to be three main paths proponents of the epistemic view have followed in tracing such a narrative from quantum theory. I will explain how the most naive such path—that quantum states can be associated with standard (probabilistic) uncertainty about some (arbitrary) real states of the world—is not tenable under some extremely mild assumptions about how any theory of reality must treat independent experiments. I will then overview the other two paths and what I see as the challenges they face.

1Research supported by the UK Engineering and Physical Sciences Research Council.

Thursday, March 21, 2013 2:30PM - 5:18PM — Session W26 GQ1: Focus Session: Semiconductor Qubits - Progress in Si 328 - Charles Tahan, Laboratory for Physical Sciences, University of Maryland

2:30PM W26.00001 Robust few-electron quantum dot devices in nuclear spin engineered Si/SiGe , DOMINIQUE BOUGEARD, Universitaet Regensburg, Institut fuer Experimentelle und Angewandte Physik, Regensburg, Germany — Spins in gate-defined quantum dots are currently discussed as one of the most promising scalable qubit architecture. Since the identification of the hyperfine interaction as a dominant spin qubit decoherence mechanism, Si/SiGe heterostructures have been receiving steadily increasing attention for realizing devices almost free of nuclear spin carrying isotopes. Building Si/SiGe heterostructures from material enriched in nuclear spin-free isotopes brings new perspectives of reaching a regime of further improved decoherence times compared to Si/SiGe of natural isotope composition. In such isotopically engineered heterostructures, the decoherence is predicted to no longer be governed by the hyperfine interaction with the nuclear spin bath, but solely by dipolar interactions. In the first part of my presentation I will review the development of two-dimensional electron systems in Si/SiGe for spin qubit applications in my group and discuss few electron double quantum dot devices based on these heterostructures. Being able to avoid hyperfine-induced decoherence then brings a second major limitation for the realization of robust spin qubits into focus. Indeed, the manipulation of such qubits relies on Coulomb interactions, enabling electronic noise to cause decoherence. Charge traps in the heterostructure may contribute to decoherence through a fluctuation of charges or through dipolar interactions of the spin degree of freedom of the trap and the qubit. In the second part of my talk I will present our recent study of charge noise in modulation-doped Si/SiGe heterostructures and discuss device and heterostructure designs which efficiently suppress charge noise.
3:06PM W26.00002 In situ isotopic enrichment and growth of $^{28}$Si for quantum information

KEVIN DWYER, Materials Science and Engineering, University of Maryland, JOSHUA POMEROY, NIST — Starting from natural abundance silane gas, we deposit $^{28}$Si films enriched in situ to 99.9% in support of solid state quantum information systems. Isotopically enriched materials such as $^{28}$Si are known to act as a "solid state vacuum" allowing for qubits with coherence (T$_2$) times of minutes. Quantum coherent devices rely on long T$_2$ times, but nuclear spin impurities are a major cause of decoherence. Isotopically enriching materials to eliminate stray nuclear spins (such as the 4.7% $^{29}$Si in natural silicon) greatly improves coherence. Our objective is to produce silicon that is not only isotopically enriched, but chemically pure and defect free. We crack and ionize a natural abundance source gas, magnetically mass filter the ions in a beam line, and deposit the enriched material hyperthermal energies. In addition to our first $^{28}$Si samples assessed by SIMS to be enriched to > 99.9%, we previously implanted $^{22}$Ne enriched at 99.4% (9.2% natural abundance) as proof of principle and have also grown $^{29}$Si films enriched at > 99.996% (98.9% natural abundance). To our knowledge, no other effort is actively producing enriched solid silicon directly from natural abundance silane. Ongoing improvements are leading us towards our goal of $^{28}$Si enriched to > 99.99% and epitaxial deposition.

