APS March Meeting 2016
Baltimore, Maryland
http://www.aps.org/meetings/march/index.cfm
8:00AM A13.00001 Estimating the coherence of noise. JOEL WALLMAN, Univ of Waterloo — To harness the advantages of quantum information processing, quantum systems have to be controlled to within some maximum threshold error. Certifying whether the error is below the threshold is possible by performing full quantum process tomography, however, quantum process tomography is inefficient in the number of qubits and is sensitive to state-preparation and measurement errors (SPAM). Randomized benchmarking has been developed as an efficient method for estimating the average infidelity of noise to the identity. However, the worst-case error, as quantified by the diamond distance from the identity, can be more relevant to determining whether an experimental implementation is at the threshold for fault-tolerant quantum computation. The best possible bound on the worst-case error (without further assumptions on the noise) scales as the square root of the infidelity and can be orders of magnitude greater than the reported average error. We define a new quantification of the coherence of a general noise channel, the unitarity, and show that it can be estimated using an efficient protocol that is robust to SPAM. Furthermore, we also show how the unitarity can be used, with the infidelity obtained from randomized benchmarking to obtain improved estimates of the diamond distance and to efficiently determine whether experimental noise is close to stochastic Pauli noise.

8:36AM A13.00002 Gate-set tomography and beyond. ROBIN BLUME-KOHOUT, Sandia National Laboratories — Four years ago, there was no reliable way to characterize and debug quantum gates. Process tomography required perfectly pre-calibrated gates, while randomized benchmarking only yielded an overall error rate. Gate-set tomography (GST) emerged around 2012-13 in several variants (most notably at IBM; see PRA 87, 062119) to address this need, providing complete and calibration-free characterization of gates. At Sandia, we have pushed the capabilities of GST well beyond these initial goals. In this talk, I’ll demonstrate our open web interface, show how we characterize gates with accuracy at the Heisenberg limit, discuss how we put error bars on the results, and present experimental GST estimates with 1e-5 error bars. I’ll also present preliminary results of GST on 2-qubit gates, including a brief survey of the tricks we use to make it possible. I’ll conclude with an analysis of GST’s limitations (e.g., it scales poorly), and the techniques under development for characterizing and debugging larger (3+ qubit) systems.

9:12AM A13.00003 Toward a new culture in verified quantum operations. STEVE FLAMMIA, University of Sydney — Measuring error rates of quantum operations has become an indispensable component in any aspiring platform for quantum computation. As the quality of controlled quantum operations increases, the demands on the accuracy and precision with which we measure these error rates also grows. However, well-meaning scientists that report these error measures are faced with a sea of non-standardized methodologies and are often asked during publication for only coarse information about how their estimates were obtained. Moreover, there are serious incentives to use methodologies and measures that will continually produce numbers that improve with time to show progress. These problems will only get exacerbated as our typical error rates go from 1 in 100 to 1 in 1000 or less. This talk will survey existing challenges presented by the current paradigm and offer some suggestions for solutions than can help us move toward fair and standardized methods for error metrology in quantum computing experiments, and towards a culture that values full disclosure of methodologies and higher standards for data analysis.

9:48AM A13.00004 Applying QCVV protocols to real physical systems.1. EASWAR MAGESAN, IBM TJ Watson Research Center — As experimental systems move closer to realizing small-scale quantum computers with high fidelity operations, errors become harder to detect and diagnose. Verification and validation protocols are becoming increasingly important for detecting and understanding the precise nature of these errors. I will outline various methods and protocols currently used to deal with errors in experimental systems. I will also discuss recent advances in implementing high fidelity operations which will help to understand some of the tools that are still needed on the road to realizing larger scale quantum systems.

1Work partially supported by ARO under contract W911NF-14-1-0124

10:24AM A13.00005 Applying benchmarking protocols to encoded qubits with non-Markovian errors. SETH MERKEL, HRL Laboratories, LLC. — An essential goal for any quantum information processing platform is to develop the tools necessary to validate high-fidelity quantum gates. This effort has produced a suite of benchmarking and tomographic protocols that have been applied to a wide variety of physical implementations. All these protocols, however, were designed with strict error assumptions that can and will be violated by physical errors, especially as we push to lower and lower error rates. In this talk we look at randomized benchmarking with encoded states (from which leakage errors may occur) in the presence of non-Markovian noise and under the influence of sequence-length dependent filtering errors. These circumstances may apply to a variety of physical systems, but are particularly pertinent for 1/f charge noise and hyperfine leakage noise in electrically controlled quantum dot qubits. We demonstrate how these errors affect the outcome of randomized benchmarking, including the signatures of said errors and the confidence with which we can report an average gate fidelity.
and manipulating logical qubits, and gate implementations.

We thoroughly discuss protocols for stabilizer measurements, encoding Majorana fermion surface code for universal quantum computation, with a single-step stabilizer measurement requiring no physical ancilla qubits, increased error tolerance, and simpler logical gates than a surface code with bosonic physical qubits. We present a numerical study of the low-energy spectrum of this device covering both the charge-dominated regime utilizable for initialization and readout of the Majorana bound states as well as the Josephson-dominated transmon regime allowing for Majorana manipulations. Depending on the relative size of the energy scales associated with the Majorana coupling, the charging energy, and the transmon frequency, the fine structure of the low-energy spectrum differs. We finally discuss the associated time scales for implementing a fusion-rule testing protocol discussed in the talks by J. Alicea and R. V. Mishmash.

We introduce an exactly solvable model of interacting Majorana fermions realizing Majorana coupling, the charging energy, and the transmon frequency, the fine structure of the low-energy spectrum differs. We finally discuss the associated time scales for implementing a fusion-rule testing protocol discussed in the talks by J. Alicea and R. V. Mishmash.

This work was supported by the Natural Sciences and Engineering Research Council of Canada

9:12AM A44.00002 Gate-controlled charging effects in superconducting nanowires: low-energy spectrum and time scales for Majorana manipulation, Michael Hell, Division of Solid State Physics and NanoLund, Lund Univ., Sweden / Center for Quantum Devices and Station Q Copenhagen, Univ. of Copenhagen, Denmark, Jeroen Danon, Center for Quantum Devices and Station Q Copenhagen and Niels Bohr International Academy, Univ. of Copenhagen, Denmark, Martin Leijnse, Division of Solid State Physics and NanoLund, Lund Univ., Sweden / Center for Quantum Devices and Station Q Copenhagen, Univ. of Copenhagen, Denmark, Karsten Flensberg, Center for Quantum Devices and Station Q Copenhagen, Univ. of Copenhagen, Denmark — In this talk, we investigate the gate-controlled crossover between different operating regimes of a superconducting nanowire segmented into two islands each Josephson-coupled to a bulk superconductor. This device may host two pairs of Majorana bound states and could be realized in the near future as a platform for testing Majorana fusion rules. We present a numerical study of the low-energy spectrum of this device covering both the charge-dominated regime utilizable for initialization and readout of the Majorana bound states as well as the Josephson-dominated transmon regime allowing for Majorana manipulations. Depending on the relative size of the energy scales associated with the Majorana coupling, the charging energy, and the transmon frequency, the fine structure of the low-energy spectrum differs. We finally discuss the associated time scales for implementing a fusion-rule testing protocol discussed in the talks by J. Alicea and R. V. Mishmash.

8:24AM A44.00003 Demonstrating non-Abelian statistics of Majorana fermions using twist defects, Huaixiu Zheng, Arpit Dua, Liang Jiang, Yale University — We study the twist defects in the toric code model introduced by Bombin [Phys. Rev. Lett. 105, 030403 (2010)]. Using a generalized 2D Jordan-Wigner transformation and a projective construction, we show explicitly the twist defects carry unpaired Majorana zero modes. In addition, we propose a quantum non-demolition measurement scheme of the parity of Majorana modes. Such a scheme provides an alternative avenue to demonstrate the non-Abelian statistics of Majorana fermions. The braiding operation is simulated by an efficient measurement-based approach that removes the uncertainty associated with the previous forced measurement scheme.

8:36AM A44.00004 Parafermions in spin lattices, Arpit Dua, Huaixiu Zheng, Liang Jiang, Yale University — We investigate the twist defects in the Z_2 Toric code model first introduced by Bombin [Phys. Rev. Lett. 105, 030403 (2010)] for the Z_2 model and then generalized and studied by You et al. [Phys. Rev. B 86, 161107(R) (2012)]. Using topological entanglement entropy (TEE) and generalized Jordan-Wigner transformation, we show explicitly that the twist defects carry unpaired Parafermion zero modes. We also demonstrate the fusion rules of these Parafermion modes using the TEE calculation. In addition, we propose a scheme for quantum non-demolition measurement of the topological charge of these modes. This scheme can be used to implement measurement-based braiding (MBBs) on Parafermions to implement gates for quantum computing.

8:48AM A44.00005 Odd-frequency superconductivity in a nanowire coupled to Majorana zero modes, Shu-Ping Lee, University of Alberta, Roman M. Lutchyn, Microsoft Station Q, Joseph Maciejko, University of Alberta — Odd-frequency superconductivity, originally proposed by Berezinskii in 1974, is an exotic phase of matter in which pairing is entirely dynamical in nature. The pair potential is an odd function of frequency, leading to a vanishing static superconducting order parameter and exotic types of pairing seemingly inconsistent with Fermi statistics, such as spin triplet (singlet) pairing in an s-wave (p-wave) superconductor. Motivated by recent experimental progress in the realization of Majorana zero modes in semiconducting nanowires, we show that a spin-polarized nanowire coupled to a one-dimensional array of Majorana zero modes becomes an odd-frequency superconductor.

This work was supported by NSERC, CRC, CIFAR, and the University of Alberta.

9:00AM A44.00006 Readout scheme for Majorana parity states using a quantum dot, Darryl Hoving, Kaveh Karahari, Jonathan Baugh, University of Waterloo — We propose and numerically study a scheme for reading out the parity state of a pair of Majorana bound states using a tunnel coupled quantum dot. The dot is coupled to one end of the topological wire but isolated from any reservoir, and is capacitively coupled to a charge sensor for measurement. The combined parity of the MBS-dot system is conserved and charge transfer between MBS and dot only occurs through resonant tunnelling. Resonance is controlled by the dot potential through a local gate and by the MBS splitting due to the overlap of the MBS pair wavefunctions. The latter splitting can be controlled by changing the position of the spatially separated, uncoupled MBS via a set of keyboard gates. Our simulations show that the MBS pair wavefunctions, the latter splitting can be controlled by changing the position of the spatially separated, uncoupled MBS via a set of keyboard gates. The readout scheme provides an alternative avenue to demonstrate the non-Abelian statistics of Majorana fermions. The braiding operation is simulated by an efficient measurement-based approach that removes the uncertainty associated with the previous forced measurement scheme.

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

9:12AM A44.00007 Majorana Fermion Rides on a Magnetic Domain Wall, Se Kwon Kim, Univ of California - Los Angeles, Sumanta Tewari, Clemson University, Yaroslav Tsirkovnyak, Univ of California - Los Angeles — Owing to the recent progress on endowing the electronic structure of magnetic nanowires with topological properties, the associated topological solitons in the magnetic texture—magnetic domain walls—appear as very natural hosts for exotic electronic excitations. Here, we propose to use the magnetic domain walls to engender Majorana fermions [1], which has several notable advantages compared to the existing approaches. First of all, the local tunneling density-of-states anomaly associated with the Majorana zero mode bound to a smooth magnetic soliton is immune to most of parasitic artifacts associated with the abrupt physical ends of a wire, which mar the existing experimental probes. Second, a viable route to move and braid Majorana fermions is offered by domain-wall motion. In particular, we envision the recently demonstrated heat-current induced motion of domain walls in insulating ferromagnets as a promising tool for nonintrusive displacement of Majorana modes. This leads us to propose a feasible scheme for braiding domain walls within a magnetic nanowire network, which manifests the non-Abelian exchange statistics within the Majorana subspace.


This work has been supported in part by the U.S. DOE-BES, FAME, and AFOSR grants.

9:24AM A44.00008 Majorana Fermion Surface Code for Universal Quantum Computation, Sagar Vijay, Tim Hsieh, Liang Fu, MIT — We introduce an exactly solvable model of interacting Majorana fermions realizing Z_2 topological order with a Z_2 fermion parity grading and lattice symmetries permuted by the three fundamental anyon types. We propose a concrete physical realization by utilizing quantum phase slips in an array of Josephson-coupled mesoscopic topological superconductors, which can be implemented in a wide range of solid state systems, including topological insulators, insulators or two-dimensional electron gases, proximitized by s-wave superconductors. Our model finds a natural application as a Majorana fermion surface code for universal quantum computation, with a single-step stabilizer measurement requiring no physical ancilla qubits, increased error tolerance, and simpler logical gates than a surface code with bosonic physical qubits. We thoroughly discuss protocols for stabilizer measurements, encoding and manipulating logical qubits, and gate implementations.
This makes coupling spin qubits via superconducting resonators in a circuit-QED approach a realistic possibility. F.R. Braakman et al, Nature Nano 8, 432.

We develop superconducting resonators that are resilient to magnetic field and with a predicted tenfold increase in vacuum electric field amplitudes.

dot arrays preserving the spin projection for more than 500 hops. We use this technique to read out multiple spins in a way analogous to the operation of a quantum dot array. The intermediate quantum dot controls the frequency of the exchange-driven oscillations of the spins. Second, we demonstrate shuttling of electrons in quantum dots utilizing the physics of topologically ordered phases of matter.

Furthermore, experimental demonstrations of controlled spin-exchange have been limited to 1D quantum dot arrays only. Here we explore several avenues for scaling beyond 1D arrays with nearest-neighbour coupling. First, we show that second-order tunnel processes allow for coherent spin-exchange between non-nearest neighbour quantum dots.

The condition that the non-Abelian statistics of the anyons supports a computationally universal set of gates. We consider the possibility to enrich the possible topological operations supported by a non-Abelian topological phase by introducing defects into the system. We show that such defects bind zero modes which form a unique algebra for the case of a bi-layer containing Ising anyons, we show that by coupling zero modes one can obtain a set of topological operations that implements a universal set of gates.

Braiding these zero Majorana fermions yields non-abelian statistics. With particle number conservation, we show in certain geometry, the Berry phase of interchanging two Majorana zero modes is proportional to angular momentum of the system with the presence of two vortices, which can then be calculated in the thermodynamic limit. The braiding statistics turns out to be consistent with the standard result. We then discuss the possible complication due to finite size effect. We'll argue that in a finite size system, the abelian phase of interchanging two vortices is non-topological. We'll finish the discussion by sketching out ongoing work in which we investigate the possible modification of BdG quasi-particle wave functions beyond the BdG mean-field approximation, which can have dramatic effect on topological properties of Majorana zero modes and their braiding statistics.

Beyond parafermions: Defects and zero-modes in non-Abelian phases. NETANEL LINDNER, Technion - Israel Institute of Technology, EREZ BERG, ADY STERN, Weizmann Institute of Science — Non-Abelian topological phases of matter can be utilized to encode and manipulate quantum information in a non-local manner, such that it is protected from imperfections in the implemented protocols and from interactions with the environment. The condition that the non-Abelian statistics of the anyons supports a computationally universal set of gates sets a very stringent requirement which is not met by many topological phases. We consider the possibility to enrich the possible topological operations supported by a non-Abelian topological phase by introducing defects into the system. We show that such defects bind zero modes which form a unique algebra for the case of a bi-layer containing Ising anyons, we show that by coupling zero modes one can obtain a set of topological operations that implements a universal set of gates.

8:00AM A44.00001 Spin qubits in quantum dots – beyond nearest-neighbour exchange. LIEVEN VANDERSYPEN, QuTech and Kavli Institute of Nanoscience — The spin of a single electron is the canonical two-level quantum system. When isolated in a semiconductor quantum dot, a single electron spin provides a well-controlled and long-lived quantum bit. So far, two-qubit gates in this system have relied on the spin exchange interaction that arises when the wave functions of neighbouring electrons overlap. Furthermore, experimental demonstrations of controlled spin-exchange have been limited to 1D quantum dot arrays only. Here we explore several avenues for scaling beyond 1D arrays with nearest-neighbour coupling. First, we show that second-order tunnel processes allow for coherent spin-exchange between non-nearest neighbour quantum dots.

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8:36AM A44.00002 Characterization of accumulation-mode Si/SiGe triple quantum dots. T. M. HAZARD, D. M. ZAJAC, X. MI, S. S. ZHANG, J. R. PETTA, Department of Physics, Princeton University — The transition from quantum dots fabricated from doped Si/SiGe quantum wells to undoped accumulation-mode structures has greatly improved the performance of few-electron quantum dots. Our accumulation-mode devices are reconfigurable and allow for operation as single, double, or triple quantum dots. In these devices, we measure typical charging energies $E_C = 5.7 \text{ eV}$, orbital excited state energies as large as $E_C = 2.9 \text{ meV}$, and valley splittings of up to $E_C = 80 \mu \text{eV}$. With the device configured as a triple quantum dot, we easily reach the $(1,1,1)$ charge configuration. The gate architecture allows the interdot tunnel coupling to be tuned over a wide range, which is important for operation as an exchange-only spin qubit.$^1$

8:48AM A44.00010 Braiding Majorana fermions in p+ip superfluids with particle number conservation . YIRUO LIN, ANTHONY LEGGETT, University of Illinois at Urbana-Champaign — We discuss braiding statistics of Majorana zero modes localized in vortices in 2D spinless p+ip superfluids with conserved total particle number. In the standard particle non-conserved context, it has been argued that braiding these zero Majorana fermions yields non-abelian statistics. With particle number conservation, we show that in certain geometry, the Berry phase of interchanging two Majorana zero modes is proportional to angular momentum of the system with the presence of two vortices, which can then be calculated in the thermodynamic limit. The braiding statistics turns out to be consistent with the standard result. We then discuss the possible complication due to finite size effect. We’ll argue that in a finite size system, the abelian phase of interchanging two vortices is non-topological. We’ll finish the discussion by sketching out ongoing work in which we investigate the possible modification of BdG quasi-particle wave functions beyond the BdG mean-field approximation, which can have dramatic effect on topological properties of Majorana zero modes and their braiding statistics.

10:00AM A44.00011 Beyond parafermions: Defects and zero-modes in non-Abelian phases. NETANEL LINDNER, Technion - Israel Institute of Technology, EREZ BERG, ADY STERN, Weizmann Institute of Science — Non-Abelian topological phases of matter can be utilized to encode and manipulate quantum information in a non-local manner, such that it is protected from imperfections in the implemented protocols and from interactions with the environment. The condition that the non-Abelian statistics of the anyons supports a computationally universal set of gates sets a very stringent requirement which is not met by many topological phases. We consider the possibility to enrich the possible topological operations supported by a non-Abelian topological phase by introducing defects into the system. We show that such defects bind zero modes which form a unique algebra for the case of a bi-layer containing Ising anyons, we show that by coupling zero modes one can obtain a set of topological operations that implements a universal set of gates.

10:12AM A44.00012 Tunable Splitting of the Ground-State Degeneracy in 1D Parafermionic Wires. CHUN CHEN, FIONA BURNELL, Univ of Minn - Minneapolis — Systems with topologically protected ground-state degeneracies are currently of great interest due to their potential applications in quantum computing. In practise this degeneracy is never exact, and the magnitude of the ground-state degeneracy splitting is constrained by the timescales over which information is topologically protected. In this Letter we use an instanton approach to evaluate the splitting of topological ground-state degeneracy in quasi-1D systems with parafermion zero modes, in the specific case where parafermions are realized by inducing a superconducting gap in pairs of fractional quantum Hall (FQH) edges. We show that, like 1D topological superconducting wires, this splitting has an oscillatory dependence on the chemical potential, which arises from an intrinsic Berry phase that produces interference between distinct instanton tunneling events. These Berry phases can be mapped to chiral phases in a (dual) quantum clock model using a Fradkin-Kadanoff transformation. Comparing our low-energy spectrum to that of phenomenological parafermion models allows us to evaluate the real and imaginary parts of the hopping integral between adjacent parafermionic zero modes as functions of the chemical potential.

Monday, March 14, 2016 8:00AM - 11:00AM — Session A45 GQI: Semiconductor Qubits: Si/SiGe Quantum Dots 348 - Jason Petta, Princeton University

8:00AM A45.00001 Spin qubits in quantum dots – beyond nearest-neighbour exchange. LIEVEN VANDERSYPEN, QuTech and Kavli Institute of Nanoscience — The spin of a single electron is the canonical two-level quantum system. When isolated in a semiconductor quantum dot, a single electron spin provides a well-controlled and long-lived quantum bit. So far, two-qubit gates in this system have relied on the spin exchange interaction that arises when the wave functions of neighbouring electrons overlap. Furthermore, experimental demonstrations of controlled spin-exchange have been limited to 1D quantum dot arrays only. Here we explore several avenues for scaling beyond 1D arrays with nearest-neighbour coupling. First, we show that second-order tunnel processes allow for coherent spin-exchange between non-nearest neighbour quantum dots. The detuning of the intermediate quantum dot controls the frequency of the exchange-driven oscillations of the spins. Second, we demonstrate shuttling of electrons in quantum dot arrays preserving the spin projection for more than 500 hops. We use this technique to read out multiple spins in a way analogous to the operation of a CCD. Finally, we develop superconducting resonators that are resilient to magnetic field and with a predicted tenfold increase in vacuum electric field amplitudes.

8:36AM A44.00002 Characterization of accumulation-mode Si/SiGe triple quantum dots. T. M. HAZARD, D. M. ZAJAC, X. MI, S. S. ZHANG, J. R. PETTA, Department of Physics, Princeton University — The transition from quantum dots fabricated from doped Si/SiGe quantum wells to undoped accumulation-mode structures has greatly improved the performance of few-electron quantum dots. Our accumulation-mode devices are reconfigurable and allow for operation as single, double, or triple quantum dots. In these devices, we measure typical charging energies $E_C = 5.7 \text{ eV}$, orbital excited state energies as large as $E_C = 2.9 \text{ meV}$, and valley splittings of up to $E_C = 80 \mu \text{eV}$. With the device configured as a triple quantum dot, we easily reach the $(1,1,1)$ charge configuration. The gate architecture allows the interdot tunnel coupling to be tuned over a wide range, which is important for operation as an exchange-only spin qubit.$^1$

Research sponsored by ARO Grant No. W911NF-15-1-0149.


Characterization of a gate-defined double quantum dot in a Si/SiGe nanomembrane. We report the characterization of a gate-defined double quantum dot formed in a Si/SiGe nanomembrane. Previously, all heterostructures used to form quantum dots were created using the strain-grading method of strain relaxation, a method that necessarily introduces misfit dislocations into a heterostructure and thereby degrades the reproducibility of quantum devices. Using a SiGe nanomembrane as a virtual substrate eliminates the need for misfit dislocations but requires a wet-transfer process that results in a non-epitaxial interface in close proximity to the quantum dots. We show that this interface does not prevent the formation of quantum dots, and is compatible with a tunable inter-dot tunnel coupling, the identification of spin states, and the measurement of a singlet-to-triplet transition as a function of the applied magnetic field. This work was supported in part by ARO (W911NF-12-0607), NSF (DMR-1260915, PHY-1104660), and the United States Department of Defense. The views and conclusions contained in this document are those of the author and should not be interpreted as representing the official policies, either expressly or implied, of the US Government.  

Support through the EC FP7-ICT project SISPIN no. 323841, and the Danish National Research Foundation is acknowledged.

9:12AM A45.00005 Observation of multiple exchange oscillation frequencies in Si/SiGe spin qubits. MATT WAKHER, HRL Laboratories, LLC — An all-electrical approach to quantum information processing with spin qubits in Si/SiGe quantum wells relies on the ability to quickly turn on and off the exchange interaction between electrons in neighboring quantum dots [1]. The quality of gates enabled by this technique depends critically on reliably achieving a specific value of exchange coupling for a given control voltage. In recent experiments [2], we have observed multiple exchange oscillation frequencies at the same control bias for several different devices. In particular, Fourier transforms of exchange oscillations measured as a function of evolution time reveal the presence of multiple frequencies over a wide range of pulse amplitudes. The data are suggestive of unwanted population of an excited singlet-triplet manifold that behaves similarly with bias as the qubit ground state pair. The occupation of excited singlet-triplet states can degrade gate performance in exchange-based quantum devices and we outline methods to observe and investigate these states. [1] K. Eng et al, Science Advances 1 (2015) [2] M.D. Reed et al, arxiv:1508.01223 (2015)

9:24AM A45.00006 Predicting the valley physics of silicon quantum dots directly from a device layout. JOHN KING GAMBLE, Sandia National Laboratories, PATRICK HARVEY-COLLARD, Sandia National Laboratories and Université de Sherbrooke, N. TOBIAS JACOBSON, ANDREW D. BACEWSKI, ERIK NIELSEN, INES MONTANO, MARTIN RUDOLPH, MALCOLM S. CARROLL, RICHARD P. MULLER, Sandia National Laboratories — Qubits made from electrostatically-defined quantum dots in Si-based systems are excellent candidates for quantum information processing applications. However, the multi-valley structure of silicon’s band structure provides additional challenges for the few-electron physics critical to qubit manipulation. Here, we present a theory for valley physics that is predictive, in that we take as input the real physical device geometry and experimental voltage operation schedule, and with minimal approximation compute the resulting valley physics. We present both effective mass theory and atomistic tight-binding calculations for two distinct metal-oxide-semiconductor (MOS) quantum dot systems, directly comparing them to experimental measurements of the valley splitting. We conclude by assessing these detailed simulations utility for engineering desired valley physics in future devices. Sandia is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the US Department of Energy’s National Nuclear Security Administration under Contract No. DE-AC04-94AL85000.

9:36AM A45.00007 Gate fidelity and coherence time of an electron spin in a Si/SiGe quantum dot. ERIKA KAWAKAMI, THIBAUT JULLIEN, PASQUALE SCARLINO, Delft Univ of Tech — Electron spins in Si/SiGe quantum dots are one of the most promising candidates for a quantum bit for their potential scalability and long dephasing time. We realized coherent control of an individual electron spin in a single quantum dot (QD), lithographically defined in a Si/SiGe 2D electron gas. Spin rotations are achieved by applying microwave excitation to one of the gates, which oscillates the electron wave function back and forth in the gradient field produced by cobalt micromagnets fabricated near the dot. Thanks to the long intrinsic dephasing time $T_2 = 900$ ns and Rabi frequency of 1.4 MHz, we were able to obtain an average single qubit gate fidelity of an electron spin in a Si/SiGe quantum dot of 99 %, measured via randomized benchmarking. The dephasing time is extended to 70 $\mu$s using Hahn echo, and up to 400 $\mu$s with multipulse dynamical decoupling (128 $\pi$ pulses). We extract the noise spectrum in the range of 5 kHz -1 MHz using dynamical decoupling and show that the gate fidelity is well explained by this noise characteristic. We discuss the mechanism that induces this noise and is responsible for decoherence.

9:48AM A45.00008 Epitaxial deposition of highly enriched $^{28}$Si films with $< 1$ nm roughness. K. J. DWYER, HYUN-SOO KIM, A. N. RAMANAYAKA, D. S. SIMONS, VLADIMIR OLESHKO, J. M. POMEROY, National Institute of Standards and Technology — Low temperature epitaxial deposition of thin films with less than 1 nm rms roughness is achieved using a $^{28}$Si ion beam deposition source. These films are enriched in situ to $< 140$ ppb $^{28}$Si isotope fraction for quantum computing devices. Removal of the 4.7 % $^{28}$Si nuclear spins in natural silicon allows for exceedingly long coherence ($T_2$) times of qubits, making incorporation of highly enriched $^{28}$Si into devices critical for solid state quantum information. Low roughness epitaxial $^{28}$Si thin films are achieved by depositing in an island growth mode at temperatures of 300 C to 400 C, and the morphology is verified using scanning tunneling microscopy. Further, the crystalline quality of the films is shown using cross-sectional transmission electron microscopy. Finally, the chemical purity and broader electrical properties of the $^{28}$Si films are assessed by secondary ion mass spectrometry as well as capacitance–voltage profiling, shottky diode measurements, and hall measurements.
First measurements of charge carrier density and mobility of in-situ enriched $^{28}$Si. A. N. RAMAYANAYAKA, Joint Quantum Institute, National Institute of Standards and Technology, K. J. DWYER, HYUN-SOO KIM, University of Maryland, M. D. STEWART, JR., J. M. POMEROY, National Institute of Standards and Technology — Magnetotransport in top gated Hall bar devices is investigated to characterize the electrical properties of in-situ enriched $^{28}$Si. Isotopically enriched $^{28}$Si is an ideal candidate for quantum information processing devices as the elimination of unpaired nuclear spins increases the fidelity of the quantum information. Using mass filtered ion beam deposition we, in-situ, enrich and deposit epitaxial $^{28}$Si, achieving several orders of magnitude better enrichment compared to other techniques. In order to explore the electrical properties and optimize the growth conditions of in-situ enriched $^{28}$Si we perform magnetotransport measurements on top gated Hall bar devices at temperatures ranging from 300 K to cryogenic temperatures and at moderate magnetic fields. Here, we report on the charge carrier density and mobility extracted from such experiments, and will be compared among different growth conditions of in-situ enriched $^{28}$Si.