3:18PM W26.00003 Coherence time of the nuclear spin of ionized phosphorus donors in $^{28}$Si at liquid He and room temperature, MICHAEL L.W. THEWALT, KAMYAR SAEEDI, Dept. of Physics, Simon Fraser University, Burnaby BC V5A 1S6 Canada, STEPHANIE SIMMONS, Dept. of Materials, Oxford University, Oxford OX1 3PH, UK, JOHN J.L. MORTON, London Centre for Nanotechnology, University College London, London WC1H OH, UK — Remarkable coherence times have recently been reported for the nuclear spin of dilute neutral $^{31}$P in highly enriched $^{28}$Si [1]. For ionized $^{31}$P, the removal of the hyperfine-coupled electron should result in a nuclear spin even more decoupled from the environment, and hence even longer coherence times at cryogenic temperatures. The coherence time of ionized $^{31}$P was recently observed in natural Si, and while the nuclear coherence time was indeed much longer than the electron coherence time measured in the same device, it was limited to 18 ms due to both the presence of $^{29}$Si as well as the readout mechanism being employed [2]. Here we report on coherence time measurements for ionized $^{31}$P in the same $^{28}$Si samples used for the previous [1] neutral donor study. In addition to the promise of longer cryogenic coherence times, the removal of the hyperfine-coupled electron should result in a profound change in the temperature dependence of T$_2$. For the neutral donor, the electron T$_2$ decreases very rapidly with increasing temperature, and even at 4.2 K the nuclear T$_2$ is limited by the electron T$_1$ [1]. This mechanism is absent for the ionized donor, and we will report on nuclear coherence time measurements for ionized $^{31}$P at room temperature.


3:30PM W26.00004 Decoherence of Neutral $^{31}$P Donor Nuclear Spins by $^{29}$Si$^1$, E.S. PETERSEN, A.M. TYRSHKIN, S.A. LYON, Princeton University, J.J.L. MORTON, University College London, K.M. ITOH, Keio University, M.L.W. THEWALT, Simon Fraser University — NMR data from degenerately doped Si:P has suggested that the coherence of $^{31}$P nuclear spins can be limited to a few ms in natural Si by spectral diffusion from $^{29}$Si [1]. Here we report measurements of the nuclear spin coherence of neutral isolated $^{31}$P donors in lightly-doped (~$10^{15}$ /cm$^3$) Si with $^{29}$Si concentrations from 1% to 50%. Pulsed ENDOR at X-band microwave frequency and a magnetic field of 0.35 T was used to measure the nuclear spins. The light doping and measurement temperature of 1.7K ensured that neither electron spin flips nor flip-flops limited the nuclear T$_2$. We find that the resulting echo intensity decays are nonexponential, and the time to reach 1/e is inversely proportional to the $^{29}$Si density. The nuclear decoherence time for natural silicon is found to be approximately 1 second, about 2000 times longer than donor electron spins in natural Si.


3:42PM W26.00005 Spin measurement in an undoped Si/SiGe double quantum dot incorporating a micromagnet, XIAN WU, JONATHAN PRANCE, DANIEL WARD, JOHN GAMBLE, DONALD SAVAGE, MAX LAGALLY, MARK FRIESEN, SUSAN COPPERSMITH, MARK ERIKSSON, University of Wisconsin-Madison — We present recent measurements on a double dot formed in an accumulation mode undoped Si/SiGe heterostructure. The double dot incorporates a proximal micromagnet to generate a stable magnetic field difference between the quantum dots. By measuring the ground state and excited state spectrum of this double dot as a function of in-plane magnetic field we identify the (1,1) and (2,0) charge degeneracy point. Using single-shot readout we measure transitions between the (2,0) singlet and the (1,1) triplet states. This method enables the identification of the crossing as a function of detuning between the (2,0) singlet and the (1,1) triplet states. The resulting echo intensity decays are nonexponential, and the time to reach 1/e is inversely proportional to the $^{29}$Si density. The nuclear decoherence time for natural silicon is found to be approximately 1 second, about 2000 times longer than donor electron spins in natural Si.

4:06PM W26.00007 A new mechanism for spin and valley relaxation in silicon quantum dots, RUSKOV RUSKOV, CHARLES TAHAN, Laboratory for Physical Sciences, College Park, MD 20740, U.S.A. — We consider spin and valley relaxation in imperfect silicon quantum dots with 1 to 3 electrons. Phonons, spin-orbit coupling, and the electrostatic confining potential of the dot all play roles in both the functional dependence on key parameters (say magnetic field) and the quantitative magnitude of the relaxation rate. Level mixing in the dot allows for spin relaxation via phonons and also explains anti-crossing behavior of dot levels as a function of magnetic field. We show that valley state relaxation can be fast in realistic dots and that spin relaxation can be a few orders of magnitude longer. Our results compare favorably to recent experimental data including the power dependence on magnetic field, location of relaxation hot spots, and the magnitude of the relaxation rates themselves. Some of this work is in collaboration with A. Dzurak group at the University of New South Wales, Australia.

4:18PM W26.00008 ABSTRACT WITHDRAWN —
4:30PM W26.00009 Interactions and valley-orbit coupling in Si quantum dots, LUYAO JIANG, ICQD, University of Science and Technology of China, C. H. YANG, University of New South Wales, ZHAO DI PAN, ICQD, University of Science and Technology of China, ANDREA MORELLO, ANDREW DZURAK, University of New South Wales, DIMITRIE CULCER, ICQD, University of Science and Technology of China — The valley-orbit coupling in a few-electron Si quantum dot is a function of its occupation number \( N \), and for \( N > 1 \) is in principle renormalized by the electron-electron Coulomb interaction, which is known to be strong. We study the interaction renormalization of the valley-orbit coupling for \( 2 \leq N \leq 4 \), showing that, counterintuitively, interaction effects on the valley-orbit coupling are weak. For \( N = 2 \) the renormalization is suppressed by valley interference, while for \( N = 3 \) all renormalization terms are zero due to spinor overlaps, and for \( N = 4 \) interaction renormalization terms cancel between different pairs of electrons. Experimental observations reveal no evidence of interaction effects on the valley-orbit coupling, consistent with these findings.

4:42PM W26.00010 Genetic Design of Enhanced Valley Splitting towards a Spin Qubit in Silicon, LI JUN ZHANG, JUN-WEI LEO, National Renewable Energy Laboratory, ANDRE SARAIVA, BELITA KOILLER, Universidade Federal do Rio de Janeiro, Brazil, ALEX ZUNGER, University of Colorado — The quantum state of an electron in the Si conduction band holds exceptional promise for quantum computing, owing to its attractive spin coherence properties and adaptability to standard electronics. A paramount challenge is the orbital degeneracy of the lowest conduction band of Si, which is potentially a serious source of decoherence for spin qubits. Hence, isolating a single electron valley state by creating a sufficiently large valley splitting (VS) is a prerequisite for the realization of Si-based spin qubits. Previous explorations of Si quantum wells confined by Si-Ge alloy barriers led thus far to a limited VS of the order of 1 meV or smaller. Here we demonstrate, via an atomically resolved pseudopotential theory, that the monolayer ordering of Si-Ge barriers within reach of modern superlattice growth techniques can be harnessed to enhance the VS by up to one order of magnitude compared to disordered random alloy barriers. A biologically inspired genetic-algorithm search allowed us to identify magic atomic layer sequences of the superlattice barriers that isolate single electron valley state in Si with VS as large as \( \sim 9 \) meV. These results may provide a roadmap for reliable spin-only quantum computing in Si.

A B. and M. J. C. were supported by FIS2009-07844 (MINECO, Spain). AS and BK's work is part of the Brazilian National Institute for Science and Technology on Quantum Information. AS and BK acknowledge partial support from FAPERJ, CNPq and CAPES.

4:54PM W26.00011 Impact of the valley degree of freedom on the control of donor electrons near a Si/SiO2 interface, ANDRE SARAIVA, IF-UFRJ, ALEJANDRA BAENA, MARIA CALDERÓN, ICCM - CSIC, BELITA KOILLER, IF-UFRJ — We analyze the valley composition of one electron bound to a shallow donor close to a Si/barrier interface as a function of an applied electric field within a multivalent effective mass model. Switching from low to high fields, the electron ground state is drawn from the donor site into the interface, leaving the donor partially ionized. Valley splitting at the interface occurs due to the valley-orbit coupling, \( V'_{\text{vo}} \). At intermediate electric fields, close to a characteristic shuttling field, the electron states may constitute hybridized states with valley compositions different from the donor and the interface ground states. The full spectrum shows crossings and anticrossings as the field varies. The degree of level repulsion depends on the relative valley compositions, which vary with \( V'_{\text{vo}}, \theta \) and the interface-donor distance. We focus on the valley configurations of the states involved in the donor-interface tunneling process, given by the anticrossing of the three lowest levels. A sequence of two anticrossings takes place and the complex phase \( \theta \) affects the symmetries of the eigenstates and level anticrossing gaps. Implications of our results on the practical manipulation of donor electrons in Si nanostructures are discussed.