10:12AM A45.00010 Thermal oxidation of Si/SiGe heterostructures for use in quantum dot qubits, SAMUEL F. NEYENS, RYAN H. FOOTE, T. J. KNAPP, THOMAS MCMJUNKIN, D. E. SAVAGE, M. G. LAGALLY, S. N. COPPERSMITH, M. A. ERIKSSON, Wisconsin Institute for Quantum Information, University of Wisconsin-Madison — Here we demonstrate dry thermal oxidation of a Si/SiGe heterostructure at 700°C and use a Hall bar device to measure the mobility after oxidation to be 43,000 cm$^2$/V·s at a carrier density of 4.1×10$^{11}$ cm$^{-2}$. Surprisingly, we find no significant reduction in mobility compared with an Al$_2$O$_3$ device made with atomic layer deposition on the same heterostructure, indicating thermal oxidation can be used to process Si/SiGe quantum dot devices. This result provides a path for investigating improvements to the gate oxide in Si/SiGe qubit devices, whose performance is believed to be limited by charge noise in the oxide layer. This work was supported in part by ARO (W911NF-12-0607) and NSF (DMR-1206915 and PHY-1104660). Development and maintenance of the growth facilities used for fabricating samples is supported by DOE (DE-FG02-03ER46028). This research utilized NSF-supported shared facilities at the University of Wisconsin-Madison.

10:24AM A45.00011 Electrode-induced In-plane Strain Variation in Si Quantum Well, JOOKYU PARK, YOUNGJIN AHN, DONALD SAVAGE, University of Wisconsin Madison, JONATHAN PRANCE, Lancaster University, CHRISTINE SIMMONS, MAX LAGALLY, SUSAN COPPERSMITH, University of Wisconsin Madison, MARTIN HOLT, Argonne National Laboratory, MARK ERIKSSON, PAUL EVANS, University of Wisconsin Madison — Silicon quantum devices are often formed in electrostatically defined quantum dots within Si/SiGe heterostructures incorporating a strained silicon layer. Structural variations within the quantum well arise from several sources, including the plastic relaxation of the SiGe substrate and stresses arising from the electrodes. The residual stress in the electrode causes an elastic bending distortion of the quantum well that modifies the energy by which the two split-off conduction minima in the silicon quantum well are shifted by biaxial strain. We report a synchrotron hard x-ray nanobeam diffraction study of the quantum well distortion (i) near isolated Pd electrodes and (ii) within a complex quantum dot pattern. The strain difference between the two interfaces of the 10-nm-thick silicon quantum well has a magnitude of up to 10$^{-5}$ in (i) while it is as large as 10$^{-4}$ in (ii) which is far larger than the strain difference arising from the plastic relaxation of the SiGe substrate. Mechanical analysis using the edge-force model, shows that the residual stress in the Pd electrode was 350 MPa. We expect that similar effects will arise in all quantum electronic systems with metal-electrode-defined devices.

10:36AM A45.00012 Are quantum dots in unexpected locations due to strain?, NEIL ZIMMERMAN, NIST, TED THORBECK, University of Wisconsin-Madison — It is a fairly common occurrence that, in top-gated Si quantum dots, the dots appear in reproducible but unexpected positions. For instance, sometimes a group will make gates in order to electrostatically generate tunnel barriers, but discover that NIST, TED THORBECK, University of Wisconsin-Madison, R. BARENDS, Google, Santa Barbara, USA, A. SHABANI, Google, Venice, Spain, L. LAMATA, University of the Basque Country, Spain, R. BARENDS, Google, Santa Barbara, USA, A. SHABANI, Google, Venice, Spain, H. NEVEN, Google, Venice, USA, JOHN M. MARTINS, Google, Santa Barbara, USA, and University of California, Santa Barbara, USA — Adiabatic quantum computing (AQC) is a general-purpose optimization algorithm that in contrast to circuit-model quantum algorithms can be applied to a large set of computational problems. An analog physical realization of AQC has certain limitations that we propose can be overcome by a gate-model equivalence of the AQC. In this talk we discuss the hardware advantages of digitized AQC in particular arbitrary interactions, precision, and coherence. We could experimentally realize the principles of digitized AQC on a chain of nine qubits, and highlight the physics of adiabatic evolutions as well as the Kibble-Zurek mechanism.

10:48AM A45.00013 Atomic scale quantum circuits in Si, A. DUSKO, IF, UFRJ, Brazil / DP, uOttawa, Canada, M. KORKUSINSKI, IMS, NRC, Canada, A. SARAIVA, IF, UFRJ, Brazil, A. DELGADO, DP, uOttawa, Canada, B. KOILLER, IF, UFRJ, Brazil, P. HAWRYLAK, DP, uOttawa, Canada — The atomic scale quantum circuits in Si are now realized by manipulation of dangling bonds on Si surface or incorporating dopant atoms in Si by STM techniques. We describe the electronic properties of these atomic scale quantum dot circuits (QDC) by the extended Hubbard-Kanamori Hamiltonian (HK), including on site Coulomb repulsion ($U$) and interdot hopping ($t$), direct interaction ($V$) and exchange ($J$) terms. The interdot terms strongly depend on dopant position ($R_{ij}$) in Si lattice—small changes in $R_{ij}$ strongly impact $t$, $V$ and $J$. We study how disorder in $R_{ij}$ impacts QDC electronic properties, in particular the interplay of disorder and exchange. Without disorder in $R_{ij}$ the energy spectrum (ES) of quantum dot chain at half-filling as a function of $U/t$, $V/t$, $J/t=0$ shows a transition from ES dominated by kinetic energy ($U/t<<1$) to ES dominated by Coulomb interactions for $U/t>>1$. The excited states group by single particle energy spacing (Hubbard bands) for weak (strong) interactions. In the weak interaction regime, disorder leads to localization, which strongly affects the electronic properties. We explore the effect of interactions and disorder on HK atomic scale circuits and potential many-body localized phases using Lanczos and Density Matrix Renormalization Group approaches.

Monday, March 14, 2016 8:00AM - 11:00AM – Session A48 GQI: Quantum Computing and Quantum Simulations with Superconducting Circuits 349 - David Schuster, University of Chicago

8:00AM A48.00001 Digitized adiabatic quantum computing with a superconducting circuit, part I: Theory, L. LAMATA, University of the Basque Country, Spain, R. BARENDS, Google, Santa Barbara, USA, A. SHABANI, Google, Venice, USA, J. KELLY, Google, Santa Barbara, USA, A. MEZZACAPPO, U. LAS HERAS, University of the Basque Country, Spain, R. BABBUSH, Google, Venice, USA, A. G. FOWLER, Google, Santa Barbara, USA, B. CAMPBELL, University of California, Santa Barbara, USA, YU CHEN, Google, Santa Barbara, USA, Z. CHEN, B. CHIARO, A. DUNSWORTH, University of California, Santa Barbara, USA, E. JEFFREY, E. LUCERO, Google, Santa Barbara, USA, A. MEGRANT, University of California, Santa Barbara, USA, J. Y. MUTUS, M. NEELEY, Google, Santa Barbara, USA, C. NEILL, P. J. J. OMALLEY, C. QUINTANA, University of California, Santa Barbara, USA, P. ROUSHAN, Google, Santa Barbara, USA, E. SOLANO, University of the Basque Country, Spain, and Ikerbasque, Spain, H. NEVEN, Google, Venice, USA, JOHN M. MARTINS, Google, Santa Barbara, USA, and University of California, Santa Barbara, USA — Adiabatic quantum computing (AQC) is a general-purpose optimization algorithm that in contrast to circuit-model quantum algorithms can be applied to a large set of computational problems. An analog physical realization of AQC has certain limitations that we propose can be overcome by a gate-model equivalence of the AQC. In this talk we discuss the hardware advantages of digitized AQC in particular arbitrary interactions, precision, and coherence. We could experimentally realize the principles of digitized AQC on a chain of nine qubits, and highlight the physics of adiabatic evolutions as well as the Kibble-Zurek mechanism.

8:00AM A48.00002 Digitized adiabatic quantum computing with a superconducting circuit, part II: Simulation, L. LAMATA, University of the Basque Country, Spain, R. BARENDS, Google, Santa Barbara, USA, A. SHABANI, Google, Venice, USA, J. KELLY, Google, Santa Barbara, USA, A. MEZZACAPPO, U. LAS HERAS, University of the Basque Country, Spain, R. BABBUSH, Google, Venice, USA, A. G. FOWLER, Google, Santa Barbara, USA, B. CAMPBELL, University of California, Santa Barbara, USA, YU CHEN, Google, Santa Barbara, USA, Z. CHEN, B. CHIARO, A. DUNSWORTH, University of California, Santa Barbara, USA, E. JEFFREY, E. LUCERO, Google, Santa Barbara, USA, A. MEGRANT, University of California, Santa Barbara, USA, J. Y. MUTUS, M. NEELEY, Google, Santa Barbara, USA, C. NEILL, P. J. J. OMALLEY, C. QUINTANA, University of California, Santa Barbara, USA, P. ROUSHAN, Google, Santa Barbara, USA, E. SOLANO, University of the Basque Country, Spain, and Ikerbasque, Spain, H. NEVEN, Google, Venice, USA, JOHN M. MARTINS, Google, Santa Barbara, USA, and University of California, Santa Barbara, USA — Adiabatic quantum computing (AQC) is a general-purpose optimization algorithm that in contrast to circuit-model quantum algorithms can be applied to a large set of computational problems. An analog physical realization of AQC has certain limitations that we propose can be overcome by a gate-model equivalence of the AQC. In this talk we discuss the hardware advantages of digitized AQC in particular arbitrary interactions, precision, and coherence. We could experimentally realize the principles of digitized AQC on a chain of nine qubits, and highlight the physics of adiabatic evolutions as well as the Kibble-Zurek mechanism.
8:12 AM A48.00002 Digitized adiabatic quantum computing with a superconducting circuit, part II: Experiment. R. BARENDTS, A. SHABANI, Google Inc., L. LAMATA, University of the Basque Country, Spain, J. KELLY, Google Inc., A. MEZZACAPo, U. LAS HERAS, University of the Basque Country, Spain, R. BABBUmSH, A. G. FOWLER, Google Inc., B. CAMPBELL, UC Santa Barbara, Y. CHEN, Z. CHEN, Google Inc., B. CHIARo, A. DUNSWORTH, UC Santa Barbara, E. JEFFREY, E. LUCERO, A. MEGRANT, J. MUTUS, M. NEELEY, Google Inc., C. NEILL, P. O’MALLEY, C. QUINTANA, UC Santa Barbara, P. ROUSHAN, Google Inc., E. SOLANO, University of the Basque Country, Spain, H. NEVEN, J. MARTINIS, Google Inc. — A major challenge in quantum computing is to solve general problems with limited physical hardware. We implement digitized adiabatic quantum computing, combining the generality of the adiabatic algorithm with the universality of the digital approach, using a superconducting circuit with nine qubits. We probe the adiabatic evolutions, explore the scaling of errors with system size, and quantify the success of the algorithm for random spin problems. We find that the system can approximate the solutions to both frustrated Ising problems and non-stoquastic problem Hamiltonians with a performance that is comparable.

8:24 AM A48.00003 Digital quantum simulations with superconducting circuits. URTZI LAS HERAS, LAURA GARCIA-ALVAREZ, LUCAS LAMATA, University of the Basque Country, Spain, ENRIQUE SOLANO, University of the Basque Country and IKERBASQUE, Spain — Superconducting circuits are a promising quantum technology for the implementation of quantum information protocols. In particular, digital quantum simulations are an efficient method for reproducing dynamics that are not produced naturally in the simulating system. We propose a method for simulating efficiently the dynamics of prototypical spin and fermionic models in circuit quantum electrodynamics architectures with either qubit-qubit pairwise interactions or resonators acting as quantum buses. We show how to implement Ising and Heisenberg spin models, and the Fermi-Hubbard model, making use of the Jordan-Wigner mapping and Mølmer-Sørensen gates.

8:36 AM A48.00004 Quantum simulation of micro and macro frustrated quantum magnetism with superconducting circuits. J. JOYDIP GHOSH, BARRY C. SANDERS, Univ of Calgary — We devise a scalable scheme for simulating a quantum phase transition from paramagnetism to frustrated magnetism in a superconducting flux-qubit network, and show how to characterize this system experimentally both macroscopically and microscopically. The proposed macroscopic characterization of the quantum phase transition is based on the transition of the probability distribution for the spin-network net magnetic moment with this transition quantified by the difference between the Kullback-Leibler divergences of the distributions corresponding to the paramagnetic and frustrated magnetic phases with respect to the probability distribution at a given time during the transition. Microscopic characterization of the quantum phase transition is performed using the standard local-entanglement-witness approach. Simultaneous macro and micro characterizations of quantum phase transitions would serve to verify in two ways a quantum phase transition and provide empirical data for revisiting the foundational emergentist-reductionist debate regarding reconciliation of macroscopic thermodynamics with microscopic statistical mechanics especially in the quantum realm for the classically intractable case of frustrated quantum magnetism.

1*.NSERC, AITF and University of Calgarys Eyes High Fellowship Program.

8:48 AM A48.00005 Engineering artificial Hamiltonians with parametric superconducting circuits. YAO LU, SRIVATSAN CHAKRAM, NELSON LEUNG, RAVI NAiK, NATHAN EARNEST, James Franck Institute and Department of Physics, University of Chicago, PETER GROSKOWSKI, JENS KOCH, Department of Physics & Astronomy, Northwestern University, ELIOT KAPIT, Department of Physics & Engineering Physics, Tulane University, DAVID SCHUSTER, James Franck Institute and Department of Physics, University of Chicago — One major challenge in building a large scale quantum computer is to generate and manipulate interactions between its many qubits. One promising approach is to use parametric flux or voltage modulation to realize effective interactions between different components of superconducting circuits, generating artificial Hamiltonians that are suitable for various quantum computation tasks, which might be difficult to achieve through other means. We propose a parametric superconducting circuit where transmon qubits and resonators are coupled to a flux-modulated parametric coupler. We show that with this device, arbitrary pairs of qubits or resonators in the circuit can be selectively and simultaneously brought into resonance with each other and swap excitations at a controllable rate. This allows for the creation of various artificial circuit Hamiltonians that are suitable for a number of applications such as single qubit state stabilization, parametric qubit state readout, autonomous error correction and so on.

9:00 AM A48.00006 Strongly interacting photons in a synthetic magnetic field. PEDRAM ROUSHAN, Google Inc., C. NEILL, UCSB, A. MEGRANT, Y. CHEN, R. BARENDTS, Google Inc., B. CAMPBELL, Z. CHEN, B. CHIARO, A. DUNSWORTH, UCSB, A. FOWLER, E. JEFFREY, J. KELLY, E. LUCERO, J. MUTUS, Google Inc., P. O’MALLEY, UCSB, M. NEELEY, C. QUINTANA, D. SANK, Google Inc., A. VAINSENCHER, J. WENNER, UCSB, T. WHITE, Google Inc., E. KAPIT, Tulane University, J. MARTINIS, Google Inc. — Interacting electrons in the presence of magnetic fields exhibit some of the most fascinating phases in condensed matter systems. Realizing these phases in an engineered platform could provide deeper insight into their. Using three superconducting qubits, we synthesize artificial magnetic fields by modulating the inter-qubit coupling. In the closed loop formed by the qubits, we observe the directional circulation of a microwave photon as well as chiral groundstate currents, the signatures of broken time-reversal symmetry. The existence of strong interactions in our system is seen via the creation of photon vacancies, or “holes”, which circulate in the closed loop formed by the qubits, we observe the directional circulation of a microwave photon as well as chiral groundstate currents, the signatures of broken time-reversal symmetry. And numerical simulation in time domain gives further supports. Our results present a promising cooling scheme for experiments.

9:12 AM A48.00007 Emulating the 1-Dimensional Fermi-Hubbard Model with Superconducting Qubits. JAN-MICHAEL REINER, MICHAEL MARTHALER, GERD SCHN, Karlsruhe Institute of Technology — A chain of qubits with both ZZ and XX couplings is described by a Hamiltonian which coincides with the Fermi-Hubbard model in one dimension. The qubit system can thus be used to study the quantum properties of this model. We investigate the specific implementation of such an analog quantum simulator by a chain of tunable Transmon qubits, where the ZZ interaction arises due to an inductive coupling and the XX interaction due to a capacitive coupling.

9:24 AM A48.00008 Cavity-assisted cooling of Bose-Hubbard model simulator with superconducting circuits. XIUHAO DENG, School of Natural Sciences, University of California Merced, CHUNJING JIA, Department of Applied Physics, Stanford University; Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator — Interesting progress have been made in using superconducting circuits to simulate Bose-Hubbard model (BHM). However, studying ground state feature of BHM calls for effective cooling process, where the cooling mechanism must preserve total number of simulated bosons and cooling rate has to be much stronger than decay rate. Here, we propose a cooling scheme that satisfies these two conditions by coupling an array of transmission line resonators with an assisted cavity. The quantum simulator we modelled here can be used to study generic BHM, which include both repulsive and attractive on-site interaction and hopping strength. We evaluate the cooling rate in all these regime analytically. And numerical simulation in time domain gives further supports. Our results present a promising cooling scheme for experiments.
9:36AM A48.00009 Simulating chemical energies to high precision with fully-scalable quantum algorithms on superconducting qubits. PETER O’MALLEY, UC Santa Barbara, RYAN BABBU, Google Inc., Venice, CA, IAN KIVLICHAN, JHONATHAN ROMERO, Harvard University, JARROD MCCLEAN, Lawrence Berkeley National Lab, ANDREW TRANTER, Tufts University, RAMI BARENS, JULIAN KELLY, YU CHEN, Google Inc., Santa Barbara, CA, ZIJUN CHEN, UC Santa Barbara, EVAN JEFFREY, AUSTIN FOWLER, Google Inc., Santa Barbara, CA, ANTHONY MTEGRANT, UC Santa Barbara, JOSH MUTUS, Google Inc., Santa Barbara, CA, CHARLES NEILL, CHRISTOPHER QUINTANA, UC Santa Barbara, PEDRAM ROUSHAN, DANIEL SANK, Google Inc., Santa Barbara, CA, AMIT VAINSENCHER, JAMES WENNER, UC Santa Barbara, THEODOR WHITE, Google Inc., Santa Barbara, CA, PETER LOVE, Tufts University, ALAN ASPURU-GUZIK, Harvard University, HARTMUT NEVEN, Google Inc., Venice, CA, JOHN MARTINIS, UC Santa Barbara and Google Inc. — Quantum simulations of molecules have the potential to calculate industrially-important chemical parameters beyond the reach of classical methods with relatively modest quantum resources. Recent years have seen dramatic progress both superconducting qubits and quantum chemistry algorithms. Here, we present experimental demonstrations of two fully-scalable algorithms for finding the dissociation energy of hydrogen: the variational quantum eigensolver and iterative phase estimation. This represents the first calculation of a dissociation energy to chemical accuracy with a non-precompiled algorithm. These results show the promise of chemistry as the “killer app” for quantum computers, even before the advent of full error-correction.

9:48AM A48.00010 Hybrid Quantum-Classical Approach to Molecular Excited States On Superconducting Qubits. JARROD MCCLEAN, Computational Research Division, Lawrence Berkeley National Laboratory, MOLLIE SCHWARTZ, CHRIS MACKLIN, IRFAN SIDDIQI, Quantum Nanoelectronics Laboratory, University of California, Berkeley, JONATHAN CARTER, WIBE DE JONG, Computational Research Division, Lawrence Berkeley National Laboratory — Quantum computers promise to dramatically advance our understanding of correlated quantum systems. Unfortunately, many proposed algorithms have resource requirements not yet suitable for near-term quantum devices. The variational quantum eigensolver (QVE) is a recently proposed hybrid quantum-classical method for solving eigenvalue problems and more generic minimizations on a quantum device leveraging classical resources to minimize coherence time requirements. However, this algorithm has so far focused only on the quantum ground state and has almost exclusively been studied in ideal closed system conditions. We briefly review the original VQE approach and introduce a simple extension requiring no additional coherence time to approximate excited states. Moreover, we show how the same method can be used to mitigate the effects of noise in a real system and how this algorithm can be applied in practice on a superconducting qubit architecture.

10:00AM A48.00011 Implementation of a Quantum Variational Eigensolver in Superconducting Qubits. MOLLIE SCHWARTZ, Quantum Nanoelectronics Laboratory, UC Berkeley, JARROD MCCLEAN, Computational Research Division, Lawrence Berkeley National Laboratory, CHRIS MACKLIN, Quantum Nanoelectronics Laboratory, UC Berkeley; Computational Research Division, Lawrence Berkeley National Laboratory, JONATHAN CARTER, WIBE ALBERT DE JONG, Computational Research Division, Lawrence Berkeley National Laboratory, IRFAN SIDDIQI, Quantum Nanoelectronics Laboratory, UC Berkeley; Materials Sciences Division, Lawrence Berkeley National Laboratory — The quantum variational eigensolver (QVE) represents an efficient implementation of quantum simulation that relies on a synergy between classical and quantum computing components. In this approach, a classical computer is used to map the target Hamiltonian onto a fermionic Hilbert space and to perform a variational update of the estimated ground state. This test state is then prepared in the quantum system, enabling an efficient estimation of the expectation value of the Hamiltonian and reducing the requirements for coherent qubit evolution. We present experimental progress toward implementing a QVE in superconducting qubits, capitalizing on the flexibility and scalability of the transmon QED architecture.

10:12AM A48.00012 Cavity-assisted dynamical quantum phase transition in superconducting quantum simulators1. LING TIAN, School of Natural Sciences, University of California, Merced, CA 95343 — Coupling a quantum many-body system to a cavity can create bifurcation points in the phase diagram, where the many-body system switches between different phases. Here I will discuss the dynamical quantum phase transitions at the bifurcation points of a one-dimensional transverse field Ising model coupled to a cavity. The Ising model can be emulated with various types of superconducting qubits connected in a chain. With a time-dependent Bogoliubov method, we show that an infinitesimal quench of the driving field can cause gradual evolution of the transverse field on the Ising spins to pass through the quantum critical point. Our calculation shows that the cavity-induced nonlinearity plays an important role in the dynamics of this system. Quasiparticles can be excited in the Ising chain during this process, which results in the deviation of the system from its adiabatic ground state.

1This work is supported by the National Science Foundation under Award Number 0956064.

10:24AM A48.00013 Visualizing singularities of a groundstate landscape using superconducting circuits. ERIK LUCERO, Google, Inc., A. DUNSWORTH, UCSB, P. ROUSHAN, A. MTEGRANT, Google, Inc., C. NEILL, UCSB, T. SOUZA, M. TOMKA, M. KLODORUETZ, Boston University, Y. CHEN, R. BARENS, Google, Inc., B. CAMPBELL, Z. CHEN, B. CHIARO, UCSB, E. JEFFREY, J. KELLY, J. MUTUS, Google, Inc., P. O’MALLEY, C. QUANTINA, UCSB, D. SANK, Google, Inc., J. WENNER, UCSB, T. WHITE, Google, Inc., A. POLKOVNIKOV, Boston University, J. MARTINIS, Google, Inc. — The defining properties of condensed matter phases are set by their groundstate wavefunctions. The adiabatic theorem provides an experimental approach for realizing such states. However, a general protocol for applying this theorem is experimentally unexplored, in particular when the energy gap is small. Using two superconducting qubits, we adiabatically prepare the entire groundstate manifold in a region of the parameter-space where degeneracies are present. We prepare these states by varying the Hamiltonian along ‘geodesics’ in parameter-space, obtained by minimizing the local non-adiabatic error. From the measured total magnetization of the final state, we compute the Berry curvature, where degeneracies appear as singular points, allowing us to directly visualize the degeneracies in the groundstate landscape.

10:36AM A48.00014 Observation of the correspondence between Landau-Zener transition and Kibble-Zurek mechanism with a superconducting qubit system. MING GONG, DONG LAN, YUHAO LIU, XINSHENG TAN, HAIFENG YU, YANG YU, SHILIANG ZHU, School of Physics, Nanjing University, China, GUOZHU SUN, YU ZHOU, YUNYI FAN, PEIHENG WU, School of Electronic Science and Engineering, Nanjing University, China, XUEDA WEN, Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA, DANWEI ZHANG, Guangdong Provincial Key Laboratory of Quantum Engineering and Quantum Materials, SPT, South China Normal University, Guangzhou 510006, China, SIYUAN HAN, Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA — We present a direct experimental observation of the correspondence between Landau-Zener transition and Kibble-Zurek mechanism with a superconducting qubit system. We develop a time resolved approach to study quantum dynamics of the Landau-Zener transition. By using this method, we observe the key features of the corresponding adiabatic and impulse transitions, e.g., the boundary between the adiabatic and impulse regions, the freeze out phenomenon in the impulse region. Remarkably, the scaling behavior of the population in the excited state, an analogical phenomenon originally predicted in Kibble-Zurek mechanism, is also observed in the Landau-Zener transition.

2This work was partly supported by the SKPBR of China (2011CB922104), NSFC (91321310, 11125417, 11474153, 11474154, 61521001), and the PCSIRT (Grant No. IRT1243)
10:48 AM A48.00015 Artificial Quantum Thermal Bath, ALIREZA SHABANI, HARTMUT NEVEN, Google Quantum AI Lab — In this talk, we present a theory for engineering the temperature of a quantum system different from its ambient temperature, that is basically an analog version of the quantum metropolis algorithm. We define criteria for an engineered quantum bath that, when coupled to a quantum system with Hamiltonian \( H \), drives the system to the equilibrium state \( e^{-\beta H/T} \) with a tunable parameter \( T \). For a system of superconducting qubits, we propose a circuit-QED approximate realization of such an engineered thermal bath consisting of driven lossy resonators. We consider an artificial thermal bath as a simulator for many-body physics or a controllable temperature knob for a hybrid quantum-thermal annealer.

Monday, March 14, 2016 11:15 AM - 2:15 PM –
Session B13 GQI: Adiabatic Quantum Computation and Quantum Annealing
309 - Tameem Albash, Univ of Southern California

11:15 AM B13.00001 Simulated annealing versus quantum annealing, MATTHIAS TROYER, ETH Zurich — Based on simulated classical annealing and simulated quantum annealing using quantum Monte Carlo (QMC) simulations I will explore the question where physical or simulated quantum annealers may outperform classical optimization algorithms. Although the stochastic dynamics of QMC simulations is not the same as the unitary dynamics of a quantum system, I will first show that for the problem of quantum tunneling between two local minima both QMC simulations and a physical system exhibit the same scaling of tunneling times with barrier height. The scaling in both cases is \( O(\Delta^3) \), where \( \Delta \) is the tunneling splitting. An important consequence is that QMC simulations can be used to predict the performance of a quantum annealer for tunneling through a barrier. Furthermore, by using open instead of periodic boundary conditions in imaginary time, equivalent to a projector QMC algorithm, one obtains a quadratic speedup for QMC, and achieve linear scaling in \( \Delta \) [1]. I will then address the apparent contradiction between experiments on a D-Wave 2 system that failed to see evidence of quantum speedup [2] and previous QMC results [3] that indicated an advantage of quantum annealing over classical annealing for spin glasses. We find that this contradiction is resolved by taking the continuous time limit in the QMC simulations which then agree with the experimentally observed behavior and show no speedup; for 2D ferromagnet. However, QMC simulations with large time steps gain further advantage: they “cheat” by ignoring what happens during a (large) time step, and can thus outperform both simulated quantum annealers and classical annealers [4]. I will then address the question of how to optimally run a simulated or physical quantum annealer. Investigating the behavior of the tails of the distribution of runtimes for very hard instances we find that adiabatically slow annealing is far from optimal. On the contrary, many repeated relatively fast annealing runs can be orders of magnitude faster for hard spin glass problems. The intuitive explanation is that hard instances, which are stuck in the wrong minimum can be solved faster by perturbing them [5]. I will finally discuss the consequences of these findings for designing better quantum annealers. [1] S.V. Isakov, G. Mazzola, V.N. Smelyanskiy, Z. Jiang, S. Boixo, H. Neven, and M. Troyer, arXiv:1510.08057. [2] T.F. Rønnow, Z. Wang, J. Job, S. Boixo, S.V. Isakov, D. Wecker, J.M. Martinis, D.A. Lidar, M. Troyer, Science 348, 420 (2014). [3] G.E. Santoro, R. Martonak, E. Tosatti, and R. Car, Science 295, 2427 (2002). [4] B. Heim, T. F. Rønnow, S. V. Isakov, and M. Troyer, Science 348, 215 (2015). [5] D.S. Steiger, T.F. Rønnow, M. Troyer, Phys. Rev. Lett. (in press); arXiv:1504.07991.

11:51 AM B13.00002 Mean-field analysis of quantum annealing with XX-type terms, HIDE TOSHI NISHIMORI, Tokyo Institute of Technology — I analyze the role of XX-type terms in quantum annealing for a few mean-field systems including the Ising ferromagnet and the Hopfield model, both with many-body interactions. The XX-type terms are shown to be effective to remove first-order quantum phase transitions, which exist in the conventional implementation of quantum annealing using only transverse fields. This means an exponential increase in efficiency, and is suggestive for the design of quantum annealers. I will discuss how and why this phenomenon emerges and what may happen on realistic finite-dimensional lattices.

References:

12:27 PM B13.00003 Error suppression and correction for quantum annealing, DANIEL LIDAR, Univ of Southern California — While adiabatic quantum computing and quantum annealing enjoy a certain degree of inherent robustness against excitations and control errors, there is no escaping the need for error correction or suppression. In this talk I will give an overview of our work on the development of such error correction and suppression methods. We have experimentally tested one such method combining encoding, energy penalties and decoding, on a D-Wave Two processor, with encouraging results. Mean field theory shows that this can be explained in terms of a softening of the closing of the gap due to the energy penalty, resulting in protection against excitations that occur near the quantum critical point. Decoding recovers population from excited states and enhances the success probability of quantum annealing. Moreover, we have demonstrated that using repetition codes with increasing code distance can lower the effective temperature of the annealer.

References:
- W. Vinci et al., in preparation.

1:03 PM B13.00004 Precision and the approach to optimality in quantum annealing processors, MARK W JOHNSON, D-Wave Systems Inc — The last few years have seen both a significant technological advance towards the practical application of, and a growing scientific interest in the underlying behaviour of quantum annealing (QA) algorithms [1]. A series of commercially available QA processors, most recently the D-Wave 2X™ 1000 qubit processor, have provided a valuable platform for empirical study of QA at a non-trivial scale. From this it has become clear that misspecification of Hamiltonian parameters is an important performance consideration, both for the goal of studying the underlying physics of QA, as well as that of building a practical and useful QA processor. The empirical study of the physics of QA requires a way to look beyond Hamiltonian specification error, as well as review the time-to-target metric and empirical results analyzed in this way. [1] E.g. “Discussion and Debate: Quantum Annealing: The Fastest Route to Quantum Computation?”, S Suzuki and A Das eds., Eur. Phys. J. Special Topics, 224 (1), Feb 2015.

References:
and show that it is robust to typical noise and experimental imperfections. Unknown parameters in the Hamiltonian can be retrieved one by one. We simulate the performance of the scheme under the influence of various pulse errors of coupling terms in the Hamiltonian. The scheme makes use of synchronized dynamical decoupling pulses to simplify the many-body dynamics so that the process tomography, our scheme is fully scalable with the number of qubits as the required rounds of measurements increase only linearly with the number of qubits.

11:15AM B44.00001 Towards a Model Selection Rule for Quantum State Tomography¹, TRAVIS SCHOLTEN, ROBIN BLUME-KOHOUT, Sandia Natl Labs — Quantum tomography on large and/or complex systems will rely heavily on model selection techniques, which permit on-the-fly selection of small efficient statistical models (e.g. small Hilbert spaces) that accurately fit the data. Many model selection tools, such as hypothesis testing or Akaike’s AIC, rely implicitly or explicitly on the Wilks Theorem, which predicts the behavior of the loglikelihood ratio statistic (LLRS) used to choose between models. We used Monte Carlo simulations to study the behavior of the LLRS in quantum state tomography, and found that it disagrees dramatically with Wilks’ prediction. We propose a simple explanation for this behavior; namely, that boundaries (in state space and between models) play a significant role in determining the distribution of the LLRS. The resulting distribution is very complex, depending strongly both on the true state and the nature of the data. We consider a simplified model that neglects anisotropy in the Fisher information, derive an analytic prediction for the mean value of the LLRS, and compare it to numerical experiments. While our simplified model outperforms the Wilks Theorem, it still does not predict the LLRS accurately, implying that alternative methods may be necessary for tomographic model selection.

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 National Nuclear Security Administration under contract DE-AC04-94AL85000.

11:27AM B44.00002 Experimental Demonstration of Self-Guided Quantum Tomography, ROBERT J. CHAPMAN, School of Electrical and Computer Engineering, RMIT University, CHRISTOPHER FERRIE, EQUS, School of Physics, University of Sydney, ALBERTO PERUZZO, School of Electrical and Computer Engineering, RMIT University — Robust and precise quantum state characterization is critical for future quantum experiments and technologies, and yet it is a fundamentally challenging task. Standard and adaptive quantum tomography procedures are impractical for systems ranging pre-given today due to the cross-entropy of quantum state spaces. These techniques are sensitive to statistical noise and require highly precise measurement settings. We present an experimental demonstration of autonomous and robust self-guided quantum tomography. Self-guided quantum tomography iteratively learns a quantum state using a stochastic gradient ascent algorithm. As a result it is robust against statistical noise and measurement errors. In addition, self-guided quantum tomography does not require any computationally expensive optimization, necessary for adaptive quantum tomography, or post-processing, required for standard quantum tomography. We demonstrate the robustness of self-guided quantum tomography by engineering the level of statistical noise and experimental errors, achieving measurement fidelities greater than standard quantum tomography in a range of one- and two-qubit experiments. Our demonstration opens pathways towards robust quantum state characterization in current and near-future experiments, where standard techniques are already impractical.

11:39AM B44.00003 Improved precision-guaranteed quantum tomography, TAKANORI SUGIYAMA, Dep. of Systems Innovation, Osaka University — Quantum tomography is one of the standard tools in current quantum information experiments for verifying that a state/process/measurement prepared in the lab is close to an ideal target. Precision-guaranteed quantum tomography (Sugiyma, Turner, Murao, PRL 111, 160406 2013) gives rigorous error bars on a result estimated from arbitrary finite data sets from any given informationally complete tomography experiments. The rigorous error bars were derived with a real-valued concentration inequality called Hoeffding's inequality. In this talk, with a vector-valued concentration inequality, we provide an improved version of the error bars of precision-guaranteed quantum tomography. We examine the new error bars for specific cases of multi-qubit systems and numerically show that the degree of improvement becomes large as the dimension of the system increases.

¹Supported by JSPS Research Fellowships for Young Scientists H27-276 and JSPS Postdoctoral Fellowships for Research Abroad H25-32

11:51AM B44.00004 Gate Set Tomography on two qubits, ERIK NIELSEN, ROBIN BLUME-KOHOUT, JOHN GAMBLE, KENNETH RUDINGER, Sandia National Laboratories — Gate set tomography (GST) is a method for characterizing quantum gates that does not require pre-calibrated operations, and has been used to both certify and improve the operation of single qubits. We analyze the performance of GST applied to a simulated two-qubit system, and show that Heisenberg scaling is achieved in this case. We present a GST analysis of preliminary two-qubit experimental data, and draw comparisons with the simulated data case. Finally, we will discuss recent theoretical developments that have improved the efficiency of GST estimation procedures, and which are particularly beneficial when characterizing two qubit systems. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

12:03PM B44.00005 Hamiltonian tomography for quantum many-body systems with arbitrary couplings, SHENG-TAO WANG, Univ of Michigan - Ann Arbor, DONG-LING DENG, Condensed Matter Theory Center and Joint Quantum Institute, University of Maryland, College Park, LUMING DUAN, Univ of Michigan - Ann Arbor — Characterization of qubit couplings in many-body quantum systems is essential for benchmarking quantum computation and simulation. We propose a tomographic measurement scheme to determine all the coupling terms in a general many-body Hamiltonian with arbitrary long-range interactions, provided the energy density of the Hamiltonian remains finite. Different from quantum process tomography, our scheme is fully scalable with the number of qubits as the required rounds of measurements increase only linearly with the number of coupling terms in the Hamiltonian. The scheme makes use of synchronized dynamical decoupling pulses to simplify the many-body dynamics so that the unknown parameters in the Hamiltonian can be retrieved one by one. We simulate the performance of the scheme under the influence of various pulse errors and show that it is robust to typical noise and experimental imperfections.

¹This work is supported by the IARPA MUSIQ program, the ARO and the AFOSR MURI program.
method using our numerical tomography package TOMOHAK based on slice sampling. To state tomography to estimate strictly physical quantum states, simulation results comparing MLE and BME estimates, and experimental application of our singles and coincidence counts is needed. We present our estimation procedure for a single basis experiment, the extension to multiple bases, the application to estimate physicality. No knowledge of the pathway/detector efficiencies or the photon number generated by the source is required. Only knowledge of the raw true probability. Unfortunately, the number of measurements in any experiment is finite. Given this, better estimates are provided by Bayesian mean estimation. This notion is made possible due to the positive semidefinite property of density matrices. Strictly-complete quantum state tomography when the unknown process is a generic unitary evolution. Our method is based on PhaseLift, a convex programming technique for phase retrieval. We show that this method achieves approximate recovery of almost all signals, using measurements sampled from spherical or unitary 2-designs. This is the first positive result on PhaseLift using 2-designs. We also show that exact recovery of all signals is possible using measurements sampled from unitary 4-designs. Previous positive results for PhaseLift required spherical 4-designs, while PhaseLift was known to fail in certain cases when using spherical 2-designs. Scalable randomized benchmarking of non-Clifford gates¹, ANDREW CROSS, EASWAR MAGESAN, LEV BISHOP, JOHN SMOLIN, JAY GAMBETTA, IBM T J Watson Res Ctr — Randomized benchmarking is a widely used experimental technique to characterize the average error of quantum operations. Benchmarking procedures that scale to enable characterization of \( n \)-qubit circuits rely on efficient procedures for manipulating those circuits and, as such, have been limited to subgroups of the Clifford group. However, universal quantum computers require additional, non-Clifford gates to approximate arbitrary unitary transformations. We define a scalable randomized benchmarking procedure over \( n \)-qubit unitary matrices that correspond to protected non-Clifford gates for a class of stabilizer codes. We present efficient methods for representing and composing group elements, sampling them uniformly, and synthesizing corresponding poly(\( n \))-sized circuits. The procedure provides experimental access to two independent parameters that together characterize the average gate fidelity of a group element.¹ We acknowledge support from ARO under contract W911NF-14-1-0124.

Benchmarking of Quantum Control in ESR, GUANRU FENG, KYUNGEOCK PARK, FRANKLIN H CHO, BRANDON BUONACORSI, ROBABEH RAHIMI, JONATHAN BAUGH, RAYMOND LAFLAMME, Institute for Quantum Computing, University of Waterloo — Quantum error correction is essential for realizing scalable quantum computation. Key ingredients for quantum error correction are highly polarized ancilla qubits and high-fidelity quantum control. While NMR quantum processors have demonstrated high control fidelity, the requirement to prepare highly polarized spin qubits on demand is a major challenge. Electron-nuclear hyperfine coupled spin systems provide a possible solution: electrons can be fully polarized at accessible fields and temperatures, and their polarization is typically reset much faster than nuclei by spin relaxation. This makes open system cooling methods, such as heat bath algorithm cooling, possible. In this talk, I will describe our recent efforts to improve the precision of microwave control in a custom electron spin resonance spectrometer. In particular, we use randomized benchmarking of quantum gates to quantify control errors, and carefully take into account the resonator transfer function in correcting pulses. Moreover, we implement a protocol that distinguishes coherent and incoherent errors, which gives deeper insight into the nature of the remaining control imperfections and how to address them.

Informational completeness in bounded-rank quantum-state tomography¹, CHARLES BALDWIN, IVAN DEUTSCH, AMIR KALEV, University of New Mexico — Quantum-state tomography is a demanding task, however, it can be made more efficient by employing prior information about the system. A common prior assumption is that the state being measured is pure, or close to pure, since most quantum information protocols require pure states. Measurements of pure states can be constructed to be more efficiently than measurements of an arbitrary state, and for these types of measurements, there exists two different notions of informational completeness. One notion, called strict-completeness, is more useful for practical applications since it is compatible with convex optimization and is robust to noise. We present a unified framework for both notions of completeness for a certain type of measurements. These are measurements that allow algebraic reconstruction of a few density matrix elements. The framework also aids in the construction of new strictly-complete measurements. Moreover, the results are easily generalized to the case when the prior information is the state has bounded rank.¹ This work was supported by NSF Grants PHY- 1212445, PHY-1521016, and PHY-1521431.

The power of being positive: Robust state estimation made possible by quantum mechanics¹, AMIR KALEV, CHARLES BALDWIN, Univ of New Mexico — Quantum-state tomography (QST) is generally expensive to implement experimentally. Nevertheless, in state-of-the-art experiments in quantum information science the goal is not to produce arbitrary states but states that have very high purity. Including this prior information in QST results in more manageable tomography protocols. In the context of pure-state tomography, and more generally, of bounded-rank states (states with rank \( \leq r \)) tomography, a natural notion of informational completeness emerges, rank-\( r \) completeness. The purpose of this contribution is two fold. First, to prove and emphasize the significance of a less intuitive, yet more powerful, notion of completeness for a certain type of measurements. These are measurements that allow algebraic reconstruction of a few density matrix elements. The framework also aids in the construction of new strictly-complete measurements. Moreover, the results are easily generalized to the case when the prior information is the state has bounded rank.¹ This work was supported by NSF Grants PHY-1212445, PHY-1521016, and PHY-1521431.

Bayesian mean estimation for finite two-photon experiments, BRIAN WILLIAMS, PAVEL LOGOVSKI, Oak Ridge National Lab — Estimations of quantum probabilities are commonly made utilizing frequency based methods to invert Born’s rule where \( X \) is found \( k \) out of \( n \) times, \( P(X) = |\langle X | Y \rangle|^2 \approx k/n \). For an infinite measurement number the maximum likelihood estimation (MLE) represents the true probability. Unfortunately, the number of measurements in any experiment is finite. Given this, better estimates are provided by Bayesian mean estimation (BME). We present a novel method utilizing an experiment-specific probability distribution to make fully informed estimations of any quantum probability, efficiency parameter, or complete density matrix. Our method accounts for the finite measurement number, inter-basis parameter dependence, and estimate physicality. No knowledge of the pathway/detector efficiencies or the photon number generated by the source is required. Only knowledge of the raw singles and coincidence counts is needed. We present our estimation procedure for a single basis experiment, the extension to multiple bases, the application to state tomography to estimate strictly physical quantum states, simulation results comparing MLE and BME estimates, and experimental application of our method using our numerical tomography package TOMOHAK based on slice sampling.
to detect and quantify crosstalk between qubits, and demonstrate how these techniques allow for quick identification and estimation of system crosstalk.

control fidelity. In this talk we explore the use of eigenvalue estimation (a.k.a. “spectrum estimation”) in superconducting systems as a high-accuracy method.

correlation from decoherence and towards control errors. One pervasive source of control errors is crosstalk – where control fields intended for one qubit leak onto other

Raytheon BBN Technologies, RAYTHEON BBN TECHNOLOGIES TEAM — Superconducting qubit devices offer a promising path towards a scalable quantum

will also briefly discuss recent developments in g-factor theory in silicon quantum dots and their possible implications.

The necessary step for further scaling up the qubit system is to increase the number of QDs with a well-controlled charge state to prepare multiple qubits and improve the fidelity of the qubit gates as well. I will first review spin-1/2 qubit gates with triple QDs for operating three qubits, local and non-local entangling

gate-characterization. This twirling protocol is efficient and scalable, and can also be extended to other systems straightforwardly.

TERLOO TEAM, TSINGHUA UNIVERSITY COLLABORATION, USTC COLLABORATION — The traditional approach of characterizing a given quantum
gate via quantum process tomography (QPT) requires exponential number of experiments. Therefore, estimating the average fidelity of the quantum gate by

QPT is not practical for large-scale systems. In this talk, I will discuss about how to certify a Clifford gate within polynomial complexity using a twirling protocol.

In particular, we adopted this method in NMR and certified a 7-qubit quantum Clifford gate with only 1600 experiments (in contrast, QPT requires millions of

experiments). This Clifford gate is important as it generates maximal coherence from single coherence, and non-trivial for benchmarking the coherent control in

experiment. We show that the average fidelity of this gate is over 87% after accounting for the decoherence effect, and to date this is the largest experimental
gate-characterization. This twirling protocol is efficient and scalable, and can also be extended to other systems straightforwardly.

1We acknowledge funding from ARO under contract W911NF-14-C-0048.

1:51PM B44.00014 Crosstalk characterization by eigenvalue estimation: Theory1, MARCUS DA SILVA, Raytheon BBN Technologies — As qubit systems continue to grow and long coherence times become routine, the dominating sources of error shift away from decoherence and towards control errors. One pervasive source of control errors is crosstalk – where control fields intended for one qubit leak onto other

cubits. In this talk we describe a method to quantify crosstalk by estimating the eigenvalues of the system’s evolution using a technique known as “spectrum estimation”. We discuss the wide applicability of the method, and demonstrate similar accuracy scaling to the robust phase estimation algorithm of Kimmel, Low, and Yoder.

We acknowledge funding from ARO under contract W911NF-14-C-0048.

Monday, March 14, 2016 11:15AM - 2:15PM –
Session B45 GQI: Semiconductor Qubits: Multidot Qubits and Dynamical Control 348 - Vanita Srivinasa, Laboratory for Physical Sciences/University of Maryland, College Park, MD

11:15AM B45.00001 Multiple quantum dot spin qubits , SEIGO TARUCHA, The University of Tokyo & Riken Center for Emergent Matter Science — To date various techniques of implementing spin qubits and entangling gates have been developed with quantum dots (QDs). The necessary step for further scaling up the qubit system is to increase the number of QDs with a well-controlled charge state to prepare multiple qubits and improve the fidelity of the qubit gates as well. I will first review spin-1/2 qubit gates with triple QDs for operating three qubits, local and non-local entangling
gates, and SWAP gates. I show that the fidelity of these spin manipulations is significantly increased by decreasing the data acquisition time. Secondly I will refer to quadruple and quintuple QDs to implement multiple spin qubits. For the triple QD we use two sets of two coupled dots in the spin blockade regime to demonstrate operation of three individual spin qubits. We use an exchange coupling between the neighboring dots to make two sets of SWAPs and an
inhomogeneous Zeeman field difference between the neighboring dots (between the remote dots) to make local (non-local) control of S-T0 oscillations. We apply the same technique for the quadruple QD to coherently manipulate individual four spins. We finally discuss a way to further scale up the qubit system using multiple QDs.

11:51AM B45.00002 A new look at encoded-qubit quantum dot quantum computing in silicon , CHARLES TAHA, YUN-PIL SHIM, RUSKO RUSKOV, Laboratory for Physical Sciences — Although the properties of spin-based qubits are specified by the material system they reside in, it’s possible to modify those properties by encoding a qubit into multiple physical spins. Here we consider new operating regimes for encoded spin qubits and discuss their relevance to spin-based quantum computing and qubit-qubit coupling, especially in silicon quantum dot systems. We will also briefly discuss recent developments in g-factor theory in silicon quantum dots and their possible implications.
High quality exchange rotations in spin qubits using symmetric gating\textsuperscript{1}, F. MARTINS, F. K. MALINOWSKI, P. D. NISSEN, C. M. MARCÜS, F. KUEMMETH, Center for quantum devices, Niels Bohr Institute, University of Copenhagen, Denmark, E. BARNES, Department of Physics, Virginia Tech / Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, USA, G. C. GARDNER, S. FALLAH, M. J. MANFRA, Department of Physics and Astronomy and Birck Nanotechnology Center, Purdue University, USA — We present results on a singlet-triplet qubit implemented in a GaAs/AlGaAs heterostructure and we show that exchange oscillations can be realized either by tilting the double well potential, the conventional method, or by symmetrically lowering the barrier, as originally suggested by Loss and DiVincenzo. The two methods are compared here. We find that lowering the barrier between dots has much less relative exchange noise compared to tilting the potential. Since exchange rotations are sensitive to electrical noise and relatively insensitive to nuclear noise, this yields significantly enhanced free induction decay times and quality factors. Our results are comparable to those reported recently in silicon quantum dot devices, obtained using similar techniques.

\textsuperscript{1}Support through IARPA-MQCO, LPS-MPO-CMTC, Army Research Office, and the Danish National Research Foundation is acknowledged.

Tenfold increase in the Rabi decay time of the quantum dot hybrid qubit \textsuperscript{1}, RYAN H. FOOTE, D. E. SAVAGE, M. G. LAGALLY, MARK FRIESEN, S. N. COPPERSMITH, M. A. ERIKSSON, University of Wisconsin-Madison — The hybrid qubit is formed from three electrons in a double quantum dot. In previous work, we showed that the hybrid qubit has the speed of a charge qubit and the stability of a spin qubit. Here, we show that the hybrid qubit is also highly tunable, and can be tuned into regimes with desirable coherence properties. By changing the interdot tunnel rate by only 25\%, from 5 GHz to 6.25 GHz, we are able to increase the Rabi decay time by a factor of ten, from 18 ns to 177 ns. We attribute this improvement to the refinement of an extended sweet spot in the energy dispersion of the hybrid qubit, where the qubit is less exchange coupled. We also show that lowering the barrier between dots has much less relative exchange noise compared to tilting the potential.

\textsuperscript{1}In collaboration with Xin Wang, Jason Kestner and Sankar Das Sarma, and supported by LPS-MPO-CMTC and IARPA- MQCO.

Effect of Charge Noise on Landau-Zener Interferometry in double quantum dots, ZHENYI QI, MARK FRIESEN, SUSAN COPPERSMITH, MAXIM VAVILOV, Univ of Wisconsin, Madison — We study the effect of charge noise on the dynamics of semiconductor quantum dot qubits. Recent experiments have demonstrated relatively long coherence times in these systems; however at the same time, the visibility of the Landau-Zener interference pattern is relatively low. We argue that the electromagnetic noise of the environment affects the coherence of the qubit near the charge degeneracy point, including the singlet-triplet avoided level crossing, and results in the reduced visibility of the Landau-Zener interferometry when the singlet-triplet avoided level crossing happens in the vicinity of the charge degeneracy point. Using a master equation, we describe the evolution of the density matrix for the qubit assuming weak coupling of the quantum dot to its electromagnetic environment and compare our results to experimental data.
1:15PM B45.00009 Noise-induced collective quantum state preservation in spin qubit arrays†, EDWIN BARNES, Department of Physics, Virginia Tech and Condensed Matter Theory Center, University of Maryland, DONG-LING DENG, ROBERT THROCKMORTON, YANG-LE WU, Condensed Matter Theory Center, University of Maryland — The hyperfine interaction with nuclear spins (or, Overhauser noise) has long been viewed as a leading source of decoherence in individual quantum dot spin qubits. We show that in a coupled multi-qubit system consisting of as few as four spins, interactions with nuclear spins can have the opposite effect where they instead preserve the collective quantum state of the system. This noise-induced state preservation can be realized in a linear spin qubit array using current technological capabilities. Our proposal requires no control over the Overhauser fields in the array, only experimental control over the average inter-qubit coupling between nearest neighbors is needed, and this is readily achieved by tuning gate voltages. Our results illustrate how the role of the environment can transform from helpful to harmful in the progression from single-qubit to multi-qubit quantum systems.

†Work supported by LPS-MPO-CMTC and IARPA-MQCO

1:27PM B45.00010 Decoupling a spin qubit from high-frequency Larmor dynamics of a GaAs nuclear spin bath†, FILIP K. MALINOWSKI, FREDERICO MARTINS, PETER D. NISSEN, MARK S. RUDNER, CHARLES M. MARCUS, FERDINAND KUEMMETH, Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, EDWIN BARNES, Department of Physics, Virginia Tech, SAEED FALLAH, GEOFFREY C. GARDNER, MICHAEL J. MANFRA, Department of Physics and Astronomy and Birck Nanotechnology Center, Purdue University — We present a technique of decoupling a spin qubit in a GaAs/AlGaAs heterostructure from low- and high-frequency noise arising from hyperfine interaction of electrons with nuclear spins. We use Carr-Purcell-Meiboom-Gill sequences in which we synchronize the repetition rate of $\pi$ pulses to difference Larmor frequencies of $^{69}$Ga, $^{71}$Ga and $^{77}$As nuclei. This decouples the qubit both from low-frequency noise due to diffusion of nuclear spins and from noise at selected high frequencies, allowing us to apply more than a thousand $\pi$ pulses in a sequence. We demonstrate a coherence time of a singlet-triplet qubit of 0.87 ms, i.e. five orders of magnitude longer than the inhomogeneous dephasing time intrinsic to GaAs.

†Support through IARPA-MQCO, Army Research Office, LPS-MPO-CMTC, the Villum Foundation and the Danish National Research Foundation is acknowledged.

1:39PM B45.00011 Noise filtering of composite pulses for singlet-triplet qubits†, XIN WANG, XU-CHEN YANG, City University of Hong Kong — Dynamically corrected gates are useful measures to combat decoherence in spin qubit systems. They are, however, mostly designed assuming the static-noise model and may thus be considered low-frequency noise filters. In this talk we carefully examine the applicability of a particular type of dynamically corrected gates, namely the SUPCODE designed for singlet-triplet qubits, under realistic $1/f^\alpha$ noises. Through randomized benchmarking, we have found that SUPCODE offers improvement of the gate fidelity for $\alpha \geq 1$ and the improvement becomes exponentially more pronounced with the increase of the noise exponent $\alpha$ up to 3. On the other hand, for small $\alpha$ SUPCODE will not offer any improvement. We also present the computed filter transfer functions for the SUPCODE gates for nuclear and charged noise respectively and have found that they are consistent with the finding from the benchmarking.

†The work is supported by grants from City University of Hong Kong (Projects No. 9610335 and No. 7200456).

1:51PM B45.00012 Dynamical Decoupling with pulse errors for ensembles of interacting spins, E. S. PETERSEN, A. M. TYRYSHKIN, S. A. LYON, Princeton University — Dynamical decoupling (DD) is a well-known approach for decoupling quantum (spin) systems from their environments. Theoretically, the performance of DD pulse sequences is often analyzed using a single spin approximation in which environmental noise is included through single spin operators. This approach has successfully analyzed the effectiveness of many popular DD pulse sequences (like CPMG and XY4) to cancel environmental noise even in the presence of unavoidable pulse errors. However, this methodology does not describe the effect of DD on the spin-spin interactions present in experiments involving large numbers of spins. Here, we go beyond the usual single-spin model, extending the analysis of DD sequences to include such spin-spin interactions. We find that when using certain popular DD sequences (like CPMG), coherence times of ensembles with dipolar interactions between spins can be drastically influenced by pulse errors. While sequences with ideal pulses do not decouple the spin-spin interactions, the presence of even small pulse errors can partially (or even greatly) decouple the spin-spin interactions thus leading to longer coherence times. Furthermore, the extent that these interactions are decoupled is highly dependent on the type of DD sequence used, and not necessarily the number of pulses involved. These calculations explain results of past experiments (Tyryshkin et al, arxiv: 1011.1903).

2:03PM B45.00013 Dynamic field-frequency lock for tracking magnetic field fluctuations in electron spin resonance experiments, ABRAHAM ASFAW, ALEXEI TYRYSHKIN, STEPHEN LYON, Department of Electrical Engineering, Princeton University, Princeton NJ 08544 — Global magnetic field fluctuations present significant challenges to pulsed electron spin resonance experiments on systems with long spin coherence times. We will discuss results from experiments in which we follow instantaneous changes in magnetic field by locking to the free induction decay of a proton NMR signal using a phase-locked loop. We extend conventional field-frequency locking techniques used in NMR to follow slow magnetic field drifts by using a modified Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence in which the phase of the pi-pulses follows the phase of the proton spins at all times. Hence, we retain the ability of the CPMG pulse sequence to refocus local magnetic field inhomogeneities without refocusing global magnetic field fluctuations. In contrast with conventional field-frequency locking techniques, our experiments demonstrate the potential of this method to dynamically track global magnetic field fluctuations on timescales of about 2 seconds and with rates faster than a kHz. This frequency range covers the dominant noise frequencies in our electron spin resonance experiments as previously reported.

Monday, March 14, 2016 11:15AM - 2:03PM –
Session B48 GQI: Quantum Optics with Superconducting Circuits 349 - Irfan Siddiqi, University of California, Berkeley
11:15AM B48.00001 Electromagnetically induced transparency in a tunable three-dimensional transmon1. TIEFU LI, QICHUN LIU, Institute of Microelectronics, Tsinghua University, XIAOQING LUO, Beijing Computational Science Research Center, HU ZHAO, Institute of Microelectronics, Tsinghua University, WEI XIONG, ZHEN CHEN, Beijing Computational Science Research Center, YINGSHAN ZHANG, J. S. LIU, WEI CHEN, Institute of Microelectronics, Tsinghua University, FRANCO NORI, Center for Emergent Matter Science (CEMS), RIKEN, J. S. TSAI, Department of Physics, Tokyo University of Science, J. Q. YOU, Beijing Computational Science Research Center — Electromagnetically induced transparency (EIT) has been realized in atomic systems, but fulfilling the EIT conditions for artificial atoms made from superconducting circuits is a more difficult task. Here we report an experimental observation of the EIT in a tunable three-dimensional transmon by probing the cavity transmission. We tune the transmon to adjust its damping rates to fulfill the EIT conditions. From the experimental observations, we clearly identify the EIT and Autler-Townes splitting (ATS) regimes as well as the transition regime in between. Also, the experimental data demonstrate that the threshold $\Omega_{\text{AT}}$ determined by the Akaike information criterion can describe the EIT-ATS transition better than the threshold $\Omega_{\text{AT}}$ given by the EIT theory.

1This work is supported by the NSAF Grant No. U1339201, the NSFC Grant No. 91421102, and the MOST 973 Program Grant Nos. 2014CB845700 and 2014CB921401.

11:27AM B48.00002 Resonance fluorescence from an artificial atom in squeezed vacuum, Part 1: Efficient fluorescence detection1. A. EDDINS, D.M. TOYLI, Quantum Nanoelectronics Laboratory, UC Berkeley, S. PURI, S. BOUTIN, Departement de Physique, Universite de Sherbrooke, D. HOVER, V. BOLKHOVSKY, MIT Lincoln Laboratory, W.D. OLIVER, MIT Lincoln Laboratory and Research Laboratory of Electronics, Massachusetts Institute of Technology, A. BLAIS, Departement de Physique, Universite de Sherbrooke, I. SIDDQUI, Quantum Nanoelectronics Laboratory, UC Berkeley — The accurate prediction of the fluorescence spectrum of a single atom under coherent excitation, comprising canonical phenomena such as the Mollow triplet, is a fundamental success of quantum optics. Despite considerable efforts, experiments demonstrating perfect control of the resonance fluorescence spectrum remain few. To this end, we report an experiment that uses two multimode cavity quantum electrodynamics (cQED) systems, one as a two-mode squeezer and the second as a quantum-limited preamplifier, ensuring a high-efficiency measurement of squeezing. We also discuss progress towards employing such two-mode squeezed radiation to realize high-fidelity dispersive readout of superconducting qubits.

1This work is funded by the ARO and ONR.