1A B. and M. J. C. were supported by FIS2009-07844 (MINECO, Spain). AS and BK's work is part of the Brazilian National Institute for Science and Technology on Quantum Information. AS and BK acknowledge partial support from FAPERJ, CNPq and CAPES.

5:06PM W26.00012 Localization of Si/SiO2 Interface States: Properties and Physical Implications, BELITA KOILLER, AMINTOR DUSKO, ANDRE SARAIVA, Physics Institute, Universidade Federal do Rio de Janeiro — Interface states (IS) form spontaneously at some semiconductor-barrier interfaces and they may improve or hinder electronic control and coherence for semiconductor-based qubits. Intrinsic Si/SiO2 IS and its hybridization to the Si bulk states were recently investigated within tight binding (TB) models [1]. From the simplest model (1D), new insights emerge regarding the IS's energy and hybridization with the band states. In this work the 1D TB Hamiltonian is further explored, here within a Green's function formalism. The problem is solved exactly via a decimation technique based on renormalization group ideas [2]. The IS thus obtained are strictly related to the junction of two semi-infinite chains modeling the SI material and the SiO2 barrier, excluding possible contributions from parameters (e.g. chain length) previously invoked [1]. We obtain the energy of IS as well as the exponential longer (shorter) localization lengths into the Si (SiO2) material. The IS may be probed experimentally by an external electric field, which modulates the capacitance of the system, or by the spacing between the two lowest levels, related to the valley splitting [1].


work partially supported by FAPERJ, CNPq, CAPES.

Thursday, March 21, 2013 2:30PM - 5:30PM – Session W27 GQI: Focus Session: Superconducting Qubits: Quantum Computing Architectures 329 -

2:30PM W27.00001 Overview of a Quantum Annealing Processor, MARK W. JOHNSON, D-Wave Systems Inc. — Quantum Adiabatic Evolution algorithms have been proposed as a potentially powerful set of methods to solve computationally hard problems[1]. One example of this approach is to find the ground state configuration of an Ising spin system with a transverse field using quantum annealing (QA)[2]. I will present an overview of the architecture and operation of the D-Wave One, an end-to-end computing platform that performs QA by slowly decreasing the transverse field of a programmable Ising spin system. After a brief review of quantum annealing, I will describe how superconducting flux qubits are used to construct the programmable Ising spins[2]. I will then discuss some recent experiments performed to determine whether or not the processor behaves as intended. Toward this end, it is particularly useful to be able to measure the spectrum of single and multiple coupled qubits as they progress through the annealing algorithm[2]. Finally, since the primary measure of the efficacy of such a machine is how well it solves problems, I will conclude with a discussion of system performance and scaling.


3:06PM W27.00002 Realization of three-qubit quantum error correction with superconducting circuits, SCHOELKOPF ROBERT, Department of Applied Physics, Yale University — No abstract available.
3:42PM W27.00003 Cross-Talk in Superconducting Transmon Quantum Computing Architecture1, DAVID ABRAHAM, JERRY M. CHOW, ANTONIO CORCOLES, MARY BETH ROTHWELL, GEORGE KEEFE, JAY GAMBETTA, MATTHIAS STEFFEN, IBM T.J. Watson Research Center, IBM QUANTUM COMPUTING TEAM — Superconducting transmon quantum computing test structures often exhibit significant undesired cross-talk. For experiments with only a handful of qubits this cross-talk can be quantified and understood [1], and therefore corrected. As quantum computing circuits become more complex, and thereby contain increasing numbers of qubits and resonators, it becomes more vital that the inadvertent coupling between these elements is by itself. The task of accurately controlling each single qubit to the level of precision required throughout the realization of a quantum algorithm is difficult by itself, but coupled with the need of nulling out leakage signals from neighboring qubits or resonators would quickly become impossible. We discuss an approach to solve this critical problem.