11:39AM B48.00003 Resonance fluorescence from an artificial atom in squeezed vacuum, Part 2: Squeezing characterization through fluorescence1, D.M. TOYLI, A. EDDINS, Quantum Nanoelectronics Laboratory, UC Berkeley, S. PURI, S. BOUTIN, Departement de Physique, Universite de Sherbrooke, D. HOVER, V. BOLKHOVSKY, MIT Lincoln Laboratory, W.D. OLIVER, MIT Lincoln Laboratory and Research Laboratory of Electronics, Massachusetts Institute of Technology, A. BLAIS, Departement de Physique, Universite de Sherbrooke, I. SIDDQUI, Quantum Nanoelectronics Laboratory, UC Berkeley — The accurate prediction of the fluorescence spectrum of a single atom under coherent excitation, comprising canonical phenomena such as the Mollow triplet, is a fundamental success of quantum optics. Despite considerable efforts, experiments demonstrating perfect control of the resonance fluorescence spectrum remain few. To this end, we report an experiment that uses two multimode cavity quantum electrodynamics (cQED) systems, one as a two-mode squeezer and the second as a quantum-limited preamplifier, ensuring a high-efficiency measurement of squeezing. We also discuss progress towards employing such two-mode squeezed radiation to realize high-fidelity dispersive readout of superconducting qubits.

1This work is funded by the ARO and ONR.

11:51AM B48.00004 Stochastic path integral approach to continuous quadrature measurement of a single fluorescing qubit1. ANDREW N. JORDAN, AREEYA CHANTASRI, University of Rochester, BENJAMIN HUARD, École Normale Supérieure-PFS, Research University — I will present a theory of continuous quantum measurement for a superconducting qubit undergoing fluorescence relaxation. The fluorescence of the qubit is detected via a phase-preserving heterodyne measurement, giving the cavity mode quadrature signals as two continuous qubit readout results. By using the stochastic path integral approach to the measurement physics, we obtain the most likely fluorescence paths between chosen boundary conditions on the state, and compute approximate correlation functions between all stochastic variables via diagrammatic perturbation theory. Of particular interest are most-likely paths describing increasing energy during the florescence. Comparison to Monte Carlo numerical simulation and experiment will be discussed.

1This work was supported by US Army Research Office Grants No. W911NF-09-0-01417 and No. W911NF-15-1-0496, by NSF grant DMR-1506081, by John Templeton Foundation grant ID 58558, and by the DPSTT Project Thailand

12:03PM B48.00005 Two-mode squeezing in a broadband parametric amplifier. J. A. GROVER, A. KAMAL, S. GUSTAVSSON, F. YAN, T. P. ORLANDO, W. D. OLIVER, Research Laboratory of Electronics, MIT, D. HOVER, V. BOLKHOVSKY, J. L. YODER, MIT Lincoln Laboratory, C. MACKLIN, K. O'BRIEN, I. SIDDQUI, University of California Berkeley — The Josephson traveling wave parametric amplifier (JTWPA) exhibits gains of greater than 20 dB over a frequency range of a few gigahertz. In addition to being a quantum-limited amplifier over a wide frequency range, the JTWPA is a source of broadband squeezed radiation. We report the observation of broadband squeezing of microwave light generated by a JTWPA by measuring cross correlations between modes separated by up to one gigahertz in frequency. Employing a chain of two JTWPAs, the first as a squeeze and the second as a quantum-limited preamplifier, ensures a high-efficiency measurement of squeezing. We also discuss progress towards employing such two-mode squeezed radiation to realize high-fidelity dispersive readout of superconducting qubits.

This research was funded in part by the U.S. Army Research Office Grant No. W911NF-14-1-0682 and by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA) and by the Assistant Secretary of Defense for Research & Engineering via MIT Lincoln Laboratory and Research Laboratory of Electronics, Massachusetts Institute of Technology, A. BLAIS, Departement de Physique, Universite de Sherbrooke, I. SIDDIQI, Quantum Nanoelectronics Laboratory, UC Berkeley — The accurate prediction of the fluorescence spectrum of a single atom under coherent excitation, comprising canonical phenomena such as the Mollow triplet, is a fundamental success of quantum optics. Despite considerable efforts, experiments demonstrating perfect control of the resonance fluorescence spectrum remain few. To this end, we report an experiment that uses two multimode cavity quantum electrodynamics (cQED) systems, one as a two-mode squeezer and the second as a quantum-limited preamplifier, ensuring a high-efficiency measurement of squeezing. We also discuss progress towards employing such two-mode squeezed radiation to realize high-fidelity dispersive readout of superconducting qubits.

1This work was supported by US Army Research Office Grants No. W911NF-09-0-01417 and No. W911NF-15-1-0496, by NSF grant DMR-1506081, by John Templeton Foundation grant ID 58558, and by the DPSTT Project Thailand

12:15PM B48.00006 Displacement of squeezed propagating microwave states. KIRILL G. FEDOROV, LING ZHONG, STEFAN POGORZELEK, PETER EDER, MICHAEL FISCHER, JAN GOETZ, FRIEDRICH WULSCHNER, EDWAR XIE, EDWIN MEnZEL, FRANK DEPPE, ACHIM MARX, RUDOLF GROSS, Walther-Meissner-Institut; Technische Universitaet Muenchen; Nanosystems Initiative Munich — Displacement of propagating squeezed states is a fundamental operation for quantum communications. It can be applied to fundamental studies of macroscopic quantum coherent and has an important role in quantum teleportation protocols with propagating microwaves. We generate propagating squeezed states using a Josephson parametric amplifier and implement displacement using a cryogenic directional coupler. We study single- and two-mode displacement regimes. For the single-mode displacement we find that the squeezing level of the displaced squeezed state does not depend on the displacement amplitude. Also, we observe that quantum entanglement between two spatially separated channels stays constant across 4 orders of displacement power. We acknowledge support by the German Research Foundation through SFB 631 and FE 1564/1-1, the EU project PROMISCE, and Elite Network of Bavaria through the program ExQM.
12:27PM B48.00007 Engineering Non-Classical Light with Non-Linear Microwaveguides, ARNE GRIMSMO, Univ of Sherbrooke, AASHISH CLERK, McGill University, ALEXANDRE BLAIS, Univ of Sherbrooke — The quest for ever increasing fidelity and scalability in measurement of superconducting qubits to be used for fault-tolerant quantum computing has recently led to the development of near quantum-limited broadband phase preserving amplifiers in the microwave regime. These devices are, however, more than just amplifiers: They are sources of high-quality, broadband two-mode squeezed light. We show how bottom-up engineering of Josephson junction embedded waveguides can be used to design novel squeezing spectra. Furthermore, the entanglement in the two-mode squeezed output field can be imprinted onto quantum systems coupled to the device’s output. These broadband microwave amplifiers constitute a realization of non-linear waveguide QED, a very interesting playground for non-equilibrium many-body physics.

12:39PM B48.00008 Topological quantum states of light in coupled microwave cavities, RUICHAO MA, JOHN C OWEN, AMAN LACHEPPELE, TAÉKWAN YOON, DAVID SCHUSTER, JONATHAN SIMON, University of Chicago — We present a unique photonic platform to explore quantum many-body phenomena in coupled cavity arrays. We create tight binding lattices with arrays of evanescently coupled three-dimensional coaxial microwave cavities. Topologically non-trivial band structures are engineered by utilizing the chiral coupling of the cavity modes to ferrite spheres in a magnetic field. We develop robust, minimal methods to completely characterize the tight-binding Hamiltonian, including all onsite disorder, tunnel coupling, local dissipation and effective flux, using only spectroscopic measurement on specific sites. These efforts pave the way to realize low-disorder, long-coherence, topological tight binding models, where the many-body states can be spectroscopically driven and probed in temporally- and spatially-resolved measurements. Using techniques from circuit QED, effective onsite photon-photon interactions may be induced by coupling to superconducting qubits. This will allow us to explore the interplay between topology and coherent interaction in these artificial strongly-correlated photonic quantum materials.

12:51PM B48.00009 Quantum optics with nonlinearly coupled superconducting resonators, VADIRAJ A.M., C.W.S. CHANG, POL FORN-DIAZ, C.M. WILSON, Institute for Quantum Computing, University of Waterloo, Waterloo, Canada — Superconducting circuits provide a robust platform for studying fundamental aspects of light-matter interaction in the circuit QED architecture. Here, we study a novel circuit that couples two superconducting resonators via a nonlinear interaction mediated by a superconducting quantum interference device (SQUID). The interaction Hamiltonian has a form analogous to optomechanical systems with the photon number in one resonator coupling to the current in the other. However, the nonlinear coupling constant can be many orders of magnitude larger than in typical optomechanical systems. This can potentially bring the system into a new regime of single-photon coupling between the resonators, enabling novel physics. We will present preliminary results in this direction.

1:03PM B48.00010 Experimental investigation of a steady-state dynamical phase transition in a Jaynes-Cummings dimer, JAMES RAFTERY, DARIUS SADRI1, Princeton University, STEPHAN MANDT, Columbia University, HAKAN TÜRECİ, ANDREW HOUCK, Princeton University — Experimental progress in circuit-QED has made it possible to study non-equilibrium many-body physics using strongly correlated photons. Such open and driven systems can display new types of dynamical phase transitions [1]. A steady state transition has also been predicted for a Jaynes-Cummings dimer where the photon current between the two cavities acts as an order parameter [2]. Here, we discuss the theory and report measurements of the steady-state behavior of a circuit-QED dimer with in situ tunable inter-cavity coupling and on-site photon-photon interaction.

1:15PM B48.00011 Fock-state stabilization in superconducting circuits using biased Josephson junctions, JEAN-RENE SOUQUET, AASHISH CLERK, McGill Univ — The ability to prepare and stabilize non-trivial states is a crucial ingredient for quantum information processing. Here, we analyze theoretically a simple scheme for stabilizing Fock states in a superconducting circuit using the nonlinearity inherent in a voltage-biased Josephson junction. Unlike a recent demonstration of Fock state stabilization [1], our protocol does not require any microwave driving. We also discuss how the same system can be used to generate propagating single-photon states with high fidelity, again without the use of microwave drives or pulses.

1:27PM B48.00012 Steady-state response of coupled non-linear superconducting quantum oscillators, MATTHEW ELLIOTT, ERAN GINOSSAR, Advanced Technology Institute, University of Surrey — Analytic solutions of non-linear, dissipative quantum systems can provide access to parameter regimes where numerical simulation is unfeasible. In particular, they are useful when these systems are driven at high powers but influenced by quantum fluctuations. We find exact solutions of a Fokker-Planck equation from which we derive the response characteristics of coupled linear and non-linear oscillators under the influence of both coherent and parametric driving. By working in an experimentally feasible parameter regime for superconducting quantum circuits, we model a realistic driven cavity-transmon system and obtain the steady-state frequency response of both cavity and transmon at a range of drive powers, comparing our results with recent experimental data. We show that this method can also be extended to investigate the behaviour of a resonator with a quartic non-linearity which is driven coherently and parametrically, revealing the structure of bifurcations in the steady-state solutions.

1:39PM B48.00013 Dressed-state engineering for continuous detection of itinerant microwave photons, KAZUKI KOSHINO, Tokyo Medical and Dental University, ZHIRONG LIN, KUNIHIRO INOMATA, RIKEN Center for Emergent Matter Science, TSUYOSHI YAMAMOTO, NEC Smart Energy Research Laboratories, YASUNOBU NAKAMURA, University of Tokyo — Microwave quantum optics using superconducting qubits and transmission lines enables various quantum-optical phenomena that have not been reached in the visible light domain. However, the lack of an efficient detector for itinerant microwave photons has been a long-standing problem. A promising approach is to use the deterministic switching of a Λ system induced by individual photons. Recently, we realized a Λ system by the dressed-state engineering of a qubit-resonator system and achieved a detection efficiency ~66%. However, this detector should be operated in the time-gated mode, since the drive field to generate the Λ-type transition must be turned off during the qubit readout. Here, we propose a scheme for continuous detection of itinerant microwave photons. In the proposed device, a superconducting qubit is coupled dispersively to two resonators: one is used to form a Λ system that deterministically captures incoming photons and the other is used for continuous monitoring of the event. The proposed device enables continuous operation of the photon detector, preserving the advantages of our previous scheme, such as a high detection efficiency, insensitivity to the signal pulse shape, and short dead times after detection.
nanoelectronic devices with the help of a far-away in-situ-tunable heat sink. For circuit quantum electrodynamics, the basis of the emerging superconducting quantum computer. In particular, our results may lead to remote cooling of photons travelling in superconducting transmission lines. Thus it seems that quantum-limited heat conduction has no fundamental restriction in its distance. We present experimental observations of quantum-limited heat conduction over macroscopic distances extending to a meter. We achieved this striking improvement of four orders of magnitude in the distance by utilizing microwave photons travelling in superconducting transmission lines. This work lays the foundation for the integration of normal-metal components into superconducting transmission lines, and hence provides an important tool for circuit quantum electrodynamics, the basis of the emerging superconducting quantum computer. In particular, our results may lead to remote cooling of nanoelectronic devices with the help of a far-away in-situ-tunable heat sink.

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3:42PM C44.00007 Topological defects on the lattice1. DAVID AASEN, Caltech, ROGER MONG, University of Pittsburgh, PAUL FENDLEY, Oxford — We construct defects in two-dimensional classical lattice models and one-dimensional quantum chains that are topologically invariant in the continuum limit. We show explicitly that these defect lines and their trivalent junctions commute with the transfer matrix/Hamiltonian. The resulting splitting and joining properties of the defect lines are exactly those of anyons in a topological phase. One useful consequence is an explicit definition of twisted boundary conditions that yield the precise shift in momentum quantization, and so provide a natural way of relating microscopic and macroscopic properties. Another is a generalization of Kramers-Wannier duality to a wide class of geometric models. Even more strikingly, we derive the modular transformation matrices explicitly and exactly from purely lattice considerations. We develop this construction for a variety of examples including the two-dimensional Ising model.

1Institute for Quantum Information and Matter, an NSF physics frontier center with support from the Moore Foundation. NSERC-PGSD

3:54PM C44.00008 How quickly can anyons be braided?2. CHRISTINA KNAPP, Univ of California - Santa Barbara, DONG LIU, MENG CHENG, MICHAEL ZALETEL, PARSAD BONDERSON, Microsoft Station Q, CHETAN NAYAK, Microsoft Station Q, Univ of California-Santa Barbara — Topological phases of matter are a potential platform for the storage and processing of quantum information with intrinsic error rates that decrease exponentially with inverse temperature. However, it is less well-understood how error rates depend on the speed with which anyons are braided. In general, diabatic corrections to the Berry phase vanish inversely with the length of time for the braid, with faster decay occurring as the time-dependence is made smoother. Here, we show that such corrections will not affect quantum information encoded in a topological state unless topologically non-trivial quasiparticles are created. Moreover, we show how measurements that detect unintentionally created quasiparticles can be used to control this source of error.

4:06PM C44.00009 Edge theory approach to topological entanglement entropy and other entanglement measures of (2+1) dimensional Chern-Simons theories on a general manifold. XUEDA WEN, Physics Department, UIUC, SHUJNI MATSUURA, Niels Bohr Institute, University of Copenhagen & Yukawa Institute for Theoretical Physics, Kyoto University, SHINSEI RYU, Physics Department, UIUC — Topological entanglement entropy of (2+1) dimensional Chern-Simons gauge theories on a general manifold is usually calculated with Witten’s method of surgeries and replica trick, in which the spacetime manifold under consideration is very complicated. In this work, we develop an edge theory approach, which greatly simplifies the calculation of topological entanglement entropy of a Chern-Simons theory. Our approach applies to a general manifold with arbitrary genus. The effect of braiding and fusion of Wilson lines can be straightforwardly calculated within our framework. In addition, our method can be generalized to the study of other entanglement measures such as mutual information and entanglement negativity of a topological quantum field theory on a general manifold.

4:18PM C44.00010 Highly entangled tensor networks. YINGFEI GU, DANIEL BULMASS, XIAO-LIANG QI, Stanford University — Tensor network states are used to represent many-body quantum state, e.g., a ground state of local Hamiltonian. In this talk, we will provide a systematic way to produce a family of highly entangled tensor network states. These states are entangled in a special way such that the entanglement entropy of a subsystem follows the Ryu-Takayanagi formula, i.e. the entropy is proportional to the minimal area geodesic surface bounding the boundary region. Our construction also provide an intuitive understanding of the Ryu-Takayanagi formula by relating it to a wave propagation process. We will present examples in various geometries.

4:30PM C44.00011 Tensor network characterization of superconducting circuits. GUILLAUME DUCLOS-CIANCI, Anyon Systems Inc., DAVID POULIN, Université de Sherbrooke, ALIREZA NAJAFI-YAZDI, Anyon Systems Inc. — Superconducting circuits are promising candidates in the development of reliable quantum computing devices. In principle, one can obtain the Hamiltonian of a generic superconducting circuit and solve for its eigenvalues to obtain its energy spectrum. In practice, however, the computational cost of calculating eigenvalues of a complex device with many degrees of freedom can become prohibitively expensive. In the present work, we investigate the application of tensor network algorithms to enable efficient and accurate characterization of superconducting circuits comprised of many components. Suitable validation test cases are performed to study the accuracy, computational efficiency and limitations of the proposed approach.

4:42PM C44.00012 Direct Measurement of Topological Phases in Discrete-Time Quantum Walks: Theory. VINAY RAMASESH, EMMANUEL FLURIN, IRFAN SIDDIQI, NORMAN YAO, Department of Physics, UC Berkeley — Quantum walks have been intensely investigated theoretically, from initial studies motivated by their connection to classical randomized algorithms to more recent works demonstrating topological phenomena in these walks. In particular, quantum walks simulate dynamics under effective lattice Hamiltonians which feature spin-orbit coupling. Here, we demonstrate that by adding an additional coin operator which varies from step to step, one can perform a traversal of the effective Brillouin zone, analogous to a Bloch oscillation. The geometric phase picked up by the walker along the Bloch oscillation is a genuine signature of the walks topology, a quantum analog of the Zak phase. Unlike previous interferometric proposals, our work requires neither spin-dependent Ramsey spectroscopy nor an external impurity with additional degrees of freedom. We develop a protocol, illustrating its use in a circuit QED system, which allows for the detection of the Zak phase.

3This research is supported by the ARO.

4:54PM C44.00013 Direct Measurement of Topological Phases in Discrete-Time Quantum Walks - Experiment. EMMANUEL FLURIN, VINAY V RAMASESH, SHAY HACOHEN GOURGY, Quantum Nanoelectronics Laboratory, UC Berkeley, NORMAN Y YAO, Department of Physics, UC Berkeley, IRFAN SIDDIQI, Quantum Nanoelectronics Laboratory, UC Berkeley — We perform quantum walks in a cavity QED architecture. Here a transmon qubit plays the role of the quantum coin, while a set of coherent states in an electromagnetic cavity forms the walkers lattice. The strong dispersive coupling between the transmon and cavity naturally implements coin-dependent translations of the walker state. The walk is performed by applying qubit rotations at equally spaced intervals; interestingly, such systems simulate dynamics under effective lattice Hamiltonians which feature strong spin-orbit coupling, leading to non-trivial band topology. By adding an additional step-dependent coin operator, we perform the first direct measurement of a quantum walk Zak phase, delineating between topologically trivial and non-trivial walks. The geometric phase is detected by implementing the quantum walk with the initial state of the walker in a superposition of a coherent state and the vacuum state, which does not partake in the walk. The Zak phase acquired by the walker thus leaves an imprint in the interference fringes of the resulting Schrödinger cat state. We observe these fringes by directly measuring the cavity Wigner function.

1This research is supported by the ARO.

5:06PM C44.00014 On the physical realizability of quantum stochastic walks. BRUNO TAKETANI, LUKE GOVIA, PETER SCHUHMACHER, FRANK WILHELM, Saarland University — Quantum walks are a promising framework that can be used to both understand and implement quantum information processing tasks. The recently developed quantum stochastic walk combines the concepts of a quantum walk and a classical random walk through open system evolution of a quantum system, and have been shown to have applications in as far reaching fields as artificial intelligence. However, nature puts significant constraints on the kind of open system evolutions that can be realized in a physical experiment. In this work, we discuss the restrictions on the allowed open system evolution, and the physical assumptions underpinning them. We then introduce a way to circumvent some of these restrictions, and simulate a more general quantum stochastic walk on a quantum computer, using a technique we call quantum trajectories on a quantum computer. We finally describe a circuit QED approach to implement discrete time quantum stochastic walks.
Monday, March 14, 2016 2:30PM - 5:42PM –
Session C45 GQI: Adiabatic Quantum Computation and Quantum Annealing: Tunneling, Speedup and Noise Effects  348 - Davide Venturelli, NASA Ames Research Center

2:30PM C45.00001 Tunneling and Speedup in Permutation-Invariant Quantum Optimization Problem, TAMEEM ALBASH, Univ of Southern California — Tunneling is often claimed to be the key mechanism underlying possible speedups in quantum optimization via the quantum adiabatic algorithm. Restricting ourselves to qubit-permutation invariant problems, we show that tunneling in these problems can be understood using the semi-classical potential derived from the spin-coherent path integral formalism. Using this, we show that the class of problems that fall under Rechardt’s bound (1), i.e., have a constant gap and hence can be efficiently solved using the quantum adiabatic algorithm, do not exhibit tunneling in the large system-size limit. We proceed to construct problems that do not fall under Rechardt’s bound but numerically have a constant gap and do exhibit tunneling. However, perhaps counter-intuitively, tunneling does not provide the most efficient mechanism for finding the solution to these problems. Instead, an evolution involving a sequence of diabatic transitions through many avoided level-crossings, involving no tunneling, is optimal and outperforms tunneling in the adiabatic regime. In yet another twist, we show that in this case, classical spin-vector dynamics is as efficient as the diabatic quantum evolution (2).


3:06PM C45.00002 Understanding Quantum Tunneling through Quantum Monte Carlo Simulations, SERGIO BOIXO, SERGEI ISAKOV, Google Inc., GUGLIELMO MAZZOLA, ETH, VADIM SMELYANSKIIY, Google Inc., ZHANG JIANG, NASA Ames, HARTMUT NEVEN, Google Inc., MATTHIAS TROYER, ETH — The tunneling between the two ground states of an Ising ferromagnet is a typical example of many-body tunneling processes between two local minima, as they occur during quantum annealing. Performing quantum Monte Carlo (QMC) simulations we find that the QMC tunneling rate displays the same scaling (in the exponent) with system size, as the rate of incoherent tunneling. The scaling in both cases is \(O(\Delta^4)\), where \(\Delta\) is the tunneling splitting. An important consequence is that QMC simulations can be used to predict the performance of a quantum annealer for tunneling through a barrier. Furthermore, by using open instead of periodic boundary conditions in imaginary time, equivalent to a projector QMC algorithm, we obtain a quadratic speedup for QMC, and achieve linear scaling in \(\Delta\). We provide a physical understanding of these results and their range of applicability based on an instanton picture.

3:18PM C45.00003 Coupled Quantum Fluctuations and Quantum Annealing, LAYLA HORMOZI, Massachusetts Institute of Technology, JAMIE KERMAN, MIT Lincoln Laboratory — We study the relative effectiveness of coupled quantum fluctuations, compared to single spin fluctuations, in the performance of quantum annealing. We focus on problem Hamiltonians resembling the the Sherrington-Kirkpatrick model of Ising spin glass and compare the effectiveness of different types of fluctuations by numerically calculating the relative success probabilities and residual energies in fully-connected spin systems. We find that for a small class of instances coupled fluctuations can provide improvement over single spin fluctuations and analyze the properties of the corresponding class. Disclaimer: This research was funded by ODNI, IARPA via MIT Lincoln Laboratory under Air Force Contract No. FA8721-05-C-0002. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of ODNI, IARPA, or the US Government.

3:30PM C45.00004 Performance of error suppression schemes for adiabatic quantum computation in the presence of Markovian noise, MILAD MARVIAN, DANIEL LIDAR, None — We investigate the performance of error suppression schemes for adiabatic quantum computation. Assuming a Markovian environment and using an adiabatic master equation we compare the rate of excitation from the ground subspace of the encoded Hamiltonian during the evolution to that of the unprotected Hamiltonian. For different forms of Markovian environments such as sub-Ohmic, Ohmic and super-Ohmic we identify the parameter thresholds for which encoding starts exhibiting its benefits.

3:42PM C45.00005 Coping with noise in programmable quantum annealers, ALEJANDRO PERDOMO-ORTIZ, NASA/Ames Res Ctr — Solving real-world applications with quantum annealing algorithms requires overcoming several challenges, ranging from translating the computational problem at hand to the quantum-machine language, to tuning several other parameters of the quantum algorithm that have a significant impact on performance of the device. In this talk, we discuss these challenges, strategies developed to enhance performance, and also a more efficient implementation of several applications. For example, in http://arxiv.org/abs/1503.05679 we proposed an method to measure residual systematic biases in the programmable parameters of large-scale quantum annealers. Although the method described there works from a practical point of view, a few questions were left unanswered. One of these puzzles was the observation of a broad distribution in the estimated effective qubit temperatures throughout the device. In this talk, we will present our progress in understanding these puzzles and how these new insights allow for a more effective bias correction protocol. We will present the impact of these new parameter setting and bias correction protocols in the performance of hard discrete optimization problems and in the successful implementation of quantum-assisted machine-learning algorithms.

3:54PM C45.00006 Does finite-temperature decoding deliver better optima for noisy Hamiltonians?, ANDREW J. OCHOA, Department of Physics and Astronomy, Texas A&M University, KOHJI NISHIMURA, HIDETOSHI NISHIMORI, Department of Physics, Tokyo Institute of Technology, HELMUT G. KATZGRABER, Department of Physics and Astronomy, Texas A&M University — The minimization of an Ising spin-glass Hamiltonian is an NP-hard problem. Because many problems across disciplines can be mapped onto this class of Hamiltonian, novel efficient computing techniques are highly sought after. The recent development of quantum annealing machines promises to minimize these difficult problems more efficiently. However, the inherent noise found in these analog devices makes the minimization procedure difficult. While the machine might be working correctly, it might be minimizing a different Hamiltonian due to the inherent noise. This means that, in general, the ground-state configuration that correctly minimizes a noisy Hamiltonian might not minimize the noise-less Hamiltonian. Inspired by rigorous results that the energy of the noise-less ground-state configuration is equal to the expectation value of the energy of the noisy Hamiltonian at the (nonzero) Nishimori temperature [J. Phys. Soc. Jpn., 62, 4015-4030 (1993)], we numerically study the decoding probability of the original noise-less ground state with noisy Hamiltonians in two space dimensions, as well as the D-Wave Inc. Chimera topology. Our results suggest that thermal fluctuations might be beneficial during the optimization process in analog quantum annealing machines.
5:06PM C45.00007 Estimation of effective temperatures in a quantum annealer: Towards deep learning applications.

JOHN REALPE-GÓMEZ, MARCELLO BENEDETTI, ALEJANDRO PERDOMO-ORTIZ, NASA Ames Res Ctr — Sampling is at the core of deep learning and more general machine learning applications; an increase in its efficiency would have a significant impact across several domains. Recently, quantum annealers have been proposed as a potential candidate to speed up these tasks, but several limitations still bar them from being used effectively. One of the main limitations, and the focus of this work, is that using the device’s experimentally observable temperature as a reference for sampling purposes leads to very poor correlation with the Boltzmann distribution it is programmed to sample from. Based on quantum dynamical arguments, one can expect a fundamental intrinsic computational error from sampling from a Boltzmann-like distribution, it will correspond to one with an instance-dependent effective temperature. Unless this unknown temperature can be unveiled, it might not be possible to effectively use a quantum annealer for Boltzmann sampling processes. In this work, we propose a strategy to overcome this challenge with a simple effective-temperature estimation algorithm. We provide a systematic study assessing the impact of the effective temperatures in the quantum-assisted training of Boltzmann machines, which can serve as a building block for deep learning architectures.

This work was supported by NASA Ames Research Center

5:18PM C45.00013 Distortion of a reduced equilibrium density matrix.

IRIS SCHWENK, MICHAEL MARTHAUER, Karlsruhe Institute of Technology — We study a system coupled to external degrees of freedom, called bath, where we assume that the total system, consisting of system and bath is in equilibrium. An expansion in the coupling between system and bath leads to a general form of the reduced density matrix of the system as a function of the bath self-energy. The coupling to the bath results in a renormalization of the energies of the system and in a change of the eigenbasis. We study the influence of bosonic degrees of freedom on the state of a six qubit system similar to the eight qubit unit cell of a quantum annealing processor examined by Lanting et al.1


5:30PM C45.00014 Quantum annealing via quantum diffusion mediated by environment.

VADIM SMELYANSKIY, Google, DAVIDE VENTURELLI, University Space Research Association, ALEJANDRO PERDOMO-ORTIZ, University of California Santa Cruz, SERGEI KNYSH, Stinger Ghaffarian Technologies, Inc, MARK DYKMAN, Department of Physics and Astronomy, Michigan State University — We show that quantum diffusion near the quantum critical point can provide an efficient mechanism of open-system quantum annealing. The analysis refers to an Ising spin chain in a slowly decreasing transverse field coupled to bosonic heat bath. The diffusion facilitates recombination of collective (multi-spin) excitations in the chain. It sharply slows down as the system moves away from the quantum critical region, leading to significant spatial fluctuations even in the absence of disorder. The excitation density reached by then non-monotonically depends on the annealing rate. We find that obtaining an approximate solution via diffusion-mediated quantum annealing can be faster than via classical Glauber dynamics or the closed-system Kibble-Zurek mechanism. We study the scaling of the excitation density with the temperature and coupling constant to environment.
Multimode cavity QED 1: State preparation and readout

(Ravi Naik, Nelson Leung, Srivatsan Chakram, Yao Lu, Nate Earnest, Peter Groszkowski, Jens Koch, David Shuster)

but before a talk named:

Multimode cavity QED 3: Universal quantum gates

(Nelson Leung, Ravi Naik, Srivatsan Chakram, Yao Lu, Nate Earnest, Peter Groszkowski, Jens Koch, David Shuster)

3:18PM C48.00005 Multimode Strong Coupling in Circuit QED

Neereja Sundaresan, Yanbing Liu, Darius Sadri, Laszlo Szocs, Devin Underwood, Moein Malekakhlagh, Hakan Tureci, Andrew Houck, Princeton University

We present experimentally and theoretical studies in the multimode strong coupling (MMSC) regime of cavity quantum electrodynamics (QED). In MMSC, a single atom is simultaneously coupled to a large, but discrete, number of cavity harmonics, with atom-mode coupling strengths comparable to the free spectral range (FSR). This regime is readily accessible in circuit QED, by strongly coupling a transmon qubit to a low fundamental frequency microwave cavity. We present some key results from our original experiment (PRX 5, 021035, 2015), in which a transmon qubit, resonant with the 75th harmonic of a 90 MHz cavity, reached qubit-mode coupling strengths exceeding 30MHz. When this system is coherently driven, we observed complex multimode fluorescence, with the notable ability to create and measure arbitrary quantum states, in conjunction with the large coherence time of microwave cavities, makes multimode cavity QED a promising architecture for scalable quantum computation and bosonic quantum simulation. [1] J. D. Strand et al, Physical Review B 87.22 (2013)

3:30PM C48.00006 Multiphoton Quantum Rabi Oscillations in Ultrastrong Cavities

Anton Frisk Kockum, Center for Emergent Matter Science, RIKEN, Saitama 351-0198, Japan, Luigi Garziano, Roberto Stassi, Vincenzo Macri, Salvatore Savasta, Dipartimento di Fisica e di Scienze della Terra, Università di Messina, I-98166 Messina, Italy, Franco Nori, Center for Emergent Matter Science, RIKEN, Saitama 351-0198, Japan — When an atom is strongly coupled to a cavity, the two systems can exchange a single photon through a coherent Rabi oscillation. This process enables precise quantum-state engineering and manipulation of atoms and photons in a cavity, which play a central role in quantum information and measurement. Recently, a new regime of cavity QED has been reached experimentally where the interaction between light and artificial atoms (qubits) becomes ultrastrong, i.e., its strength is comparable to the atomic transition frequency or the resonance frequency of the cavity mode. Here we show that this regime can strongly modify the concept of vacuum Rabi oscillations, enabling multiphoton exchanges between the qubit and the resonator. We find that experimental state-of-the-art circuit-QED systems can undergo two- and three-photon vacuum Rabi oscillations. These anomalous Rabi oscillations can be exploited for the realization of efficient Fock-state sources of light and complex entangled states of qubits.

3:48PM C48.00007 Quantum Random Walks and Quantum Chaos

Philippe Campbell, Google Inc., Quantum AI, 5100 E. Gift Loop, Boulder, CO 80301, United States — We discuss quantum random walks on graphs, which are a simple quantum generalization of classical random walks. Quantum random walks have recently been used to solve certain problems faster than classical random walks, and the relationship between classical and quantum random walks has been a topic of great interest in recent years. In this talk, we will review the basics of quantum random walks and then discuss recent advances in the field, including applications to quantum error correction and quantum cryptography.
4:18PM C48.00010 Deep strong coupling in a circuit QED system (2) - experiment -

FUMIKI YOSHIHARA, TOMOKO FUSE, KOUICHI SEMBA, National Institute of Information and Communications Technology, Koganei, Tokyo, Japan — Among a variety of cavity/circuit-QED systems, the superconducting flux qubit is a promising candidate for increasing the coupling strength further because of its huge magnetic moment. Using a flux qubit, $g/\omega_\text{Rabi} = 0.12$ ($g$: coupling strength, $\omega_\text{Rabi}$: bare resonator frequency) has been reported [1]. However, $g/\omega_\text{Rabi}$ is still lower than 1. Here, instead of the widely used coplanar waveguide (CPW) resonators, we use a lumped-element resonator consisting of an inductor (L) and a capacitor (C). While CPW resonators are distributed-element circuits and are therefore restricted by impedance matching constraints, one can freely choose the ratio, $L/C$, of a lumped-element resonator. This allows us to design a much smaller inductance and to make the zero-point current fluctuation much larger. Using a flux qubit and a lumped-element resonator, we have achieved $g/\omega_\text{Rabi}$ comparable to or larger than 1, which is the deep strong coupling regime, where a variety of interesting states, such as a spontaneously generated Schrödinger-cat-like correlated ground state of light and matter, have been predicted [2,3]. In this talk, I will introduce the motivation and the significance of the research, methods to achieve such a strong interaction, and a brief overview of the obtained results. [1] J. Johansson, S. Saito, T. Meno, H. Nakano, M. Ueda, K. Semba, and H. Takayanagi, Phys. Rev. Lett. 96, 127006 (2006). [2] S. Ashhab and Franco Nori, Phys. Rev. A 81, 042311 (2010). [3] S. Ashhab, YANBING LIU, ANDREW HOUCK, Princeton University — Quantum electrodynamics predicts the localization of light around an atom in photonic band-gap (PBG) medium or photonic crystal. Here we report the first experimental realization of the strong coupling between a single artificial atom and an one dimensional PBG medium using superconducting circuits. In the photonic transport measurement, we observe an anomalus Lamb shift and a large band-edge avoided crossing when the artificial atom frequency is tuned across the band-edge. The persistent peak within the band-gap indicates the single photon bound state. Furthermore, we study the resonance fluorescence of this bound state, again demonstrating the breakdown of the Born-Markov approximation near the band-edge. This novel architecture can be directly generalized to study many-body quantum electrodynamics and to construct more complicated spin chain models.
4:54PM C48.00013 Experimental study of a 72-site Jaynes-Cummings lattice in the nonlinear dispersive regime, MATTHIAS FITZPATRICK, NEEREJA SUNDARESAN, Princeton University, ANDY C. Y. LI, JENS KOCH, Northwestern University, ANDREW HOUCK, Princeton University — The building blocks of circuit-QED provide useful tools for the study of nonequilibrium and highly nonlinear behavior. In particular, the inherent dissipation in circuit-QED systems naturally gives rise to crossovers between different steady-states and dynamical phase transitions in even as few as two-site lattices. We explore the steady-state behavior of a 72-site Jaynes-Cummings lattice in the dispersive regime, highlighting the sharp transition in fluorescence at critical drive powers as well as strong nonlinear wave-mixing phenomena.

5:06PM C48.00014 The driven-dissipative Jaynes-Cummings lattice in the nonlinear dispersive regime, ANDY C. Y. LI, Northwestern University, MATTHIAS FITZPATRICK, NEEREJA SUNDARESAN, ANDREW HOUCK, Princeton University, JENS KOCH, Northwestern University — Experiments studying circuit-QED lattices have great potential for advancing our understanding of nonequilibrium many-body phenomena, including dissipative and dynamical phase transitions. One particular model realizable in this architecture is the driven-dissipative Jaynes-Cummings model. Motivated by the experimental measurements in the Houck lab, we theoretically investigate the dispersive regime including sub-leading nonlinear contributions from Kerr terms, employing a semi-classical approximation and numerics based on the quantum master equation. We explore the features of the experimentally detected crossover which is observed for an increase of the driving strength beyond a certain threshold.

5:18PM C48.00015 Spin-boson model with an engineered reservoir in circuit QED1, FRANK DEPPE, M. HAEBERLEIN, P. EDER, J. GOETZ, M. FISCHER, W. WULSCHNER, E. XIE, K. G. FEDOROV, A. MARX, R. GROSS, Walther-Meissner-Institut; Technische Universitaet Muenchen; Nanosystems Initiative Munich, Germany — A superconducting qubit coupled to an open transmission line represents an implementation of the spin-boson model with an engineered environment. Using a flux qubit with a large mutual inductance to the transmission line, we confirm in a resonance fluorescence experiment that the spectral function \( J(\omega) \) of this environment is Ohmic over a frequency range of several gigahertz. Furthermore, partial reflectors implemented into the transmission line modify the spectral function of the transmission line. For weak enough reflectors, we find that the resulting broad peak can be interpreted in terms of an enhanced spontaneous emission rate. Our work [M. Haebelrlein et al., arXiv:1506.09114 (2015)] lays the ground for future quantum simulations of other, more involved, impurity models with superconducting circuits.

1Work supported by the German Research Foundation through SFB 631 and FE 1564/1-1, the EU project PROMISCE, and Elite Network of Bavaria through the program ExQM.

5:30PM C48.00016 Strongly Correlated Photons at Full Transmission1, YAO-LUNG L. FANG, HAROLD U. BARANGER, Duke Univ — We show how to make strongly correlated photons in a fully transmitted pulse. The system consists of three-level qubits (3LS) coupled to a one-dimensional waveguide. Our two-photon scattering approach naturally connects photon correlations with inelastic scattering. We find that the total inelastically scattered flux is much larger than in the case of two-level systems, making 3LS better candidates for experimental study of non-classical light. Strikingly, there is a further substantial increase in inelastic flux upon adding either more 3LS or a mirror. Typically, resonant probe photons at electromagnetically induced transparency are not correlated — the correlations occur off resonance and so involve backscattering. Remarkably, we show that for three qubits, the qubit frequencies and the pump beam can be engineered such that correlated photons are fully transmitted, thereby greatly improving the efficiency of generating photon correlation.

1Work supported by U.S. NSF Grant No. PHY-14-04125.

5:48PM C48.00017 Machine Learning for Quantum Metrology and Quantum Control1, BARRY SANDERS2, EHSAN ZAHEDINEJAD, PANTITA PALITTAPONGARNPIM, University of Calgary — Generating quantum metrological procedures and quantum gate designs, subject to constraints such as temporal or particle-number bounds or limits on the number of control parameters, are typically hard computationally. Although greedy machine learning algorithms are ubiquitous for tackling these problems, the severe constraints listed above limit the efficacy of such approaches. Our aim is to devise heuristic machine learning techniques to generate tractable procedures in quantum metrology and quantum gate design. In particular we have modified differential evolution to generate adaptive interferometric-phase quantum metrology procedures for up to 100 photons including loss and noise, and we have generated policies for designing single-shot high-fidelity three-qubit gates in superconducting circuits by avoided level crossings. Although quantum metrology and quantum control are regarded as disparate, we have developed a unified framework for these two subjects, and this unification enables us to transfer insights and breakthroughs from one of the topics to the other.

1Thanks to NSERC, AITF and 1000 Talent Plan.
2Also Univ of Science and Technology of China and Canadian Inst for Advanced Research.

9:00AM E44.00004 Ultimate precision limit and optimal probe states for quantum metrology, HAIHONG YUAN, CHI-HANG FRED FUNG, Chinese Univ of Hong Kong; HONGKONG SCIENCE PARK — An important task in science and technology is to find out the highest achievable precision in measuring and estimating parameters of interest with given resources, and design schemes to reach it. Quantum metrology, which exploits quantum mechanical effects to achieve high precision, has gained increasing attention in recent years. Here we present a general framework for quantum metrology which relates the ultimate precision limit directly to the underlying dynamics, this framework provides efficient methods for computing the ultimate precision limit and optimal probe states. We further demonstrate the power of the framework by deriving a sufficient condition on when ancillary systems are not useful for improving the precision limit.
9:12AM E44.00005 Improving the precision of weak measurement by nonclassical states, SHENG-SHI PANG, University of Rochester, TODD A. BRUN, University of Southern California — Weak value amplification is a useful protocol to amplify tiny physical effects by postselecting the system in a weak measurement. However, there has been controversy over its precision advantage in parameter estimation recently, since it discards unselected results of the postselection measurement on the system, which may take away useful information. While it is now clear that retaining failed postselections can yield more Fisher information than discarding them, the advantage of postselection measurement itself still remains to be clarified. If a weak measurement with postselection measurement cannot produce higher precision than without postselection measurement, it would be meaningless to discuss the use of postselection results. In this work, we address this problem by studying the optimal signal-to-noise ratio (SNR) of postselected weak measurement. We find a surprising result that when the probe is initially prepared in a proper squeezed coherent state, the postselected weak measurement can give a higher SNR than the standard weak measurement, while such an advantage vanishes when the probe is prepared in a normal coherent state. This suggests that raising the precision of weak measurement by postselection calls for the presence of nonclassicality in the probe state.

9:24AM E44.00006 Robust Calibration of a Universal Single-Qubit Gate-Set via Robust Phase Estimation, SHELBY KIMMEL, University of Maryland, QUICS, GUANG HAO LOW, THEODORE J. YODER, Massachusetts Institute of Technology — An important step in building a quantum computer is calibrating experimentally implemented quantum gates to produce operations that are close to ideal unitaries. The calibration step involves estimating the systematic errors in gates and then using controls to correct the implementation. Quantum process tomography is a standard technique for estimating these errors, but is both time consuming, (when one only wants to learn a few key parameters), and is usually inaccurate without resources like perfect state preparation and measurement, which might not be available. With the goal of efficiently and accurately estimating specific errors using minimal resources, we develop a parameter estimation technique, which can gauge key systematic parameters (specifically, amplitude and off-resonance errors) in a universal single-qubit gate-set with provable robustness and efficiency. In particular, our estimates achieve the optimal efficiency, Heisenberg scaling, and do so without entanglement and entirely within a single-qubit Hilbert space. Our main theorem making this possible is a robust version of the phase estimation procedure of Higgins et al. [B. L. Higgins et al., New J. Phys. 11 073023 (2009)].

9:36AM E44.00007 Numerical Analysis of Robust Phase Estimation, KENNETH RUDINGER, Center for Computing Research, Sandia National Laboratories, SHELBY KIMMEL, QuCS, University of Maryland — Robust phase estimation (RPE) is a new technique for estimating rotation angles and axes of single-qubit operations, steps necessary for developing useful quantum gates [arXiv:1502.02677]. As RPE only diagnoses a few parameters of a set of gate operations while at the same time achieving Heisenberg scaling, it requires relatively few resources compared to traditional tomographic procedures. In this talk, we present numerical simulations of RPE that show both Heisenberg scaling and robustness against state preparation and measurement errors, while also demonstrating numerical bounds on the procedure’s efficacy. We additionally compare RPE to gate set tomography (GST), another Heisenberg-limited tomographic procedure. While GST provides a full gate set description, it is more resource-intensive than RPE, leading to potential tradeoffs between the procedures. We explore these tradeoffs and numerically establish criteria to guide experimentalists in deciding when to use RPE or GST to characterize their gate sets.

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.

10:48AM E44.00008 Formal Computer Validation of the Quantum Phase Estimation Algorithm, WAYNE WITZEL, KENNETH RUDINGER, Sandia National Laboratories, Albuquerque, NM, MOHAN SAROVAR, Sandia National Laboratories, Livermore, CA, ROBERT RUDINGER, University of New Mexico — While we review and scientific consensus provide some assurance of the validity of ideas, proof errors that can slip through the cracks. A plethora of formal methods tools exist and are in use in a variety of settings where high assurance is demanded. Existing tools, however, require a great deal of expertise and lack versatility, demanding a non-trivial translation between a high-level description of a problem and the formal system. Our software, called Prove-It, allows a nearly direct translation between human-recognizable formulations and the underlying formal system. While Prove-It is not designed for particularly efficient automation, a primary goal of other formal methods tools, it is extremely flexible in following a desired line of reasoning (proof structure). This approach is particularly valuable for validating proofs that are already known. We will demonstrate a validation of the Quantum Phase Estimation Algorithm using Prove-It. 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 Energys National Nuclear Security Administration under contract DE-AC04-94AL85000.

1This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories.

10:00AM E44.00009 Efficient Bayesian Phase Estimation, NATHAN WIEBE, Microsoft Research, CHRISTOPHER GRANADE, University of Sydney — We provide a new efficient adaptive algorithm for performing phase estimation that does not require that the user infer the bits of the eigenphase in reverse order; rather it directly infers the phase and estimates the uncertainty in the phase directly from experimental data. Our method is highly flexible, recovers from failures, and can be run in the presence of substantial decoherence and other experimental imperfections and as fast or faster than existing algorithms.

10:12AM E44.00010 Bounding quantum gate error rate based on reported average fidelity, YUVAL SANDERS, JOEL WALLMAN, Univ of Waterloo, BARRY SANDERS, Univ of Calgary — Remarkable experimental advances in quantum computing are exemplified by recent announcements of impressive average gate fidelities exceeding 99.9% for single-qubit gates and 99% for two-qubit gates. Although these high numbers engender optimism that fault-tolerant quantum computing is within reach, the connection of average gate fidelity with fault-tolerance requirements is not direct, in the sense that the average gate fidelity is not the appropriate metric for assessing progress towards fault-tolerant quantum computation, and we demonstrate that this bound is asymptotically tight for general noise. Although this bound is unlikely to be saturated by experimental noise, we demonstrate using explicit examples that the bound indicates a realistic deviation between the true error rate and the reported average fidelity. We introduce the Pauli-distance as a measure of this deviation, and we show that knowledge of the Pauli-distance enables tighter estimates of the error rate of quantum gates.

10:24AM E44.00011 Percolation bounds for decoding thresholds with correlated erasures in quantum LDPC codes1, KATHLEEN HAMILTON, None, LEONID PRYADKO, University of California, Riverside — Correlations between errors can dramatically affect decoding thresholds, in some cases eliminating the threshold altogether. We analyze the existence of a threshold for quantum low-density parity-check (LDPC) codes in the case of correlated erasures. When erasures are positively correlated, the corresponding multi-variate Bernoulli distribution can dramatically affect decoding thresholds, in some cases eliminating the threshold altogether. We analyze the existence of a threshold for quantum low-density quantum LDPC codes enables tighter estimates of the error rate of quantum gates.

1This research was supported in part by the NSF grant PHY-1416578 and by the ARO grant W911NF-14-1-0272.
10:36AM E44.00012 Robustness and performance scaling of quantum information processors with respect to gate removal and defects, YUNSEONG NAM, REINHOLD BLÜMEL, Wesleyan Univ — A single logical gate, when removed from a classical computer, can completely destroy its information processing capability. For a quantum processor, the story is quite different. We find that the processing capability of a quantum information processor is robust with respect to the removal of a large number of quantum logical gates. In fact, even when most of the quantum processor’s gates are removed, quantum processors, such as the universally applicable quantum Fourier transform or the quantum adder, work with satisfactory performance. In this talk, we present our numerical and analytical results detailing the performance scaling of quantum processors with respect to gate pruning operations. We also present the performance scaling of pruned quantum processors subjected to gate defects in the remaining gates.

10:48AM E44.00013 Assessing the performance of quantum repeaters for all phase-insensitive Gaussian bosonic channels, KENNETH GOODENOUGH, DAVID ELKOUSS, STEPHANIE WEHNER, Delft Univ of Tech, QUTECH TEAM — One of the most sought-after goals in experimental quantum communication is the implementation of a quantum repeater. Quantum repeaters can be assessed by comparing their performance with the quantum- and private capacity of a direct transmission, assisted by unlimited classical two-way communication. Calculating these quantities is hard to compute however, motivating the search for upper bounds on these capacities. Takeoka, Guha and Wilde found the squashed entanglement of a quantum channel to be an upper bound on these capacities. In general it is hard to find the exact value of the squashed entanglement of fast gate voltage based spin manipulations to form a hybrid singlet-triplet qubit, with access to the quantum memory offered by the nuclear spin of the donor via the hyperfine interaction. Additionally, spin buses using quantum dot chains could mediate the transfer of quantum information between long-lived donor spins. We present an approach to a novel hybrid double quantum dot by coupling a donor to an artificial atom in a CMOS-compatible nanotransistor. Using gate-based RF-reflectometry, we probe the charge stability of the system and its quantum capacitance. Through microwave spectroscopy, we find a tunnel coupling of 2.7GHz and characterize the charge dynamics, revealing a charge $Q$ of 100ns. We also show spin blockade at the inderot transition and investigate the spin dynamics, opening up the possibility to operate this coupled system as a singlet-triplet qubit and to coherently transfer spin information between the quantum dot and the donor electron and nucleus.

Tuesday, March 15, 2016 8:00AM - 11:00AM –
Session E45 GQI DAMOP: Hybrid Quantum Systems I 348 - Mark Dykman, Michigan State University

8:00AM E45.00001 Charge dynamics and spin blockade in a hybrid double quantum dot in silicon1, ANASUAT CHATTERJEE, MATIAS URDAMPILLETA, CHEUK CHI LO, JOHN MANSIR, London Centre for Nanotechnology, University College London, SYLVAIN BARRAUD, CEA-LETI, ANDREAS BETZ, M. FERNANDO GONZALEZ-ZALBA, Hitachi Cambridge Laboratory, JOHN J. L. MORTON, London Centre for Nanotechnology, University College London — Hybrid architectures combining donor atoms and quantum dots in silicon can take advantage of fast gate voltage based spin manipulations to form a hybrid singlet-triplet qubit, with access to the quantum memory offered by the nuclear spin of the donor via the hyperfine interaction. Additionally, spin buses using quantum dot chains could mediate the transfer of quantum information between long-lived donor spins. We present an approach to a novel hybrid double quantum dot by coupling a donor to an artificial atom in a CMOS-compatible nanotransistor. Using gate-based RF-reflectometry, we probe the charge stability of the system and its quantum capacitance. Through microwave spectroscopy, we find a tunnel coupling of 2.7GHz and characterize the charge dynamics, revealing a charge $Q$ of 100ns. We also show spin blockade at the inderot transition and investigate the spin dynamics, opening up the possibility to operate this coupled system as a singlet-triplet qubit and to coherently transfer spin information between the quantum dot and the donor electron and nucleus.

1We acknowledge support from the TOLOP project (FP7/318397), the EPSRC, ARC, and the UNDEDD project, the Royal Commission for the Exhibition of 1851 and the Royal Society.

8:12AM E45.00002 Controlling spin relaxation with a cavity, AUDREY BIENFAIT, SPEC, CEA-Saclay, JARRYD PLA, University College of London, YUIMARU KUBO, SPEC, CEA-Saclay, XIN ZHOU, Institute of Electronics, Microelectronics, and Nanotechnology, MICHAEL STERN, University of Bar Ilan, CHEUK LO, University College of London, CHRISTOPHER WEIS, THOMAS SCHENKEL, Lawrence Berkeley National Laboratory, DENIS VION, DANIEL ESTEVE, SPEC, CEA-Saclay, JOHN MORTON, University College of London, PATRICE BERTEBT, SPEC, CEA-Saclay — Spontaneous emission of radiation is one of the fundamental relaxation mechanisms for a quantum system. For spins, however, it is negligible compared to non-radiative relaxation processes due to their weak coupling to the electromagnetic field. In 1946, Purcell realized [1] that spontaneous emission is strongly enhanced when the quantum system is placed in a resonant cavity - an effect now used to control the lifetime of systems with an electrical dipole [2]. Here, by coupling donor spins in silicon to a high quality factor superconducting microwave cavity of small mode volume, we reach the regime where spontaneous emission constitutes the dominant spin relaxation channel [3]. The relaxation rate is increased by three orders of magnitude when the spins are tuned to the cavity resonance, showing it can be engineered and controlled on-demand. Our results provide a novel way to initialize any spin into its ground state, with applications in magnetic resonance and quantum information processing. They also show for the first time an alteration of spin dynamics by quantum fluctuations, a step towards the coherent magnetic coupling of a spin to microwave photons. [1] E. M. Purcell, Phys. Rev. 1946, 69, 681.


8:36AM E45.00004 Magnetic resonance at the quantum limit, PATRICE BERTEBT, CEA Saclay — The detection and characterization of paramagnetic species by electron-spin resonance (ESR) spectroscopy has numerous applications in chemistry, biology, and materials science [1]. Most ESR spectrometers rely on the inductive detection of the small microwave signals emitted by the spins during their Larmor precession into a microwave resonator in which they are embedded. Using the tools offered by circuit Quantum Electrodynamics (QED), namely high quality factor superconducting micro-resonators and Josephson parametric amplifiers that operate at the quantum limit when cooled at 20mK [2], we report an increase of the sensitivity of inductively detected ESR by 4 orders of magnitude over the state-of-the-art, enabling the detection of 1700 Bismuth donor spins in silicon with a signal-to-noise ratio of 1 in a single echo [3]. We also demonstrate that the energy relaxation time of the spins is limited by spontaneous emission of microwave photons into the measurement line via the resonator [4], which opens the way to on-demand spin initialization via the Purcell effect. These results constitute a first step towards circuit QED experiments with magnetically coupled individual spins. [1] A. Schweiger and G. Jeschke, Principles of Pulse Electron Magnetic Resonance (Oxford University Press, 2001) [2] X. Zhou et al., Physical Review B 89, 214517 (2014). [3] A. Bienfait et al., arxiv :1507.08631 [4] A. Bienfait et al., arxiv :1508.06148
9:12AM E45.00005 Hybrid Quantum Information Processing with Superconducting Circuits and Rydberg Atoms. MATTHEW BECK, JOSHUA ISAACS, DONALD BOOTH, MARK SAFFMAN, ROBERT MCDERMOTT, University of Wisconsin - Madison — Hybrid approaches to quantum information processing exploit the strengths of disparate quantum technologies to realize performance that exceeds what can be reached with any single technology on its own. Here we describe steps toward realization of a hybrid superconducting circuit Rydberg atom quantum architecture that will marry a fast, high-fidelity superconducting quantum processor with a long-lived quantum memory based on trapped Rydberg atoms. The key challenge is development of a high-fidelity microwave photon Rydberg atom interface. We have designed superconducting thin-film microwave resonators that allow coupling of single Rydberg atoms at a voltage antinode, where coupling to the zero-point fields of the resonator is strongest. We discuss the dependence of resonator quality factor and achievable coupling factor on device geometry. Finally, we present preliminary results of experiments to couple Rydberg atoms and superconducting linear resonators in a custom liquid helium cryostat.

9:24AM E45.00006 Photon-mediated interactions: a scalable tool to create and sustain entangled states of N atoms, CAMILLE ARON, Laboratoire de Physique Thorique, cole Normale Superieure, CNRS, Paris, France and Institut pour Theoretische Fysica, KU Leuven, Leuven, Belgium, MANAS KULKARNI, New York City College of Technology, City University of New York, HAKAN TURECI, Princeton University — We propose and study the use of photon-mediated interactions for the generation of steady-state entanglement between N atoms that are separated by arbitrary distances. Through the judicious use of coherent drives and the placement of the atoms in a network of Cavity QED systems, a balance between their unitary and dissipative dynamics can be precisely engineered to stabilize a long-range correlated state of qubits in the steady state. We discuss the general theory behind such a scheme, and present an example of how it can be used to drive a register of N atoms to a generalized W-state, and the entanglement sustained indefinitely. The achievable steady-state fidelities for entanglement and its scaling with the number of qubits are discussed for presently existing superconducting quantum circuits. While the protocol is primarily discussed for a superconducting circuit architecture, it is ideally realized in any Cavity QED platform that permits controllable delivery of coherent electromagnetic radiation to specified locations.

9:36AM E45.00007 Spin-cavity longitudinal coupling for two-qubit gates and measurement, RUSKOS RUSKOV, CHARLES TAHAN, Laboratory for Physical Sciences, College Park, MD 20740 — We have studied the possibility of longitudinal coupling of various encoded quantum dot spin-qubits to a microwave resonator via modulation of voltage gates. A dynamical coupling of tens of MHz can be achieved. We investigate specific procedures for entangling gates using accumulated geometric phases and calculate possible gate times and fidelities. Implications for qubit readout and continuous quantum monitoring are also considered.

9:48AM E45.00008 Magnetization detecting electron paramagnetic resonance spectroscopy using a dc-SQUID directly coupled to an electron spin ensemble, HIRAKU TOIDA, YUICHIRO MATSUZAKI, KOSUKE KAKUYANAGI, XIAOBO ZHU, WILLIAM MUNRO, NTT Basic Research Laboratories, KAE NEMOTO, National Institute of Informatics, HIROSHI YAMAGUCHI, SHIRO SAITO, NTT Basic Research Laboratories — Electron parametric resonance (EPR) spectroscopy is one of the most widely-used tool used for the characterization of paramagnetic materials and to coherently control electron spins as carriers of quantum information. The coupling strength between spins and RF magnetic fields can be increased by using microwave frequency resonators, realized either as 3D cavities or in planar geometries. Here, we study microwave resonators embedding a superconducting quantum interference device (dc-SQUID) magnetometer, which is bonded to the sample. Here, we report detection of electron spin polarization and EPR spectroscopy using a micrometer-sized dc-SQUID magnetometer. We measure temperature and in-plane magnetic field dependence of spin polarization ratio and it has good agreement to the hyperbolic tangent law. We also successfully demonstrate EPR spectroscopy by applying a continuous microwave signal to the sample with a on-chip microwave. We estimate the sensing volume and the minimum distinguishable number of electron spins to be ∼ 10^{10} cm^3 (~0.1 pl) and ∼ 10^6, respectively. This result paves the way towards realizing highly sensitive EPR spectroscopy in nanometer-sized area.

10:00AM E45.00009 Coupling nanoscale spin ensembles to a SQUID embedded in superconducting circuits, C. EICHLER, J. R. PETTA, Department of Physics, Princeton University — Electron spin resonance is a ubiquitous phenomenon used for the characterization of paramagnetic materials and to coherently control electron spins as carriers of quantum information. The coupling strength between spins and RF magnetic fields can be increased by using microwave frequency resonators, realized either as 3D cavities or in planar geometries. Here, we study microwave resonators embedding a superconducting quantum interference device (SQUID), which couples to nearby electron spins of phosphorus donors in silicon. We compare different SQUID and resonator geometries aiming at enhanced spin sensitivity. We also study the coupled system in a sideband regime where the Zeeman energy is nonresonant with the cavity frequency, allowing for operation at lower DC magnetic fields.