1We acknowledge support from IARPA under contract W911NF-10-1-0324.

3:54PM W27.00004 Implementation of a two-qubit Grover algorithm using superconducting qubits1, MATTHIAS STEFFEN, ANTONIO CORCOLES, JERRY CHOW, JAY GAMBETTA, JOHN SMOLIN, IBM, MATT WARE, JOEL STRAND, BRITTON PLOURDE, Syracuse University — High fidelity two-qubit gates have previously been demonstrated with fixed frequency superconducting qubits and employing the cross-resonance effect generating the qubit-qubit interaction in which qubit 1 is driven at the frequency of qubit 2. The drawback of previous implementations of the cross-resonance gate is the fact that single qubit gates on qubit 2 emerge when the qubits are multi-level systems instead of strictly two-level systems. As a result, two-qubit gates must be tuned up by careful timing or by explicitly applying single-qubit correction pulses. This is a cumbersome procedure and can add overall errors. Instead, we show a refocusing scheme which preserves the two-qubit interaction but eliminates the single-qubit gates. The total gate length is only increased by the duration of two single qubit pi-pulses which is a low overhead. When tuning up this composite pulse we show an implementation of a two-qubit Grover’s algorithm without applying any correction pulses. The average success probability of the algorithm is consistent with fidelity metrics obtained by independent randomized benchmarking experiments (both single and two-qubit).

1We acknowledge support from IARPA under contract W911NF-10-1-0324.

4:06PM W27.00005 Emulating a mesoscopic system using superconducting quantum circuits , YU CHEN, R. BARENDTS, J. BOCHMANN, B. CAMPBELL, B. CHIARO, E. JEFFREY, J. KELLY, M. MARIANTONI, A. MEGRANT, J. MUTUS, C. NEILL, P. O’MALLEY, S. OHYA, P. ROUSHAN, D. SANK, A. VAINSENCHER, J. WENNER, T. WHITE, A. N. CLELAND, J. M. MARTINIS, UC Santa Barbara — We demonstrate an emulation of a mesoscopic system using superconducting quantum circuits. Taking advantage of our ReZQu-architected quantum processor, we controllably split a microwave photon and manipulated the split photons before they recombined for detection. In this way, we were able to simulate the weak localization effect in mesoscopic systems - a coherent backscattering process due to quantum interference. The influence of the phase coherence was investigated by tuning the coherence time of the quantum circuit, which in turn mimics the temperature effect on the weak localization process. At the end, we demonstrated an effect resembling universal conductance fluctuations, which arises from the frequency beating between different coherent backscattering processes. The universality of the observed fluctuation was shown as the independence of the fluctuation amplitude on detailed experimental conditions.

4:18PM W27.00006 Speed limits for quantum gates in multiquit solid-state systems , SAHEL ASHHAB, The Institute of Physical and Chemical Research (RIKEN), Wako-shi, Japan, and The University of Michigan at Ann Arbor, USA, PIETER DE GROOT, Delft University of Technology, The Netherlands; and Max Planck Institute for Quantum Optics, Garching, Germany, FRANCO NORTI, The Institute of Physical and Chemical Research (RIKEN), Wako-shi, Japan; and The University of Michigan at Ann Arbor, USA — We derive speed limits for various unitary quantum operations in multiquit systems under typical experimental conditions, using parameters and constraints that are commonly encountered with superconducting qubits. In particular we focus on two- and three-qubit gates. We find that simple methods for implementing two-qubit gates generally provide the fastest possible implementations of these gates. We also find that the three-qubit Toffoli gate time varies greatly depending on the type of interactions and the system’s geometry, taking only slightly longer than a two-qubit controlled-NOT (CNOT) gate for a triangle geometry.