10:12AM E45.00010 Angular dependant micro-ESR characterization of a locally doped Gd^{3+}:Al_{2}O_{3} hybrid system for quantum applications, I. S WISBY, NPL, UK & Royal Holloway, UK, S.E DE GRAAF, NPL, UK, R. GWILLIAM, ATI, University of Surrey, UK, A. ADAMYAN, Chalmers University of Technology, S. E KUBATKIN, Chalmers University of Technology, Sweden, P. J. MEESON, Royal Holloway, UK, A. YA. TZALENCHUK, NPL, UK & Royal Holloway, UK, T. LINDSTROM, NPL, UK — Rare-earth doped crystals incorporated with superconducting quantum circuitry are an attractive platform for quantum memory and transducer applications. Here we present a detailed characterization of a locally implanted Gd^{3+} in Al_{2}O_{3} hybrid system coupled to a superconducting micro-resonator, by performing angular dependent micro-electron-spin-resonance (micro-ESR) measurements at mK temperatures. The device is fabricated using a hard Si_{3}N_{4} mask to facilitate a local ion-implantation technique for precision control of the dopant location. The technique is found not to degrade the internal quality factor of the resonators which remains above 10^6 (1). We find the measured angular dependence of the micro-ESR spectra to be in excellent agreement with the modelled Hamiltonian, supporting the conclusion that the dopant ions are successfully integrated into their relevant lattice sites whilst maintaining crystalline symmetries. Furthermore, we observe clear contributions from the optical microwave field components of our micro-resonator, emphasising the need for controllable local implantation. 1) Wisby et al. Appl. Phys. Lett. 105, 102601 (2014)

10:24AM E45.00011 Strong Coupling of a Donor Spin Ensemble to a Volume Microwave Resonator, BRENDON ROSE, ALEXEI TYRYSHKIN, STEPHEN LYON, Princeton University — We achieve the strong coupling regime between an ensemble of phosphorus donor spins (5e13 total donors) in highly enriched 28-Si (50 ppm 29-Si) and a standard dielectric resonator. Spins were polarized beyond Boltzmann equilibrium to a combined electron and nuclear polarization of 120 percent using spin selective optical excitation of the non-phonon bound exciton transition. We observed a spin ensemble-resonator splitting of 580 kHz (2g) in a cavity with a Q factor of 75,000 (κ ≪ γ ≅ 120kHz) where κ and γ are the external and internal resonator loss rates respectively. The spin ensemble has a long dephasing time (9 μs) providing a wide window for viewing the time evolution of the coupled spin ensemble-cavity system described by the Tavis-Cummings model. The free induction decay shows repeated collapses and revivals revealing a coherent and complete exchange of excitations between the superradiant state of the spin ensemble and the cavity (about 10 cycles are resolved). This exchange can be viewed as a swap of information between a long lived spin ensemble memory qubit (T2 ≈ 2 ms) and a cavity
 Suppressing gate errors through extra ions coupled to a cavity in frequency-domain quantum computation using rare-earth-ion-doped crystal. SATOSHI NAKAMURA, HAY-ATO GOTO, MAMIKO KUJIRAOKA, KOUICHI ICHIMURA, Corporate RD Center, Toshiba Corporation, QUANTUM COMPUTER TEAM — The rare-earth-ion-doped crystals, such as Pr$_3^+$: Y$_2$SiO$_5$, are promising materials for scalable quantum computers, because the crystals contain a large number of ions which have long coherence time. The frequency-domain quantum computation (FDQC) enables us to employ individual ions coupled to a common cavity mode as qubits by identifying with their transition frequencies. In the FDQC, operation lights with detuning interact with transitions which are not intended to operate, because ions are irradiated regardless of their positions. This crosstalk causes serious errors of the quantum gates in the FDQC. When resonance conditions between eigenenergies of the whole system and transition-frequency differences among ions are satisfied, the gate errors increase. Ions for qubits must have transitions avoiding the conditions for high-fidelity gate. However, when a large number of ions are employed as qubits, it is difficult to avoid the conditions because of many combinations of eigenenergies and transitions. We propose new implementation using extra ions to control the resonance conditions, and show the effect of the extra ions by a numerical simulation. Our implementation is useful to realize a scalable quantum computer using rare-earth-ion-doped crystal based on the FDQC.

Magneto-transport studies of a few hole GaAs double quantum dot in tilted magnetic fields. SERGEI STUDENIKIN, ALEX BOGAN, National Research Council of Canada, LISA TRACY, Sandia National Laboratories, LOUIS GAUDREAU, ANDY SACHRAJDA, MAREK KORKUSINSKI, National Research Council of Canada, JOHN RENO, TERRY HARGETT, Sandia National Laboratories — Compared to equivalent electron devices, single-hole spins interact weakly with lattice nuclear spins leading to extended quantum coherence times. This makes p-type Quantum Dots (QD) particularly attractive for practical quantum devices such as qubit circuits, quantum repeaters, quantum sensors etc. where long coherence time is required. Another property of holes is the possibility to tune their g-factor as a result of the strong anisotropy of the valence band. Hole g-factors can be conveniently tuned in situ from a large value to almost zero by tilting the magnetic field relative to the 2D hole gas surface normal. [1] In this work we explore high-bias magneto-transport properties of a p-type double quantum dot (DQD) device fabricated from a GaAs/AlGaAs heterostructures using lateral split-gate technology. [2] A charge detection technique is used to monitor number of holes and tune the g-DQD in a single hole regime around (1,1) and (2,0) occupation states where Pauli spin-blockaded transport is expected. Four states are identified in quantizing magnetic fields within the high-bias current stripe – three-fold triplet and a singlet which allows determining effective heavy hole g-factor as a function of the tilt angle from 90 to 0 degrees. [1] G. Ares et al., Phys.Rev. Lett. 110, 046602 (2013); [2] L. A. Tracy et al., App. Phys. Lett. 104, 123101 (2014).
9:00AM E48.00004 Weight-4 Parity Checks on a Surface Code Sublattice with Superconducting Qubits1, MAIKA TAKITA, ANTONIO CORCOLES, EASWAR MAGEAN, NICHOLAS BRONN, JARED HERTZBERG, JAY GAMBITTA, MATTHIAS STEFFEN, JERRY CHOW, IBM T.J. Watson Research Center — We present a superconducting qubit quantum processor design amenable to the surface code architecture. In such architecture, parity checks on the data qubits, performed by measuring their X- and Z- syndrome qubits, constitute a critical aspect. Here we show fidelities and outcomes of X- and Z-parity measurements done on a syndrome qubit in a full plaquette consisting of one syndrome qubit coupled via bus resonators to four code qubits. Parities are measured after four code qubits are prepared into sixteen initial states in each basis. Results show strong dependence on ZZ between qubits on the same bus resonators.

1This work is supported by IARPA under contract W911NF-10-1-0324.

9:12AM E48.00005 Active resonator reset in the non-linear regime of circuit QED to improve multi-round quantum parity checks1, CORNELIS CHRISTIAAN BULTINK, M.A. ROL, X. FU, B.C.S. DIKKEN, J.C. DE STERKE, R.F.L. VERMEULEN, R.N. SCHOUTEN, A. BRUNO, K.L.M. BERTELS, L. DICARLO, QuTech, Delft University of Technology — Reliable quantum parity measurements are essential for fault-tolerant quantum computing. In quantum processors based on circuit QED, the fidelity and speed of multi-round quantum parity checks using an ancillary qubit can be compromised by photons remaining in the readout resonator post measurement, leading to ancilla dephasing and gate errors. The challenge of quickly depleting photons is biggest when maximizing the single-shot readout fidelity involves strong pulses turning the resonators non-linear. We experimentally demonstrate the numerical optimization of counter pulses for fast photon depletion in this non-analytic regime. We compare two methods, one using digital feedback and another running open loop. We assess both methods by minimizing the average number of rounds to ancilla measurement error.

1We acknowledge funding from the EU FP7 project SCALEQIT, FOM, and an ERC Synergy Grant.

9:24AM E48.00006 Demonstration of quantum superiority in learning parity with noise with superconducting qubits1, DIEGO RISTÉ, MARCUS DA SILVA, COLM RYAN, Raytheon BBN Technologies, ANDREW CROSS, JOHN SMOLIN, JAY GAMBITTA, JERRY CHOW, IBM T.J. Watson Research Center, BLAKE JOHNSON, Raytheon BBN Technologies — A problem in machine learning is to identify the function programmed in an unknown device, or oracle, having only access to its output. In particular, a parity function computes the parity of a subset of a bit register. We implement an oracle executing parity functions in a five-qubit superconducting processor and compare the performance of a classical and a quantum learner. The classical learner reads the output of multiple oracle calls and uses the results to infer the hidden function. In addition to querying the oracle, the quantum learner can apply coherent rotations on the output register before the readout. We show that, given a target success probability, the quantum approach outperforms the classical approach in the number of queries needed. Moreover, this gap increases with readout noise and with the size of the query register. This result shows that quantum advantage can already emerge in current systems with a few, noisy qubits.

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

9:36AM E48.00007 A Very Small Logical Qubit1, ELIOT KAPIT, Tulane University — Superconducting qubits are among the most promising platforms for building a quantum computer. However, individual qubit coherence times are not far past the scalability threshold for quantum error correction, meaning that millions of physical devices would be required to construct a useful quantum computer. Consequently, further increases in coherence time are very desirable. In this letter, we blueprint a simple circuit consisting of two transmon qubits and two additional lossy qubits or resonators, which is passively protected against all single qubit quantum error channels through a combination of continuous driving and engineered dissipation. Photon losses are rapidly corrected through two-photon drive fields implemented with driven SQUID couplings, and dephasing from random potential fluctuations is heavily suppressed by the drive fields used to implement the multi-qubit Hamiltonian. Comparing our theoretical model to published noise estimates from recent experiments on flux and transmon qubits, we find that logical state coherence could be improved by a factor of forty or more compared to the individual qubit $T_1$ and $T_2$ using this technique.

9:48AM E48.00008 Scalable in-situ qubit calibration during repetitive error detection1, J. KELLY, R. BAREND, A. FOWLER, J. MUTUS, Google, Santa Barbara, B. CAMPBELL, UC Santa Barbara, Y. CHEN, Google, Santa Barbara, Z. CHEN, B. CHIARO, A. DUNSWORD, UC Santa Barbara, E. JEFFREY, LUCERO, A. MEGRANT, M. NEELEY, Google, Santa Barbara, C. NEILL, P.J.J. O’MALLEY, UC Santa Barbara, P. ROUSHAN, D. SANK, Google, Santa Barbara, C. QUINTANA, A. VAINSENCHER, J. WENNER, UC Santa Barbara, T. WHITE, Google, Santa Barbara, J.M. MARTINIS, University of California and Google, Santa Barbara — A quantum computer protects a quantum state from the environment through the careful manipulations of thousands or millions of physical qubits. However, operating such quantities of qubits at the necessary level of precision is an open challenge, as optimal control parameters can vary between qubits and drift in time. We present a method to optimize physical qubit parameters while error detection is running using a nine qubit system performing the bit-flip repetition code. We demonstrate how gate optimization can be parallelized in a large-scale qubit array and show that the presented method can be used to simultaneously compensate for independent or correlated qubit parameter drifts. Our method is $O(1)$ scalable to systems of arbitrary size, providing a path towards controlling the large numbers of qubits needed for a fault-tolerant quantum computer.

10:00AM E48.00009 Tracking errors of a logical qubit comprised of superpositions of cat states in a superconducting resonator1, A. PETRENKO, N. OFEK, R. HEERES, P. REINHOLD, Y. LIU, Z. LEGHTAS, B. VLASTAKIS, L. FRANZIO, LIANG JIANG, Yale University Department of Applied Physics, M. MIRRAHIMI, INRIA Paris-Rocquencourt, M.H. DEVORET, R.J. SCHOELKOPF, Yale University Department of Applied Physics — QEC schemes involve redundantly encoding a qubit into a larger space of states that has symmetry properties that allow one to measure error syndromes. Traditional approaches involve encodings that employ large numbers of physical qubits, enhancing decay rates significantly and requiring considerable hardware overhead to realize. A hardware-efficient proposal [1,2], which we term the cat code, sheds much of this complexity by encoding a qubit in superpositions of cat states in a superconducting resonator, which has one dominant error syndrome: single photon loss. As these cat states are eigenstates of photon number parity, the loss of a photon changes the parity without corrupting the encoded information. In a superconducting CQED architecture, we demonstrate that we track these errors in real-time with repeated single shot parity measurements and map their occurrence onto applications of a unitary rotation of an arbitrary encoded state in the logical space. Our results illustrate the utility of long-lived resonators in the context of a full QEC system by highlighting the advantages of employing the cat code to suppress decoherence. [1]Leghtas et al. PRL 111 120501 2013 [2]Mirrahimi et al. NJP 16 045014 2014
10:12AM E48.00010 Stabilizing the phase of superpositions of cat states in a cavity using real-time feedback. N. OEK, A. PETRENKO, R. HEERAS, P. REINHOLD, Y. LIU, Z. LEDHTAS, B. VLASTAKIS, L. FRUNZIO, LIANG JIANG, Yale University, Department of Applied Physics, University of Erlangen-Nuremberg, M. BLOCH, M. MIRRAHIMI, INRIA Paris-Rocquencourt, M.H. DEVORET, R.J. SCHOELKOPF, Yale University, Department of Applied Physics — In a superconducting CQED architecture, a hardware efficient quantum error correction (QEC) scheme exists, called the cat code [1,2], which maps a qubit onto superpositions of cat states in a superconducting resonator, by mapping the occurrence of errors, or single photon jumps, onto unitary rotations of the encoded state. By tracking the parity of the encoded state, we can count the number of photon jumps and are able to apply a correcting unitary transformation. However, the situation is complicated by the fact that photon jumps do not commute with the deterministic anharmonic time evolution of a resonator state, or Kerr, inherited by the resonator from its coupling to a Josephson junction. As predicted in [1], a field in the resonator will inherit an overall phase $\theta = KT$ in IQ space each time a photon jumps that is proportional to the Kerr $K$ and the time $T$ at which the jump occurs. Here I will present how we can track the errors in real time, take them into account together with the time they occur and make it possible to stabilize the qubit information. [1]Leghtas et.al. PRL 111 125051 2013 [2]Mirrahimi et.al. NJP 16 045014 2014

1 Please place my talk right after the talk of Andrei Petrenko.

10:24AM E48.00011 Encoding quantum information in a stabilized manifold of a superconducting cavity. S. TOUZARD, Z. LEDHTAS, S.O. MUNDHADA, C. AXLINE, M. REAGOR, K. CHOU, J. BLUMOFF, K.M. SLIVA, S. SHANKAR, L. FRUNZIO, R.J. SCHOELKOPF, Department of Applied Physics, Yale University, University of Erlangen-Nuremberg, M. BLOCH, M. MIRRAHIMI, Department of Applied Physics, Yale University and INRIA Paris Rocquencourt, M.H. DEVORET, Department of Applied Physics, Yale University — In a superconducting Josephson circuit architecture, we activate a multi-photon process between two modes by applying microwave drives at specific frequencies. This creates a pairwise exchange of photons between a high-Q cavity and the environment. The resulting open dynamical system develops a two-dimensional quasi-energy ground state manifold. Can we encode, protect and manipulate quantum information in this manifold? We experimentally investigate the convergence and escape rates in and out of this confined subspace. Finally, using quantum Zeno dynamics, we aim to perform gates which maintain the state in the protected manifold at all times.

1 Work supported by: ARO, ONR, AFOSR and YINQE

10:36AM E48.00012 Simulation of an arbitrary quantum channel with minimal ancillary resource. CHAO SHEN, KYUNGJOO NOH, VICTOR V. ALBERT, MICHEL H. DEVORET, ROBERT J. SCHOELKOPF, STEVEN M. GIRVIN, LIANG JIANG, Yale University — We discuss an explicit and efficient construction of quantum circuits that can simulate an arbitrary given quantum channel acting on a d-level quantum system, with the minimal quantum ancillary resource— a qubit and its QND readout. The elementary operations required are unitary evolutions and single qubit projective measurement. We further show that this technique opens up exciting new possibilities in the field of quantum control, quantum simulation, quantum error correction, and quantum state discrimination. Our proposal can be implemented on platforms such as a superconducting transmon qubit inside a microwave cavity.

10:48AM E48.00013 Quantum Parameter Estimation in Continuous Measurement-Based Quantum Control. LUIS CORTEZ-GONZALEZ, Universidad Autonoma de Nuevo Leon, ANDREW N. JORDAN, University of Rochester — We consider continuous measurement as a quantum tracking and control method for superconducting quantum systems. In experiments with superconducting qubits information about the quantum state of the system is extracted in the form of a noisy analog voltage signal reflected from a coupled readout resonator. Every element of the measurement sequence describes a weak measurement that provides uncertain information about the quantum state of the qubit. In this talk we describe how the information contained in the continuous readout signal is used to estimate unknown parameters of the system as well as the most probable state evolution to produce the observed measurement record. We will theoretically compare a variety of estimation techniques including Maximum Likelihood methods and Bayesian hypothesis testing among others.

Tuesday, March 15, 2016 11:15AM - 2:15PM — Session F44 GQI: Gravity and Quantum Information 347 — Caslav Brukner, IQOQI, Austrian Academy of Sciences; Faculty of Physics, University of Vienna

11:15AM F44.00001 Constraining Dark Energy in Table-Top Quantum Experiments. HOLGER MUELLER, UC Berkeley — If dark energy is a light scalar field, it might interact with normal matter. The interactions, however, are suppressed in the leading models, which are thus compatible with current cosmological observations as well as solar-system and laboratory studies. Such suppression typically relies on the scalar’s interaction with macroscopic amounts of ordinary matter but can be bypassed by studying the interaction with individual particles. Using an atom-interferometer, we have placed tight constraints on so-called chameleon models, ruling out interaction parameters smaller than $2.3 \times 10^{-15}$, while $M \sim 1$ or larger would lead to conflict with macroscopic experiments. In order to close this gap, we have already increased the sensitivity hundredfold and are expecting a new constraint soon. Purpose-built experiments in the lab or on the international space station will completely close the gap and rule out chameleons and other theories such as symmetrons or f(R) gravity.


11:51AM F44.00002 Gravity and Quantum Mechanics. MILES BLENCOWE, Dept. of Physics and Astronomy, Dartmouth College, Hanover NH 03755 — The emergence of the macroscopic classical world from the microscopic quantum world is commonly understood to be a consequence of the fact that any given quantum system is open, unavoidably interacting with unobserved environmental degrees of freedom that will cause it to decohere rapidly. However, different results are obtained when the system is described in terms of classical fields, resulting in classical mixtures of either-or alternatives. A fundamental question concerns how large a macroscopic object can be placed in a manifest quantum state, such as a center of mass superposition state, under conditions where the effects of the interacting environmental degrees of freedom are reduced (i.e. in ultrahigh vacuum and at ultralow temperatures). Recent experiments have in fact demonstrated manifest quantum behavior in nano-to-micron-scale mechanical systems. Gravity has been invoked in various ways as playing a possible fundamental role in enforcing classicality of matter systems beyond a certain scale. Adopting the viewpoint that the standard perturbative quantization of general relativity provides an effective description of quantum gravity that is valid at ordinary energies, we show that it is possible to describe quantitatively how gravity as an environment can induce the decoherence of matter superposition states. The justification for such an approach follows from the fact that we are considering laboratory scale systems, where the matter is localized to regions of small curvature. As with other low energy effects, such as the quantum gravity correction to the Newtonian potential between two ordinary masses, it should be possible to quantitatively gravitationally induced decoherence rates by employing standard perturbative quantum gravity as an effective field theory; whatever the final form the eventual correct quantum theory of gravity takes, it must converge in its predictions with the effective field theory description at low energies.

1 Research supported by the National Science Foundation (NSF) and the Foundational Questions Institute (FQXi).
12:27PM F44.00003 Bidirectional holographic codes and sub-AdS locality\(^1\). ZHAO YANG, PATRICK HAYDEN, XIAOLIANG QI, Stanford Univ — Tensor networks implementing quantum error correcting codes have recently been used as toy models of the holographic duality which explicitly realize some of the more puzzling features of the AdS/CFT correspondence. These models reproduce the Ryu-Takayanagi entropy formula for boundary intervals, and allow bulk operators to be mapped to the boundary in a redundant fashion. These exactly solvable, explicit models have provided valuable insight but nonetheless suffer from many deficiencies, some of which we attempt to address in this talk. We propose a new class of tensor network models that subsume the earlier advances and, in addition, incorporate additional features of holographic duality, including: (1) a holographic reinterpretation of all boundary states, not just those in a “code” subspace, (2) a set of bulk states playing the role of “classical geometries” which reproduce the Ryu-Takayanagi formula for boundary intervals, (3) a bulk gauge symmetry analogous to diffeomorphism invariance in gravitational theories, (4) emergent bulk locality for sufficiently sparse excitations, and the ability to describe geometry at sub-AdS resolutions or even flat space.

\(^1\)David and Lucile Packard Foundation

12:39PM F44.00004 An extension to Galilean relativity gives rise to quantum mechanics framework\(^1\), SIMON BERKOVICH\(^1\), The George Washington University — The presented scheme for quantum mechanics appeared from considering Cellular Automaton Universe in view of the hidden energy associated with the property of inertia [1]. Galilean relativity states that all inertial frames are equivalent. Our consideration reveals one seemingly small exception - the original frame of reference for the material formations of the Cellular Automaton infrastructure is not isotropic. This frame of reference has a distinctive direction as long as elementary particles of matter are generated by cellular automaton relocations As a result, Cellular Automaton Evolved by Gravity (CAEGR) does not have a uniform Lagrangian. Why the states of microobjects are described by complex numbers is obscure. The observables are presented by real numbers through corresponding macro manipulations. In the inertial frame with unidirectional anisotropy isolated particles are characterized by two numbers; magnitude of their velocity and inclination angle to motion direction. So, these quantum states are mapped to a complex Hilbert space with zero vector representing bulk bodies. The effect of spin may be associated with the sign of the inclination angle trending separations for Stern-Gerlach output and Paul Principle. [1]Simon Berkovich, Law of inertia and the primal energy in the cellular automaton universe, Journal of Energy Challenges and Mechanics, vol.2(2015), issue 2, pp. 62-67

1\(^\text{Emeritus}\)

12:51PM F44.00005 Asymptotically Limitless Quantum Energy Teleportation via Qudit Probes\(^1\), GUILLAUME VERDON-AKZAM, Institute for Quantum Computing - University of Waterloo, EDUARDO MARTIN-MARTINEZ, Institute for Quantum Computing - University of Waterloo — We propose a modified Quantum Energy Teleportation (QET) scheme that uses arbitrary-dimensional qudit probes and polynomially localized Hamiltonians. We find that with an appropriate scaling of parameters, the teleported energy scales with the teleportation distance more favourably than the nonlocal tails of the Hamiltonians. We show that by allowing the exchange of arbitrary amounts of information between agents and in a suitable limit, an arbitrarily large amount of energy can be teleported through a massless quantum field.

\(^1\)arXiv:1510.03751 - E.M-M and AK acknowledge funding from the NSERC Discovery program.

1:03PM F44.00006 Relativistic Quantum Communication and the Structure of Spacetime, EDUARDO MARTIN-MARTINEZ, University of Waterloo and Perimeter Institute — We study the transmission of information and correlations through quantum fields in cosmological backgrounds. With this aim, we make use of quantum information tools to quantify the classical and quantum correlations induced by a quantum massless scalar field in two particle detectors, one located in the early universe (Alice’s) and the other located at a later time (Bob’s). In particular, we focus on two phenomena: a) the consequences on the transmission of information of the violations of the strong Huygens principle for quantum fields, and b) the analysis of the field vacuum correlations via correlation harvesting from Alice to Bob. We will study a standard cosmological model first and then assess whether these results also hold if we use other than the general relativistic dynamics. As a particular example, we will study the transmission of information through the Big Bounce, that replaces the Big Bang, in the effective dynamics of Loop Quantum Cosmology. We show that much more information reaches us through timelike channels (not mediated by real photons) than it is carried by rays of light, which are usually regarded as the only carriers of information.

1:15PM F44.00007 Einstein’s Equivalence Principle and Universal Decoherence in Massive Composite Quantum Systems, BELINDA PANG, YANBEI CHEN, Caltech — We demonstrate that in matter wave interferometry, the presence of a uniform gravitational field acting on massive particles with internal degrees of freedom will lead to dephasing and a loss of visibility in the interference pattern, as also shown by previous authors. However, unlike the previous authors, we argue that this is not a universal decoherence mechanism in the sense that any quantum information is lost, and furthermore, that the quantum interference is recoverable. This is a key distinction, because irreversible effects such as decoherence on a quantum system due to uniform gravity implies a violation of Einstein’s Equivalence Principle (EEP) in the quantum regime. We show that the dephasing result can be recovered by considering an accelerating observer measuring a freely propagating system, and can be simply understood in terms of the difference in the internal state dependent time of arrival of particles to the screen. One can contrive detection schemes that adjusts the path lengths of particles to compensate for this difference and recover the full visibility, while coupling to no additional degrees of freedom. Therefore, the dephasing is an observer dependent effect. EEP is not violated, and uniform gravity is not a mechanism for universal decoherence.

1:27PM F44.00008 Complete Sets of Solutions in Quantum Mechanics and their Connection with Gravity, RAFAEL SIERRA, Southern Methodist University — In typical non-relativistic quantum mechanical theory, solutions which are not normalizable are thrown away on the basis of being non-physical. The author does not contend that these solutions exist or are physically reasonable, but, these solutions do introduce interesting physics that can serve to connect the force of gravity with the laws of thermodynamics in a shockingly intimate way. The author will discuss the necessary extensions to the formalism of Schrodinger in order to better deal with and make sense of these solutions. In particular, some time will be devoted to the notion of entropy in systems involving these solutions. For particles sufficiently spaced-out, the second law of thermodynamics will yield dynamics that resemble classical expectations for gravity. Ultimately, gravity will be presented as a force necessary for the preservation of the second law of thermodynamics. Gravity and statistical mechanics will become connected at the quantum domain, provided the quantum domain is enlarged to include wave functions that are generally considered unreasonable.
simulations of thermally-assisted quantum tunneling in spin systems and by ODNI, IARPA via MIT Lincoln Laboratory Air Force Contract No. FA8721-05-C-0002.

Suzuki-Trotter representations to calculate the escape rate and most probable escape path in QMC dynamics. Analytical results are in a good agreement the scaling of the QMC time with the problem size to simulate the tunneling transitions. We develop path-integral instanton approach in coherent state and...
12:15PM F45.00004 Validating the solutions of the D-Wave quantum annealers through graph mirroring1, DILINA PERERA, J.S. HALL, M.A. NOVOTNY, Mississippi State University — D-Wave quantum annealers seek to find the ground states of Ising spin glasses. The problem Hamiltonian is formulated as an undirected graph that can be embedded into the devices native disordered Chimera graph structure. However, depending on the complexity of the problem and the specifications of the annealing schedule, the device may not necessarily find the global minimum during a given annealing process. We present a method, which we call answer checking, that enhances the expectation that the solution provided by the device is the true ground state of the problem. The underlying principle is to embed a mirrored graph $G'$ of the original graph $G$, and connect the two graphs via ferromagnetic/antiferromagnetic couplers. This allows one to rule out solutions for the composite graph that do not comply with the underlying mirror symmetry inherent to the true ground state, which in turn, reduces the uncertainty associated with the solutions. Using the 1097 qubit D-Wave 2X, we test this approach by applying it to a range of problems, including random spanning trees and generally allowed graphs $G'$.

1Supported in part by Pacific Northwest National Laboratory. D-Wave time provided by USRA.

12:27PM F45.00005 Quantum Annealing for Constrained Optimization, ITAY HEN, FEDERICO SPEDALIERI, Information Sciences institute, USC — Recent advances in quantum technology have led to the development and manufacturing of experimental programmable quantum annealers that could potentially solve certain quadratic unconstrained binary optimization problems faster than their classical analogues. The applicability of such devices for many theoretical and practical optimization problems, which are often constrained, is severely limited by the sparse, rigid layout of the devices' quantum bits. Traditionally, constraints are addressed by the addition of penalty terms to the Hamiltonian of the problem which in turn requires prohibitively increasing physical resources while also restricting the dynamical range of the interactions. Here we propose a method for encoding constrained optimization problems on quantum annealers that eliminates the need for penalty terms and thereby removes many of the obstacles associated with the implementation of these. We argue the advantages of the proposed technique and illustrate its effectiveness. We then conclude by discussing the experimental feasibility of the suggested method as well as its potential to boost the encodability of other optimization problems.

12:39PM F45.00006 Embedding parameters for Quantum Annealing, DAVIDE VENTURELLI, NASA Ames Research Center — Many optimization problems are defined on highly connected graphs and many interesting physical spin-glass systems are featuring long-range interactions. One method to solve for the optimum/ground state is quantum annealing (QA). Most architectures for QA devices, manufactured or proposed, are based on optimizing Hamiltonians having spins connected in a non-complete graph, with nodes with a small maximum degree, compared to the requirements. To overcome this limitation ‘embedding’ is employed: the native graph is tiled with ferromagnetic chains of spins that now are meant to represent the logical binary variables. While it is known how the strength of the ferromagnetic bonds can ensure that the classical Ising ground state of the embedded system can be univocally mapped to the ground state of the original system, there is very little study on the impact of these parameters on QA. Programmers have taken conservative choices for the parameters and the common practices can be improved. Starting from the physics of connected ferromagnetic Ising chains, we will review several parameter choices and discuss previous and new results obtained on the D-Wave 2X machine, on carefully designed problems that allow to isolate and evaluate the role of connectivity in embedded systems.

12:51PM F45.00007 Systematic and Deterministic Graph-Minor Embedding of Cartesian Products of Complete Graphs, ARMAN ZARIBAFIYAN, DOMINIC J.J. MARCHAND, SEYED SAEED CHANGIZ REZAEI, 1QBit — The limited connectivity of current and next-generation quantum annealers motivates the need for efficient graph-minor embedding methods. The overhead of the widely used heuristic techniques is quickly proving to be a significant bottleneck for real-world applications. To alleviate this obstacle, we propose a systematic deterministic embedding method that exploits the structures of both the input graph of the specific combinatorial optimization problem and the quantum annealer. As the first case study, we consider the OKF problem of embedding the Cartesian product of two complete graphs, a graph structure that occurs in many problems. We first divide the problem by embedding one of the factors of the Cartesian product in a repeatable unit. The resulting simplified problem consists of placing copies of this unit and connecting them together appropriately. Aside from the obvious speed and efficiency advantages of a systematic deterministic approach, the embeddings produced can be easily scaled for larger processors and show desirable properties with respect to the number of qubits used and the chain length distribution.

1:03PM F45.00008 Simulating highly nonlocal Hamiltonians with less nonlocal Hamiltonians1, YIGIT SUBASI, CHRISTOPER JARZYNSKI, University of Maryland at College Park — The need for Hamiltonians with many-body interactions arises in various applications of quantum computing. However, interactions beyond two-body are difficult to realize experimentally. Perturbative gadgets were introduced to obtain arbitrary many-body effective interactions using Hamiltonians with two-body interactions only. Although valid for arbitrary $k$-body interactions, their use is limited to small $k$ because the strength of interaction is $k$th order in perturbation theory. Here we develop a nonperturbative technique for obtaining effective $k$-body interactions using Hamiltonians consisting of at most $l$-body interactions with $l < k$. This technique works best for Hamiltonians with a few interactions with very large $l$ and can be used together with perturbative gadgets to embed Hamiltonians of considerable complexity in proper subspaces of two-local Hamiltonians. We describe how our technique can be implemented in a hybrid (gate-based and adiabatic) as well as solely adiabatic quantum computing scheme.

1We gratefully acknowledge financial support from the Lockheed Martin Corporation under contract U12001C.

1:15PM F45.00009 Crushing runtimes in adiabatic quantum computation with Energy Landscape Manipulation (ELM): Application to Quantum Factoring, NIKE DATTANI, Kyoto University, RICHARD TANBURN, OLIVER LUNT, Oxford University — We introduce two methods for speeding up adiabatic quantum computations by increasing the energy between the ground and first excited states. Our methods are even more general. They can be used to shift a Hamiltonian’s density of states away from the ground state, so that fewer states occupy the low-lying energies near the minimum, hence allowing for faster adiabatic passages to find the ground state with less risk of getting caught in an undesired low-lying excited state during the passage. Even more generally, our methods can be used to transform a discrete optimization problem into a new one whose unique minimum still encodes the desired answer, but with the objective function’s values forming a different landscape. Aspects of the landscape such as the objective function’s range, or the values of certain coefficients, or how many different inputs lead to a given output value, can be decreased *or* increased. One of the many examples for which these methods are useful is in finding the ground state of a Hamiltonian using NMR. We apply our methods to an AOQ algorithm for integer factorization, and the first method reduces the maximum runtime in our example by up to 754%, and the second method reduces the maximum runtime of another example by up to 250%.

1:27PM F45.00010 On universal adiabatic quantum computation, ARI MIZEL, Laboratory for Physical Sciences — We give a careful proof that ground state quantum computation can efficiently simulate universal gate model quantum computation. The proof allows for general gate model quantum computations; no restrictions are required on qubit geometry or on the locality of two-qubit gates. Our lower-bound technique may have more general application.
1:15PM F48.00001 High-fidelity resonator-induced phase gate with single-mode squeezing  
SHRUTI PURI, Dapartement de Physique, Universit de Sherbrooke, ALEXANDRE BLAIS, Dapartement de Physique, Universit de Sherbrooke and Canadian Institute for Advanced Research — Despite recent breakthroughs in the demonstration of small-scale quantum error correction, reaching the fidelity required for fault-tolerance with entangling gates still remains a challenge. We propose a protocol to increase the fidelity of a two-qubit resonator induced phase gate by using a off-resonant narrowband squeezing drive. For this gate, two superconducting transmon qubits are dispersively coupled to a microwave resonator. By off-resonantly driving the resonator, a controlled-Z gate can be implemented between the qubits [1]. However, photons leaving the resonator reveal the qubit which-path information leading to decoherence. We show that driving the resonator with a field squeezed at an optimal angle and strength erases the qubit which-path information and consequently increases the gate fidelity. We find that, under realistic conditions and modest squeezing power, it is possible to implement a high-fidelity two-qubit controlled-Z gate with short gate times. [1] A. W. Cross and J. M. Gambetta Phys Rev A 91, 032325 (2015).

1:27AM F48.00002 Characterization of the resonator induced phase gate [1], ANTONIO MEZZACAPO, H. PAIK, M. O. SANDBERG, D. T. MCCLURE, B. ABDO, O. E. DIAL, A. W. CROSS, A. D. CORCOLES, S. SHELDON, E. MAGESAN, S. J. SRINIVASAN, J. M. CHOW, J. M. GAMBITTA, IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA, D. BOGORIN, B. L. T. PLOURDE, Department of Physics, Syracuse University, Syracuse, New York, 13244 - 1130, USA — The Resonator induced phase (RIP) gate is a versatile microwave gate that can perform collective qubit operations. We characterize the performance of the RIP gate using various drive powers and detunings in a 4-qubit superconducting system. We find a good agreement between the experimental results and the theoretical predictions in the gate rate and minimum gate time. The minimum gate time is limited by residual photons in the bus cavity caused by a non-adiabatic response to the drive. We measure the multi-qubit interactions and analyze how the rates depend on the cavity-qubit coupling and the detuning to the drive and how these interactions can be used for quantum information processing.

1:39AM F48.00003 Demonstrating Multi-Qubit Operations in a Superconducting 3D circuit  
QED Architecture [1], HANHEE PAIK, M. O. SANDBERG, A. MEZZACAPO, D. T. MCCLURE, B. ABDO, O.E. DIAL, A. W. CROSS, A. D. CORCOLES, S. SHELDON, E. MAGESAN, S.J. SRINIVASAN, J.M. GAMBITTA, J.M. CHOW, IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA, D. BOGORIN, B.L.T. PLOURDE, Department of Physics, Syracuse University, Syracuse, NY 13244, USA — We present our recent results on multi-qubit operations in a superconducting 3D circuit QED (cQED) system using a resonator-induced phase (RIP) gate. In our system, four qubits are coupled by a single bus resonator. The RIP gate is implemented by applying a microwave pulse to the bus that performs entangling operations. We demonstrate controlled-phase gates using RIP on 2-qubit subsystems with gate fidelities between 95%-97% evaluated by randomized benchmarking. Via a multi-qubit echo scheme, we perform isolated two-qubit interactions in the full 4-qubit system to generate a GHZ state.

1:51AM F48.00004 Understanding and improving the cross resonance gate in superconducting qubits [1], SARAH SHELDON, EASWAR MAGESAN, JERRY M. CHOW, JAY M. GAMBITTA, IBM T.J. Watson Research Center — We present improvements in both theoretical understanding and experimental implementation of the cross resonance (CR) gate that have led to shorter two qubit gate times and interleaved randomized benchmarking fidelities exceeding 99%. The CR gate is an all-microwave two qubit gate offers that does not require tunability and is therefore well suited to quantum computing architectures based on 2D superconducting qubits. The performance of the gate has previously been hindered by long gate times and fidelities averaging 95-97%. We have developed a calibration procedure that accurately measures the full CR Hamiltonian. The resulting measurements agree with theoretical analysis of the gate and also elucidate the error terms that have previously limited the gate fidelity. The increase in fidelity that we have achieved was accomplished by introducing a second microwave drive tone on the target qubit to cancel unwanted components of the CR Hamiltonian.

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

1Support provided by National Research Council Post-Doctoral Research Associateship.
12:03PM F48.00005 High-fidelity single-shot three-qubit gates via machine learning,1 EHSAN ZAHEDINEJAD, JOYDIP GHOSH, BARRY C. SANDERS, University of Calgary — Three-qubit quantum gates play a crucial role in quantum error correction and quantum information processing. Here I discuss how to generate policies for quantum control to design three-qubit gates namely, Toffoli, Controlled-Not-Not and Fredkin gates for an architecture of nearest-neighbor-coupled superconducting artificial atoms. The resulted fidelity for each gate is above the 99.9% which is the threshold fidelity for fault-tolerant quantum computing. We test our policy in the presence of decoherence-induced noise as well as show its robustness under random external noise. The three-qubit gates are designed via our machine learning algorithm called Subspace-Selective Self-Adaptive Differential Evolution (SuSSADE).

1NSERC, AITF and University of Calgarys Eyes High Fellowship Program

12:15PM F48.00006 All-microwave cavity-mediated three-qubit gate between superconducting qubits, SOPHIA ECONOMOU, ED BARNES, Department of Physics, Virginia Tech — While single-qubit and entangling two-qubit operations are universal for quantum computing, in practice the availability of a single-shot multi-qubit entangling gate can be faster and of higher fidelity. For the case of three qubits coupled to a common cavity mode, we show that a high fidelity, fast CCZ gate can be implemented. Our proposal is based on partial spectrum engineering and pulse shaping. Because our approach does not rely on frequency selectivity, instead driving more than one transitions simultaneously, our three-qubit gate can be achieved on a timescale comparable to that of a two-qubit gate. Our protocol generalizes our recently introduced SWIPHT two-qubit gates.

12:27PM F48.00007 Tunable coupling between fixed-frequency superconducting transmon qubits, Part I: Concept, design, and prospects1 STEFAN FILIPP, IBM Research - Zurich, 8803 Rueschlikon, Switzerland, DAVID C. MCKAY, EASWAR MAGESAN, ANTONIO MEZZACAPO, JERRY M. CHOW, JAY M. GAMBITTA, IBM T.J. Watson Research Center, Yorktown Heights, NY, USA — The controlled realization of qubit-qubit interactions is essential for both the physical implementation of quantum error-correction codes and for reliable quantum simulations. Ideally, the fidelity and speed of corresponding two-qubit gate operations is comparable to those of single qubit operations. In particular, in a scalable superconducting qubit architecture coherence must not be compromised by the presence of additional coupling elements mediating the interaction between qubits. Here we present a coupling method between fixed-frequency transmon qubits based on AC Stark shift, thereby minimizing crosstalk and collisions. Looking forward, this gate is a prime candidate for implementing the surface code because it can couple highly coherent qubits which are spaced far apart in frequency thereby minimizing crosstalk and collisions.

This work is supported by ARO under contract W911NF-14-1-0124. 

1We acknowledge financial support from Microsoft Project Q and the Danish National Research Foundation.

12:39PM F48.00008 Tunable coupling between fixed-frequency superconducting transmon qubits, Part II: Implementing a two-qubit XX-90 gate1, STEFAN FILIPP, IBM Research - Zurich, 8803 Rueschlikon, Switzerland, ANTONIO MEZZACAPO, EASWAR MAGESAN, JERRY M. CHOW, JAY M. GAMBITTA, IBM T.J. Watson Research Center, Yorktown Heights NY, USA — In this talk we will present a two-qubit gate implemented in a tunable architecture which consists of a flux-tunable qubit (‘coupler’) coupling two fixed-frequency transmons (‘qubits’). In this architecture, a resonant SWAP (XX+YY) interaction is generated between the qubits when the coupler is modulated at the qubit frequency difference, typically a few hundred MHz. This interaction has a number of advantages, in particular, it only requires AC flux control and can resonantly address individual qubit pairs. Here we present a protocol which realizes the XX-90 gate based on this interaction. This gate has the specific characteristic that it takes any of the four basis states (|00⟩, |10⟩, |01⟩, |11⟩) to Bell states. We demonstrate gate fidelities greater than 96% characterized by state tomography and randomized benchmarking. Looking forward, this gate is a prime candidate for implementing the surface code because it can couple highly coherent qubits which are spaced far apart in frequency thereby minimizing crosstalk and collisions.

This work is supported by ARO under contract W911NF-14-1-0124.

12:51PM F48.00009 Gatemon Benchmarking and Two-Qubit Operation1, LUCAS CASPARIS, THORVALD LARSEN, MICHAEL OLSEN, KARL PETERSSON, FERDINAND KUEMMETH, PETER KROGSTUP, JESPER NYGARD, CHARLES MARCUS, Center for Quantum Devices and Station Q Copenhagen, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark — Recent experiments have demonstrated superconducting transmon qubits with semiconductor nanowire Josephson junctions. These hybrid gatemon qubits utilize field effect tunability singular to semiconductors to allow complete qubit control using gate voltages, potentially a technological advantage over conventional flux-controlled transmons. Here, we present experiments with a two-qubit gatemon circuit. We characterize qubit coherence and stability and use randomized benchmarking to demonstrate single-qubit gate errors of ~0.5 % for all gates, including voltage-controlled Z rotations. We show coherent capacitive coupling between two gatemons and coherent SWAP operations. Finally, we perform a two-qubit controlled-phase gate with an estimated fidelity of ~91 %, demonstrating the potential of gatemon qubits for building scalable quantum processors.

1We acknowledge financial support from Microsoft Project Q and the Danish National Research Foundation.

12:03PM F48.00010 Dephasing-induced Leakage in Superconducting Qubits, FREDERICK STRAUCH, Williams College — Dephasing is a significant mechanism for loss in superconducting quantum systems. Dephasing is induced by the presence of non-idealities such as finite temperature, coupling to an environment, or finite energy levels. In this talk, we present a method to measure the effects of dephasing induced leakage in superconducting qubits, using single-shot multi-qubit entangling gate. We show that the leakage is directly related to the fidelity of the gate and that by manipulating the leakage, we can improve the fidelity of the gate.

12:45PM F48.00011 Suppression of Single Qubit Leaks for Superconducting Qubits, SOPHIA ECONOMOU, ED BARNES, Department of Physics, Virginia Tech — Suppression of single qubit leaks is crucial for the development of scalable quantum computers. In this talk, we present a method to suppress single qubit leaks using a novel design of superconducting qubits. We show that this design suppresses single qubit leaks by more than 90% and allows for the implementation of high-fidelity quantum gates. Our method is based on a combination of design improvements and control techniques, which can be applied to a variety of superconducting qubit architectures. This work has the potential to significantly impact the development of scalable quantum computers.

1The work was supported by Google Inc., and by the NSFGRF under Grant No. DGE 1144085
1:27PM F48.00012 Circuit design implementing longitudinal coupling: a scalable scheme for superconducting qubits, SUSANNE RICHER, DAVID DIVINCENZO, JARA Institute for Quantum Information, RWTH Aachen University, D-52056 Aachen, Germany — We present a circuit construction for a new fixed-frequency superconducting qubit and show how it can be scaled up to a grid with strictly local interactions. The circuit QED realization we propose implements $\sigma_z$-type coupling between a superconducting qubit and any number of LC resonators. The resulting longitudinal coupling is inherently different from the usual $\sigma_x$-type transverse coupling, which is the one that has been most commonly used for superconducting qubits. In a grid of fixed-frequency qubits and resonators with a particular pattern of always-on interactions, coupling is strictly confined to nearest and next-nearest neighbor resonators. We note that just four distinct resonator frequencies, and only a single unique qubit frequency, suffice for the scalability of this scheme. There is never any direct coupling between the qubits. A controlled phase gate between two neighboring qubits can be realized with microwave drives on the qubits, without affecting the other qubits. This fact is a supreme advantage for the scalability of this scheme.


1:39PM F48.00013 Controllable frequency comb generation in a tunable superconducting coplanar waveguide resonator, J. Q. YOU, SHUAIPENG WANG, YIPU WANG, DENGKE ZHANG, XIAOQING LUO, ZHEN CHEN, Quantum Physics and Quantum Information Division, Beijing Computational Science Research Center, TIEFU LI, Institute of Microelectronics, Department of Micro and Nanoelectronics, Tsinghua University — Frequency combs have attracted considerable interest because they are extremely useful in a wide range of applications, such as optical metrology and high precision spectroscopy. Here we report the design and characterization of a controllable frequency comb generated in a tunable superconducting coplanar waveguide resonator in the microwave regime. Both the center frequency and teeth density of the comb are precisely controllable. The teeth spacing can be adjusted from Hz to MHz. The experimental results can be well explained via theoretical analysis.

1This work is supported by the NSAF Grant No. U1330201, the NSFC Grant No. 91421102, and the MOST 973 Program Grant Nos. 2014CB845700 and 2014CB921401.

1:51PM F48.00014 Design and Measurement of a Tunable Thin-Film LC Resonator for Coupling to Superconducting Circuits, C. J. BALLARD, R. P. BUDOYO, K. D. VOIGT, S. K. DUTTA, C. J. LOBB, F. C. WELLSTOOD, University of Maryland-College Park — We have designed and measured a tunable lumped element LC resonator for coupling to transmon qubits. We use an rf SQUID loop as a variable inductive element that shunts the inductor of the resonator and produces a shift in the resonator frequency that depends on the flux applied to the loop. In order to achieve a balanced response, we shunt the inductor with two single junction SQUID loops. Each junction has a critical current of approximately 300pA, which is small enough to prevent multiple trapped flux states. We tune the effective inductance of the loops by using a split, gradiometric modulation coil that is well isolated from the cavity at the resonance frequency. Our resonator is made of thermally evaporated aluminum on a sapphire substrate and has a resonance frequency of 5.3 GHz. It is mounted inside a 3D microwave cavity that has a TE101 frequency of 6.3 GHz.

2:03PM F48.00015 Quantization of lumped elements electrical circuits revisited, KEVIN LALUMIERE, ALI REZA NAJAFI-YAZDI, Anyon Systems Inc. — In 1995, the Les Houches seminar of Michel Devoret introduced a method to quantize lumped elements electrical circuits [1]. This method has since been formalized using the matricial formalism, in particular by G. Burkard [2,3]. Starting from these seminal contributions, we present a new algorithm to quantize electrical circuits. This algorithm unites the features of Devoret and Burkard’s approaches. We minimize the set of assumptions made so that the method can treat directly most electrical circuits. This includes circuits with resistances, mutual inducances, voltage and current sources. We conclude with a discussion about the choice of the basis in which the Hamiltonian operator should be written, an issue which is often overlooked. [1] M. H. Devoret, Les Houches, Session LXIII, 1995 [2] G. Burkard et al., Phys. Rev. B, 69, 064503, 2004 [3] F. Solgun, Ph.D. Dissertation, RWTH Aachen, 2015

Tuesday, March 15, 2016 2:30PM - 5:30PM
Session H3 DCMP GQI: Charge Noise Mitigation in Multiple Quantum Dot Qubits Ballroom III - Thaddeus Ladd, Hrl Laboratories

2:30PM H3.00001 Reduced sensitivity to charge noise in semiconductor spin qubits via symmetric operation, MATTHEW REED, HRL Laboratories, LLC — Gated semiconductor quantum dots controlled with the exchange interaction are attractive candidates for quantum information processing because of their long coherence time and electrical controllability. Exchange is conventionally modulated by detuning the chemical potentials of neighboring dots over a fixed tunnel barrier, an approach whose precision is limited by charge noise. In this talk we demonstrate a symmetric mode of operation which substantially reduces the sensitivity of exchange operations to gate fluctuations. The method involves biasing a double-dot symmetrically between the charge-state anti-crossings, where the derivative of the exchange energy with respect to gate voltages is minimized. Exchange remains highly tunable by adjusting the tunnel coupling. We propose a metric, insensitivity, to quantify the techniques improvement and find that it increases by at least a factor of five between operating regimes. We also demonstrate a substantial increase in the number of Rabi fringes observed.

3:06PM H3.00002 Symmetric operation and nuclear notch filtering in GaAs double quantum dots, FERDINAND KUEMMETH, Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen — Spin qubits based on few-electron semiconductor quantum dots are promising candidates for quantum computation, due to their potential for miniaturization, scalability and fault tolerance. In this talk I will present recent results on how to mitigate electrical and nuclear noise in GaAs singlet-triplet qubits. The traditional way of implementing exchange rotations in singlet-triplet qubits involves detuning the qubit away from the symmetric (1,1) charge configuration, thereby temporarily hybridizing with the (0,2) charge state. Due to the large dipole coupling the resulting qubit oscillation suffers from detuning noise, motivating exchange remains highly tunable by adjusting the tunnel coupling. We propose a metric, insensitivity, to quantify the techniques improvement and find that it increases by at least a factor of five between operating regimes. We also demonstrate a substantial increase in the number of Rabi fringes observed.

Support through IARPA-MQCO, Army Research Office, and the Danish National Research Foundation is acknowledged.

3:06PM H3.00002 Symmetric operation and nuclear notch filtering in GaAs double quantum dots, FERDINAND KUEMMETH, Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen — Spin qubits based on few-electron semiconductor quantum dots are promising candidates for quantum computation, due to their potential for miniaturization, scalability and fault tolerance. In this talk I will present recent results on how to mitigate electrical and nuclear noise in GaAs singlet-triplet qubits. The traditional way of implementing exchange rotations in singlet-triplet qubits involves detuning the qubit away from the symmetric (1,1) charge configuration, thereby temporarily hybridizing with the (0,2) charge state. Due to the large dipole coupling the resulting qubit oscillation suffers from detuning noise, motivating exchange remains highly tunable by adjusting the tunnel coupling. We propose a metric, insensitivity, to quantify the techniques improvement and find that it increases by at least a factor of five between operating regimes. We also demonstrate a substantial increase in the number of Rabi fringes observed.

In order to decouple the singlet-triplet qubit from nuclear spin fluctuations, we investigate Carr-Purcell-Meiboom-Gill (CPMG) sequences in more detail. At high magnetic fields we find that qubit dephasing is limited by narrow-band high-frequency noise arising from Larmor precession of $^{79}$Ga, $^{71}$Ga, $^{77}$As nuclear spins, similar to what has been observed at intermediate magnetic field [4]. By aligning the notches of the CPMG filter function with differences of the discrete nuclear Larmor frequencies we demonstrate a qubit coherence time of 0.87 ms, i.e. more than five orders of magnitude longer than the duration of a $\pi$ exchange gate in the same device.

to other qubit encodings and exchange based two-qubit gates optimization minimizes the impact of fast charge noise. Both types of noise make relevant contributions to gate errors. The general approach is also adaptable to systematic errors. Randomized benchmarking yields an average gate fidelity exceeding 98% and a leakage rate into invalid states of 0.2%. These gates exhibit a dot. Starting from a set of numerically optimized control pulses control approaches based on Rabi flopping. Furthermore, the exchange interaction typically used to electrically manipulate encoded spin qubits is inherently same magnitude as the hopping parameters between the dots. By calculating and comparing the charge dephasing rates at the various operating points of the RX qubit, we identify a new favorable operating regime for the RX qubit in the case of weak noise, based on these double sweet spots. In contrast, spin noise can be mitigated using exchange-based dynamical decoupling sequences that have been optimized using two different strategies, Uhrig dynamical decoupling (UDD) and optimized filter function dynamical decoupling (OFDD) [2]. Finally, we give a brief outlook towards the possibility of long-distance coupling between resonant exchange qubits mediated by a microwave cavity [3].

1 Supported by DFG through SFB 767 and ARO through grant No. W911NF-15-1-0149.

4:54PM H44.00005 Feedback-tuned, noise resilient gates for encoded spin qubits, HENDRIK BLUHM, RWTH Aachen University — Spin 1/2 particles form native two level systems and thus lend themselves as a natural qubit implementation. However, encoding a single qubit in several spins entails benefits, such as reducing the resources necessary for qubit control and protection from certain decoherence channels. While several varieties of such encoded spin qubits have been implemented, accurate control remains challenging, and leakage out of the subspace of valid qubit states is a potential issue. Optimal performance typically requires large pulse amplitudes for fast control, which is prone to systematic errors and prohibits standard control approaches based on Rabi flopping. Furthermore, the exchange interaction typically used to electrically manipulate encoded spin qubits is inherently sensitive to charge noise. I will discuss all-electrical, high-fidelity single qubit operations for a spin qubit encoded in two electrons in a GaAs double quantum dot. Starting from a set of numerically optimized control pulses we employ an iterative tuning procedure based on measured error syndromes to remove systematic errors. Randomized benchmarking yields an average gate fidelity exceeding 98% and a leakage rate into invalid states of 0.2%. These gates exhibit a certain degree of resilience to both slow charge and nuclear spin fluctuations due to dynamical correction analogous to a spin echo. Furthermore, the numerical optimization minimizes the impact of fast charge noise. Both types of noise make relevant contributions to gate errors. The general approach is also adaptable to other qubit encodings and exchange based two-qubit gates.


Tuesday, March 15, 2016 2:30PM - 5:30PM – Session H44 GQI: Quantum Algorithms 347 - Kenneth Rudinger, Sandia National Labs

2:30PM H44.00001 Quantum linear systems algorithm with exponentially improved dependence on precision, ROLANDO SOMMA, Los Alamos National Laboratory, ANDREW CHILDS, University of Maryland, ROBIN KOTHARI, Massachusetts Institute of Technology — Harrow, Hassidim, and Lloyd showed that for a suitably specified N × N matrix and N-dimensional vector , there is a quantum algorithm that outputs a quantum state proportional to the solution of the linear system of equations , exponentially improving the dependence on precision while keeping essentially the same dependence on other parameters. Our algorithm is based on a general technique for implementing any operator with a suitable Fourier or Chebyshev series representation. This allows us to bypass the quantum phase estimation algorithm, whose dependence on is prohibitive.

1 The authors acknowledge support from AFSOR, ARO, CIFAR, IARPA, NRO, and NSF

4:2PM H44.00002 QUANTUM ALGORITHM FOR LINEAR PROGRAMMING PROBLEMS, PRAMOD JOAG, Professor, DHANANJAY MEHENDALE, Associate Professor — The quantum algorithm (PRL 103, 150502, 2009) solves a system of linear equations with exponential speedup over existing classical algorithms. We show that the above algorithm can be readily adopted in the iterative algorithms for solving linear programming (LP) problems. The first iterative algorithm that we suggest for LP problem follows from duality theory. It consists of finding nonnegative solution of the equation forduality condition; for constraints imposed by the given primal problem and for constraints imposed by its corresponding dual problem. This problem is called the problem of nonnegative least squares, or simply the NNLS problem. We use a well known method for solving the problem of NNLS due to Lawson and Hanson. This algorithm essentially consists of solving in each iterative step a new system of linear equations. The other iterative algorithms that can be used are those based on interior point methods. The same technique can be adopted for solving network flow problems as these problems can be readily formulated as LP problems. The suggested quantum algorithm can solve LP problems and Network Flow problems of very large size involving millions of variables.

2:54PM H44.00003 A quantum Algorithm for the Moebious Function, PETER LOVE, Tufts Univ — We give an efficient quantum algorithm for the Moebius function from the natural numbers to . The cost of the algorithm is asymptotically quadratic in and does not require the computation of the prime factorization of as an intermediate step.

1 This work was supported in part by ARO (W911NF-12-0607), NSF (PHY-1104660), and ONR (N00014-15-1-0029).
3:06PM H44.00004 The Deutsch-Jozsa algorithm as a suitable framework for MapReduce in a quantum computer. SAMIR LIPOVACA, None — The essence of the MapReduce paradigm [1] is a parallel, distributed algorithm across hundreds or thousands machines. In crude fashion this parallelism relies on the method of computation by quantum parallelism which is possible only with quantum computers. Deutsch and Jozsa [2] showed that there is a class of problems which can be solved more efficiently by quantum computer than by any classical or stochastic method. The method of computation by quantum parallelism solves the problem with certainty in exponentially less time than any classical computation. This leads to question would it then be possible to implement the MapReduce paradigm in a quantum computer and harness this incredible speedup over the classical computation performed by the current computers. Although present quantum computers are not robust enough for code writing and executing it is worth to explore this question from a theoretical point of view. We will show from a theoretical point of view that the Deutsch-Jozsa algorithm is a suitable framework to implement the MapReduce paradigm in a quantum computer. References: [1] Chuck Lam, Hadoop in Action, (Manning Publications Co. Greenwich, CT, USA ©2010). [2] Deutsch, D., Jozsa, R. 1992 Proc. R. Soc. Lond. A 439, 535-558.

3:18PM H44.00005 Optimizing Qubit Resources for Quantum Chemistry Simulations in Second Quantization on a Quantum Computer. NIKOLAJ MOLL, ANDREAS FUHRER, PETER STAAR, IVANO TAVERNELLI, IBM Research - Zurich — Quantum chemistry simulations on a quantum computer suffer from the overhead needed for encoding the fermionic problem in a bosonic system of qubits. By exploiting the block diagonality of a fermionic Hamiltonian, we show that the number of required qubits can be reduced by a factor of two or more. There is no need to go into the basis of the Hilbert space for this reduction because all operations can be performed in the operator space. The scheme is conceived as a pre-computational step that would be performed on a classical computer prior to the actual quantum simulation. We apply this scheme to reduce the number of qubits necessary to simulate both the Hamiltonian of the two-site Fermi-Hubbard model and the hydrogen molecule. Both quantum systems can then be simulated with a two-qubit quantum computer.

3:30PM H44.00006 Modelling Quantum Subsystem Dynamics1. JASON DOMINY, University of Southern California, ALIREZA SHABANI, Google Research, DANIEL LIDAR, University of Southern California — We describe a general and consistent mathematical model for linear subsystem quantum dynamical maps, developed from a minimal set of postulates, primary among which is a relaxation of the usual, restrictive assumption of uncorrelated initial system-bath states. The resulting space of physically realizable dynamical maps, far from being limited to only completely positive (CP) maps, comprises essentially all C-linear, Hermiticity-preserving, trace-preserving subsystem maps. We will discuss some implications for the standard theory of open quantum systems and the search for necessary and sufficient conditions for complete positivity. See [1], [2] for additional details. [1] Jason M. Dominy, Alireza Shabani, and Daniel A. Lidar. A general framework for complete positivity. Quantum Inf. Proc., 2015. (To appear). URL: http://dx.doi.org/10.1007/s11128-015-1148-0. [2] Jason M. Dominy and Daniel A. Lidar. Beyond complete positivity. arXiv:1503.05342.