4:30PM W27.00007 Designing entangling microwave gates between fixed frequency superconducting circuits coupled by resonators1, SETH MERKEL, JAY GAMBETTA, JOHN SMOLIN, IBM, IBM QUANTUM COMPUTING TEAM TEAM — Many of the recent techniques for controlling superconducting quantum circuits are directly derived from the atomic theory of cavity QED, and the fixed frequency transmon provides a particularly close analogy to an “artificial atom.” However, even in this case new modelling techniques are required as we engineer parameter regimes that have been previously unexplored in atomic systems. In this talk we develop the Schrieffer-Wolff transformation as a means of adiabatically eliminating high-energy subspaces in order to derive effective entangling Hamiltonians. We can use this theory to explain many of the recent, experimentally demonstrated fixed frequency gates such as the cross-resonance gate and the two-photon 00 to 11 transition. In the case of the cross-resonance gate this more detailed model predicts spurious single qubit rotations, and their rates, which can then be removed through refocusing techniques.

1We acknowledge support from IARPA under contract W911NF-10-1-0324.

4:42PM W27.00008 Hardware-efficient quantum memory protection1, ZAKI LEGHTAS, GERHARD KIRCHMAIR, BRIAN VLASTAKIS, ROBERT SCHOELKOPF, MICHEL DEVORET, Applied Physics Department, Yale University, MAZYAR MIRRAHIMI, INRIA Paris-Rocquencourt / Applied Physics Department, Yale University — We propose a new method to autonomously correct for errors of a logical qubit induced throughout the realization of a quantum algorithm. This gives rise to strong multi-mode coupling and can be utilized in multiple ways to create strongly correlated microwave photons. We acknowledge support from DARPA through the QuEST program and by NSERC Discovery grants.

4:54PM W27.00009 Engineered circuit QED with dense resonant modes1, FRANK WILHELM, DANIEL EGGERT, Saarland University — In circuit quantum electrodynamics even in the ultrastrong coupling regime, strong quasi-resonant interaction typically involves only one mode of the resonator as the mode spacing is comparable to the frequency of the mode. We are going to present an engineered hybrid transmission line consisting of a left-handed and a right-handed port that has a low-frequency van-Hove singularity hence showing a dense mode spectrum at an experimentally accessible point. This gives rise to strong multi-mode coupling and can be utilized in multiple ways to create strongly correlated microwave photons.

1Supported by DARPA through the QuEST program and by NSERC Discovery grants.

2On leave from the Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Canada.
Observing the nonequilibrium dynamics of the quantum transverse-field Ising chain in circuit QED

OLIVER VIEHMANN, JAN VON DELFT, Physics Department, ASC, and CeNS, LMU Munich, FLORIAN MARQUARDT, Institute for Theoretical Physics, FAU Erlangen-Nuremberg — Circuit QED architectures of superconducting artificial atoms and microwave resonators are currently moving towards multi-atom, multi-resonator setups with drastically enhanced coherence times, making them increasingly attractive candidates for quantum simulations of interesting interacting quantum many-body systems. Here we propose and analyze a circuit QED design that implements the quantum transverse-field Ising chain coupled to a microwave resonator for readout. Our setup can be used to study quench dynamics, the propagation of localized excitations, and other nonequilibrium features, in a field theory exhibiting a quantum phase transition, and based on a design that is feasible with current technology and could easily be extended to break the integrability of the system.

Strongly-coupled Josephson junction array for simulation of frustrated one-dimensional spin models

ZHENGWEI ZHOU, LIANGHUI DU, XINGXUANG ZHOU, YONGJIAN HAN, GUANGCAN GUO, Key Laboratory of Quantum Information, University of Science and Technology of China — We study the capacitance-coupled Josephson-junction array beyond the small-coupling limit. We find that, when the scale of the system is large, its Hamiltonian can be obtained without the small-coupling approximation and the system can be used to simulate strongly frustrated one-dimensional Ising spin problems. To engineer the system Hamiltonian for an ideal theoretical model, we apply a dynamical-decoupling technique to eliminate undesirable couplings in the system. Using a six-site junction array as an example, we numerically evaluate the system to show that it exhibits important characteristics of the frustrated spin model.