1This research was supported by the ARO MURI grant W911NF-11-1-0268 and by NSF grant numbers PHY-096969 and PHY-083304.

3:42PM H44.00007 Hybrid quantum-classical approach to correlated materials. BELA BAVER, DAVE WECKER, Microsoft Research, ANDREW J. MILLIS, Columbia University, MATTHEW B. HASTINGS, Microsoft Research, MATTHIAS TROYER, ETH Zurich — Recent improvements in control of quantum systems make it seem feasible to finally build a programmable general-purpose quantum computer within a decade. While it has been shown that such a quantum computer can in principle solve certain small electronic structure problems and idealized model Hamiltonians, the highly relevant problem of directly solving a complex correlated material appears to require a prohibit amount of resources. Here, we show that by using a hybrid quantum-classical algorithm that incorporates the power of a small quantum computer into a framework of classical embedding algorithms, the electronic structure of complex correlated materials can be efficiently tackled using a quantum computer. In our approach, the quantum computer solves a small effective quantum impurity problem that is self-consistently determined via a feedback loop between the quantum and classical computation. Use of a quantum computer enables much larger and more accurate simulations than with any known classical algorithm, and we will allow many open questions in quantum materials to be resolved once a small quantum computer with around one hundred logical qubits becomes available.

3:54PM H44.00008 A method to efficiently simulate the thermodynamic properties of the Fermi-Hubbard model on a quantum computer. PIERRE-LUC DALLAIRE-DEMERS, FRANK WILHELM-MAUCH, Saarland University — Many phenomena of strongly correlated materials are encapsulated in the Fermi-Hubbard model whose thermodynamic properties can be computed from its grand canonical potential. In general, there is no closed form expression of the grand canonical potential for lattices of more than one spatial dimension, but solutions can be approximated with cluster perturbation theory. To model long-range effects such as order parameters, a powerful method to compute the cluster’s Green’s function consists in finding its self-energy through a variational principle. This opens the possibility of studying various phase transitions at finite temperature in the Fermi-Hubbard model. However, a classical cluster solver quickly hits an exponential wall in the memory (or computation time) required to store the computation variables. Here it is shown theoretically that that the cluster solver can be mapped to a subroutine on a quantum computer whose quantum memory scales as the number of orbitals in the simulated cluster. A quantum computer with a few tens of qubits could therefore simulate the thermodynamic properties of complex fermionic lattices inaccessible to classical supercomputers.

4:06PM H44.00009 Efficient Simulation of Dissipative Dynamics. KYUNGJOO NOH, VICTOR V. ALBERT, CHAO SHEN, LIANG JIANG, Yale University — Open quantum systems with engineered dissipations may have more than one steady states. These steady states may form a non-trivial decoherence free subspace (DFS) that can store quantum information against major decoherences. Besides unitary operations within DFS, it is also useful to have dissipative/cooling operations within the DFS. We investigate the possibility of using Hamiltonian perturbation to the engineered dissipation to induce an effective dissipative dynamics within the DFS in a controlled manner. The major challenge is to simulate all the Lindblad jump operators in the master equation. By designing the dissipation within the subspace complementary to the DFS, we can simply use the Hamiltonian perturbation to the designed dissipation with a single jump operator to produce an effective dissipation with multiple Lindblad jump operators.

4:18PM H44.00010 Racing in parallel: Quantum versus Classical. DAMIAN S. STEIGER, MATTHIAS TROYER, ETH Zurich — In a fair comparison of the performance of a quantum algorithm to a classical one it is important to treat them on equal footing, both regarding resource usage and parallelism. We show how one may otherwise mistakenly attribute speedup due to parallelism as quantum speedup. We apply such an analysis both to analog quantum devices (quantum annealers) and gate model algorithms and give several examples where a careful analysis of parallelism makes a significant difference in the comparison between classical and quantum algorithms.

4:30PM H44.00011 How far can we push quantum variational algorithms without error correction? RYAN BABBUSH, Google — Recent work has shown that parameterized short quantum circuits can generate powerful variational ansatze for ground states of classically intractable fermionic models. This talk will present numerical and experimental evidence that quantum variational algorithms are also robust to certain errors which plague the gate model. As the number of qubits in superconducting devices keeps increasing, their dynamics are becoming prohibitively expensive to simulate classically. Accordingly, our observations should inspire hope that quantum computers could provide useful insight into important problems in the near future. This talk will conclude by discussing future research directions which could elucidate the viability of executing quantum variational algorithms on classically intractable problems without error correction.
4:42PM H44.00012 | A Quantum Algorithm for Estimating Hitting Times of Markov Chains

ANINBAN NARAYAN CHOWDHURY, University of New Mexico, ROLANDO SOMMA, Los Alamos National Laboratory — We present a quantum algorithm to estimate the hitting time of a reversible Markov chain faster than classically possible. To this end, we show that the hitting time is given by an expected value of the inverse of a Hermitian matrix. To obtain this expected value, our algorithm combines three important techniques developed in the literature. One such technique is called spectral gap amplification and we use it to amplify the gap of the Hermitian matrix or reduce its condition number. We then use a new algorithm by Childs, Kothari, and Somma to implement the inverse of a matrix, and finally use methods developed in the context of quantum metrology to reduce the complexity of expected-value estimation for a given precision.

1The authors acknowledge support from AFOSR grant number FA9550-12-1-0057 and the Google Research Award.

4:54PM H44.00013 | Continuous Time Quantum Walks in finite Dimensions

SHANSHAN LI, STEFAN BOETTCHER, Emory University — Continuous time quantum walk (CTQW) provides optimal quadratic speedup for spatial search on complete graphs, hypercubes, and connected random graphs compared to classical algorithms. Instead of these high dimensional graphs, we consider the performance of CTQW on the finite dimensional Migdal-Kadanoff lattices. We relate the critical point for the walk Hamiltonian to the lattice Laplacian. Using renormalization group analysis, we calculate the critical point and derive the search performance on instances of different spectral dimension. For those with integer dimension, we reproduce the known algorithmic efficiency on regular lattices. In particular, we show that on these finite dimensional graphs, the algorithmic efficiency of quantum walk is entirely determined by the spectral dimension of the Laplacian. Quadratic speedup can only be achieved when the spectral dimension is larger than four.

5:06PM H44.00014 | Spatial search by quantum walk is optimal for almost all graphs

SHANTANAV CHAKRABORTY, LEONARDO NOVO, University of Lisbon, ANDRIS AMBAINSIS, University of Latvia, YASSER OMAR, Instituto de Telecomunicaciones, Lisbon — The problem of finding a marked node in a graph can be solved by the spatial search algorithm based on continuous-time quantum walks (CTQW). However, this algorithm is known to run in optimal time only for a handful of graphs. In this work, we prove that for Erdős-Rényi random graphs, i.e. graphs of \( n \) vertices where each edge exists with probability \( p \), search by CTQW is almost surely optimal as long as \( p \geq \log^{3/2}(n)/n \). Consequently, we show that quantum spatial search is in fact optimal for almost all graphs, meaning that the fraction of graphs of \( n \) vertices for which this optimality holds tends to one in the asymptotic limit. We obtain this result by proving that search is optimal on graphs where the ratio between the second largest and the largest eigenvalue is bounded by a constant smaller than 1. Finally, we show that we can extend our results on search to establish high fidelity quantum communication between two arbitrary nodes of a random network of interacting qubits, namely to perform quantum state transfer, as well as entanglement generation. Our work shows that quantum information tasks typically designed for structured systems retain performance in very disordered structures.

5:18PM H44.00015 | Connecting the Discrete-time and Continuous-time Quantum Walks

ALBERT SCHMITZ, University of North Dakota — Much work has gone into connecting the discrete-time and continuous-time versions of the quantum walk. This talk will demonstrate a method for finding an appropriate coin operator to simulate the continuous-time dynamics generated by a graph Hamiltonian for any arbitrary bigraph. This method draws a connection between a continuous-time model on the standard 1D and 2D lattice and the Hadamard walk. Furthermore, some extensions will be discussed with applications to algorithm design.

Tuesday, March 15, 2016 2:30PM - 5:18PM — Session H45 QI DAMOP: Quantum Information with Ions, Photons and Spins

3:06PM H45.00002 | Quantum information processing with long-wavelength radiation

DAVID MURGIA, Imperial College London, SEBASTIAN WEIDT, University of Sussex, JOSEPH RANDALL, Imperial College London, BOJERN LEKITSCH, SIMON WEBSTER, TOMAS NAVICKAS, ANTON GROUNDS, ANDREA RODRIGUEZ, ANNA WEBB, EAMON STANDING, University of Sussex, STUART PEARCE, IBRAHIM SARI, KIAN KIANG, HWANJIT RATTANASONTI, MICHAEL KRAFT, University of Southampton, WINFRIED HENSINGER, University of Sussex — To this point, the entanglement of ions has predominantly been performed using lasers. Using long wavelength radiation with static magnetic field gradients provides an architecture to simplify construction of a large scale quantum computer. The use of microwave-dressed states protects against decoherence from fluctuating magnetic fields, with radio-frequency fields used for qubit manipulation. I will report the realization of spin-motion entanglement using long-wavelength radiation, and a new method to efficiently prepare dressed-state qubits and qutrits, reducing experimental complexity of gate operations. I will also report demonstration of ground state cooling using long wavelength radiation, which may increase two-qubit entanglement fidelity. I will then report demonstration of a high-fidelity long-wavelength two-ion quantum gate using dressed states. Combining these results with microfabricated ion traps allows for scaling towards a large scale ion trap quantum computer, and provides a platform for quantum simulations of fundamental physics. I will report progress towards the operation of microchip ion traps with extremely high magnetic field gradients for multi-ion quantum gates.

1We are grateful for funding from the Swiss National Science Foundation and the ETH Zurich.
2Leibfried et al. PRA 76:032324 (2007)
3:18PM H45.00003 Controlled-phase gate for photons based on stationary light. IVAN IAKOPOV, Niels Bohr Institute, JOHANNES BORREGAARD, Harvard University, ANDERS S. SØRENSEN, Niels Bohr Institute — We propose a controlled-phase gate for optical photons based on an atomic ensemble coupled to a one-dimensional waveguide. When an ensemble of Λ-type atoms is subject to a standing wave control field, it creates a stationary light [1] effect where the ensemble develops a band gap for light propagation. For frequencies close to the band gap, the light-matter interactions are enhanced due to the reduced group velocity of the light pulses. Changing the internal state of one of the atoms, such that it behaves as an absorbing two-level atom instead of a transparent Λ-type atom, can change the scattering properties of the whole ensemble, switching it from being completely transmissive to being completely reflective. To realize a controlled-phase gate between photons, we store one of the photons inside the atomic ensemble (thereby changing the internal state of one of the atoms), scatter a second photon off the ensemble, and retrieve the first photon. Finally, we consider an application of the proposed controlled-phase gate — a quantum repeater.

References


3:30PM H45.00004 Photonic Quantum Logic with Narrowband Light from Single Atoms. ALLISON RUBENOK, University of Bristol, ANNEMARIE HOLLECZEK, OLIVER BARTER, JEROME DILLEY, PETER B. R. NISBET-JONES, GUNNAR LANGFAHL-KLABES, AXEL KUHN, University of Oxford, CHRIS SPARROW, University of Bristol, Imperial College London, GRAHAM D. MARSHALL, JEREMY L. O’BRIEN, KONSTANTINOS POULIOS, JONATHAN C. F. MATTHEWS, University of Bristol — Atom-cavity sources of narrowband photons are a promising candidate for the future development of quantum technologies. Likewise, integrated photonic circuits have established themselves as a fore-running contender in quantum computing, security, and communication. Here we report on recent achievements to interface these two technologies: Atom-cavity sources coupled to integrated photonic circuits. Using narrow linewidth photons emitted from a single 87Rb atom strongly coupled to a high-finesse cavity we demonstrate the successful operation of an integrated control-not gate. Furthermore, we are able to verify the generation of post-selected entanglement upon successful operation of the gate. We are able to see non-classical correlations in detection events that are up to three orders of magnitude farther apart than the time needed for light to travel across the chip. Our hybrid approach will facilitate the future development of technologies that benefit from the advantages of both integrated quantum circuits and atom-cavity photon sources.

3:42PM H45.00005 Scalable Boson Sampling with Noisy Components. TYLER KEATING, University of New Mexico, JOSEPH SLOTE, Carleton College, GOPIKRISHNAN MURALEEDHARAN, EZEQUIEL CARRASCO, IVAN DEUTSCH, University of New Mexico — The goal of a Boson Sampler is to efficiently and scalably sample from a probability distribution that cannot be simulated efficiently on a classical computer, thus violating the Extended Church-Turing Thesis (ECTT). To properly falsify the ECTT, the physical device must do so even in the face of realistic noise. Scaling a Boson Sampler requires increasing quantities of a set of fixed-size components (beamsplitters, detectors, etc.), so it is natural to consider noise models that act on each component independently. We show that for any such model, the per-component noise need only decrease polynomially to keep the sampling problem hard. In this sense, Boson Sampling with noise is scalable. However, the same result applies to a number of other quantum information systems, including universal circuit-model quantum computers. Such devices are widely believed to require error correction in order to be truly scalable, even though polynomial reduction of per-component errors would allow them to work without error correction. This belief is consistent with the stricter requirement that error rates should be not just polynomially small, but constant in problem size. We conclude that a more precise definition of scalability with noise is needed to properly evaluate Boson Samplers.

3:54PM H45.00006 Spin models and boson sampling1. JUAN JOSE GARCIA RIPOLL, Institute of Fundamental Physics, IFF-CSIC, Spain, BORJA PEROPADRE, ALAN ASPURU-GUZIK, Department of Chemistry and Chemical Biology, Harvard University — Aaronson & Arkhipov showed that predicting the measurement statistics of random linear optics circuits (i.e. boson sampling) is a classically hard problem for highly non-classical input states [1]. A typical boson-sampling circuit requires N single photon emitters and M photodetectors, and it is a natural idea to rely on few-level systems for both tasks. Indeed, we show that 2M two-level emitters at the input and output ports of a general M-port interferometer interact via an XY-model with collective dissipation and a large number of dark states that could be used for quantum information storage. More important is the fact that, when we neglect dissipation, the resulting long-range XY spin-spin interaction is equivalent [2] to boson sampling under the same conditions that make boson sampling efficient. This allows efficient implementations of boson sampling using quantum simulators & quantum computers. [1] S. Aaronson, A. Arkhipov, Proc. of the 43rd annual ACM symposium on Theory of computing (ACM, 2011) 333-342 [2] arXiv:1509.02703

1We acknowledge support from Spanish Mineco Project FIS2012-33022, CAM Research Network QUTITEMAD+ and EU FP7 FET-Open project PROMISCE

4:06PM H45.00007 Experimental fault tolerant universal quantum gates with solid-state spins under ambient conditions.1. XING RONG, University of Science and Technology of China — Quantum computation provides great speedup over classical counterpart for certain problems, such as quantum simulations, prime factoring and database searching. One of the challenges for realizing quantum computation is to execute precise control of the quantum system in the presence of noise. Recently, high fidelity control of spin-qubits has been achieved in several quantum systems. However, control of the spin-qubits with the accuracy required by the fault tolerant quantum computation under ambient conditions remains elusive. Here we demonstrate a universal set of logic gates in nitrogen-vacancy centers with an average single-qubit gate fidelity of 0.99995 and two qubit gate fidelity of 0.992. These high control fidelities have been achieved in the C naturally abundant diamonds at room temperature via composite pulses and optimal control method. This experimental implementation of quantum gates with fault tolerant control fidelity sets an important step towards the fault-tolerant quantum computation under ambient conditions.

1National Key Basic Research Program of China (Grant No. 2013CB921800)

4:18PM H45.00008 Universal Superadiabatic Geometric Quantum Gates in Nitrogen-Vacancy Centers. HUI YAN, ZHENTAO LIANG, South China Normal University, SHILIANG ZHU, Nan Jing University — We propose a scheme to implement a universal set of quantum gates based on geometric phases and superadiabatic quantum control. The proposed quantum gates consolidate the advantages of both strategies for robust and fast. The diamond nitrogen-vacancy center system is adopted as a typical example to illustrate the scheme. We show those gates can be realized in a simple two-level configuration by appropriately controlling the amplitude, phase and frequency of just one microwave field. The robust and fast features are confirmed by comparing the fidelities of the proposed superadiabatic geometric phase gate with three other kinds of phase gates, replacing MAR16-2015-000077.
present experimental results for this protocol and discuss the factors influencing the success probability and the fidelity of the generated entangled states.

photons interfere on a beam-splitter and are concurrently detected by a novel microwave photo-multiplier that employs a third qubit-cavity system. In this

centers. First, each qubit is entangled with a single cavity photon (Fock state $n=1$) using sideband pulses. On their way out of the cavity, the now flying

distant qubits on demand. This can be realized in circuit QED using a protocol inspired by recent experiments based on trapped ions and nitrogen-vacancy

quantum memories that are connected via a quantum router. A fundamental requirement for this modular quantum computer is the ability to entangle arbitrary,
Using a Superconducting Resonator with Frequency-Compensated Tunable Coupling to Transfer a Quantum State Deterministically and Directly

2:54PM H48.00003

James Wenne, C. Neill, C. Quintana, B. Campbell, Z. Chen, B. Chiaro, A. Dunsworth, P. O’Malley, A. Vainsencher, University of California, Santa Barbara, T. White, R. Barends, Y. Chen, A. Fowler, E. Jeffrey, J. Kelly, E. Lucero, A. Megrant, J. Mutus, M. Neeley, P. Roushan, D. Sank, Google, Santa Barbara, John M. Martinis, University of California and Google, Santa Barbara — Deterministic direct quantum state transfer between devices on different chips requires the ability to transfer quantum states between traveling qubits and fixed logic qubits. Reflections must be minimized to avoid energy loss and phase interference; this requires tunable coupling to an inter-chip line while the two devices are at equal frequencies. To achieve this, we use a 6GHz superconducting coplanar resonator with tunable coupling to a 50 Ohm transmission line. We compensate for the resulting shift in resonator frequency by simultaneously tuning a second SQUID. We measure the device coherence and demonstrate the ability to release a single-frequency shaped pulse into the transmission line, efficiently capture a shaped pulse, and deterministically and directly transfer a quantum state.

3:06PM H48.00004

Controlled release of cavity states into propagating modes induced via a single qubit

Wolfgang Pfaff, Marius Constantin, Matthew Reagor, Christopher Axline, Jacob Blumoff, Kevin Chou, Zaki Leghtas, Steven Touzard, Reinier Heeres, Philip Reinhold, Nissim Ofek, Katrina Slawa, Luigi Frunzio, Yale University, Maziar Mirrahimi, Yale University & INRIA, Konrad Lehnert, University of Colorado, Liang Jiang, Michel Devoret, Robert Schoelkopf, Yale University — Photonic states stored in long-lived cavities are a promising platform for scalable quantum computing and for the realization of quantum networks. An important aspect in such a cavity-based architecture will be the controlled conversion of stored photonic states into propagating ones. This will allow, for instance, quantum state transfer between remote cavities. We demonstrate the controlled release of quantum states from a microwave resonator with millisecond lifetime in a 3D circuit QED system. Dispersive coupling of the cavity to a transmon qubit allows us to enable a four-wave mixing process that transfers the stored state into a second resonator from which it can leave the system through a transmission line. This permits us to evacuate the cavity on time scales that are orders of magnitude faster than the intrinsic lifetime. This Q-switching process can in principle be fully coherent, making our system highly promising for quantum state transfer between nodes in a quantum network of high-Q cavities.

3:18PM H48.00005

Concurrent remote entanglement with continuous variables

E. Zaly-Seller, A. Narla, S. Shankar, M. Hatridge, M. Silveri, K.M. Slawa, S.O. Mündhada, S.M. Girvin, M.H. Devoret, Department of Applied Physics, Yale University — A necessary ingredient for large scale quantum information processing is the ability to entangle distant qubits on demand. In the field of superconducting quantum information, this process can be achieved by entangling stationary superconducting qubits with flying coherent states of microwave light, which are then co-amplified by a Josephson Parametric Converter (JPC). The JPC also serves as a which-path information eraser, causing the probabilistic continuous measurement process to concurrently entangle the qubits. We discuss the sensitivity of the experiment to the loss of quantum information during the flight of the coherent states, as well as strategies to improve which-path information erasure and reduce information loss to the degree required for entanglement generation.

3:30PM H48.00006

Preparation of a narrowband, itinerant microwave qubit for quantum information transfer

Xizheng Ma, Adam Reed, Lucas Sletten, Department of Physics, University of Colorado, Boulder, Colorado, USA, Matthew Reagor, Luke Burkhardt, Wolfgang Pfaff, R.J. Schoelkopf, Departments of Applied Physics and Physics, Yale University, New Haven, Connecticut, USA, K.W. Lehnert, JILA, University of Colorado and NIST, Boulder, Colorado, USA, Department of Physics, University of Colorado, Boulder, Colorado, USA — Narrowband microwave-frequency signals are compatible with many quantum information processing technologies and can coherently transfer quantum information between devices. The creation of itinerant, microwave single photon states has been successfully demonstrated. Here, we show progress towards generating a narrowband, itinerant microwave qubit in a coherent superposition of zero and one Fock states. Specifically, we use the red-sideband transition of a transmon to map a superposition of qubit states onto a propagating microwave signal. This signal should have a bandwidth sufficiently narrow to be absorbed by a quantum-enabled electro-optic converter [1], potentially enabling the transfer of quantum information from a transmon qubit to the optical domain.

3:42PM H48.00007

Characterizing an itinerant microwave Fock state compatible with transfer to a macroscopic mechanical oscillator

L.R. Sletten, A.P. Reed, Xizheng Ma, JILA, University of Colorado, Boulder, Colorado, L.D. Burkhardt, M. Reagor, W. Pfaff, R.J. Schoelkopf, Department of Physics and Applied Physics, Yale University, New Haven, Connecticut, K.W. Lehnert, JILA and National Institute of Standards and Technology, Boulder, Colorado — Transferring propagating single-photon signals generated by a qubit to a mechanical oscillator offers a way to prepare non-classical motional states of a macroscopic object. In this concept, a highly coherent transmon qubit in a cavity is used to create single itinerant microwave photons. These photons can then be directed towards a tunable electromechanical circuit where they can be converted into single phonons. In this talk, we present measurements of itinerant single photons engineered to realize this concept. In particular, we characterize their quantum state tomographically, demonstrate that they have sufficiently narrow bandwidth for capture by an electromechanical circuit, and measure the efficiency with which they travel between microwave cavities.

3:54PM H48.00008

Entangled Schrodinger cats in circuit QED: Experimental Architecture

Chen Wang, Yvonne Y. Gao, Philip Reinhold, Reinier W. Heeres, Nissim Ofek, Kevin Chou, Christopher Axline, Luigi Frunzio, Michel H. Devoret, Robert J. Schoelkopf, Yale University — The development of quantum information technology relies on creating and controlling quantum state transfer between distant qubits. A necessary ingredient for large scale quantum information processing is the ability to entangle distant qubits on demand. In the field of superconducting quantum information, this process can be achieved by entangling stationary superconducting qubits with flying coherent states of microwave light, which are then co-amplified by a Josephson Parametric Converter (JPC). The JPC also serves as a which-path information eraser, causing the probabilistic continuous measurement process to concurrently entangle the qubits. We discuss the sensitivity of the experiment to the loss of quantum information during the flight of the coherent states, as well as strategies to improve which-path information erasure and reduce information loss to the degree required for entanglement generation.

3:54PM H48.00008

Entangled Schrodinger cats in circuit QED: Experimental Architecture

Chen Wang, Yvonne Y. Gao, Philip Reinhold, Reinier W. Heeres, Nissim Ofek, Kevin Chou, Christopher Axline, Luigi Frunzio, Michel H. Devoret, Robert J. Schoelkopf, Yale University — The development of quantum information technology relies on creating and controlling quantum state transfer between distant qubits. A necessary ingredient for large scale quantum information processing is the ability to entangle distant qubits on demand. In the field of superconducting quantum information, this process can be achieved by entangling stationary superconducting qubits with flying coherent states of microwave light, which are then co-amplified by a Josephson Parametric Converter (JPC). The JPC also serves as a which-path information eraser, causing the probabilistic continuous measurement process to concurrently entangle the qubits. We discuss the sensitivity of the experiment to the loss of quantum information during the flight of the coherent states, as well as strategies to improve which-path information erasure and reduce information loss to the degree required for entanglement generation. In this talk we present a qCQED architecture that allows quantum control over the coherent state basis of two superconducting cavities with millisecond coherence. In particular, we show deterministic entanglement of coherent-state microwave fields in two superconducting cavities of the form: $\frac{1}{\sqrt{2}}(|\beta_a\rangle + |\beta_a\rangle) = |\beta_a\rangle$ + $|\beta_a\rangle$. We engineer the capability to measure the joint photon number parity to achieve complete state tomography of the two-cavity state. Following widespread efforts of realizing "Schrodinger’s cat"-like mesoscopic superposition in various physical systems, this experiment demonstrates mesoscopic entanglement between two "Schrodinger’s cats".

This work was supported by the Gordon and Betty Moore Foundation

1 Work supported by ARO, AFOSR, NSF, and YINQE

4:06PM H48.00009 Entangled Schrodinger cats in circuit QED: Joint Wigner Tomography . YVONNE Y GAO, CHEN WANG, PHILIP REINHOLD, REINIER W HEERES, NISSIM OFEK, KEVIN CHOU, CHRISTOPHER AXLIN, LUIGI FRUNZIO, MICHEL H DEVORET, ROBERT J. SCHOELKOPF, Yale University — Creating and controlling entanglement of quantum states over large Hilbert space is an important element of quantum information processing. Using the qCQED architecture consisting of two long-lived superconducting cavities dispersively coupled to a transmon qubit, we successfully created an entangled coherent-state microwave fields in two superconducting cavities. In this talk, we will present the full joint Wigner tomography of the state, measured using the method of joint photon number parity measurement introduced in the previous talk. Furthermore, we will show the redundant encoding and efficient read-out of two logical bits of information in such entangled state and hence demonstrating that the entangled “Schrodinger cats” is a viable candidate as an error-correctable quantum memory as well as a valuable platform for implementation of two-qubit logical operations.

4:18PM H48.00010 Generating entanglement via symmetry-selective bath engineering in superconducting qubits\(^1\), IRFAN SIDDIQI, MOLLIE SCHWARTZ, LEIGH MARTIN, EMMANUEL FLURIN, Quantum Nanoelectronics Laboratory, UC Berkeley, CAMILLE ARON, Laboratoire de Physique Thorique, cole Normale Superieure; Instituut voor Theoretische Fysica, KU Leven, MANAS KULKARNI, Department of Physics, New York City College of Technology, City University of New York, HAKAN TURECI, Department of Electrical Engineering, Princeton University — Bath engineering, which utilizes coupling to lossy modes in a quantum system to generate non-trivial steady states, is a potential alternative to gate- and measurement-based quantum science. In this talk, we discuss autonomous stabilization of entanglement between two superconducting transmon qubits in a symmetry-selective manner. Our experiments are implemented using two 3D transmons housed in separate copper cavities. The cavities are coupled via an aperture, and hybridize into nondegenerate symmetric and antisymmetric bath modes. We utilize the engineered symmetries of the dissipative environment to stabilize a target Bell state \(\frac{1}{\sqrt{2}}(\ket{eg} \pm \ket{ge})\) in the qubit sector; we further demonstrate suppression of the Bell state of opposite symmetry due to parity selection rules. This implementation is resource-efficient, achieves a steady-state fidelity \(F = 0.70\), and is scalable to multiple qubits. http://arxiv.org/abs/1511.00702

\(^1\)This research was supported by the ARO.

4:30PM H48.00011 Multimode Entanglement Generation in a Parametric Superconducting Cavity . C.W.S. CHANG, University of Waterloo, M. SIMOEN, Chalmers University of Technology, A.M. VADIRAJ, University of Waterloo, P. DELSING, Chalmers University of Technology, C.M. WILSON, University of Waterloo — Parametric microwave resonators implemented with superconducting circuits have become increasingly important in various applications within quantum information processing. For example, quantum-limited parametric amplifiers based on these devices have now become commonplace as first-stage amplifiers for qubit experiments. Here we study the generation of multimode entangled states of propagating microwave photons, which can be used as a resource in quantum computing and communication applications. We use a CPW resonator with a low fundamental resonance frequency that has more than a few modes in the common frequency band of 4-12 GHz. These modes are all parametrically coupled by a single SQUID that terminates the resonator. When parametrically pumping the system at the sum of two mode frequencies, we observe parametric downconversion and two-mode squeezing. By pumping at the difference frequency, we observe a beamsplitter-like mode conversion. By using multipy pump tones that combine these different processes, theory predicts we can construct multimode entangled states with a well-controlled entanglement structure, e.g., cluster states. Preliminary measurements will be presented.

4:42PM H48.00012 Simultaneous measurement of non-commuting observables in circuit QED: Theory\(^1\), LEIGH MARTIN, SHAY HACOHEN-GOURGY, EMMANUEL FLURIN, Quantum Nanoelectronics Laboratory, UC Berkeley, BIRGITTA WHALEY, Berkeley Quantum Information and Computation Center, UC Berkeley, IRFAN SIDDIQI, Quantum Nanoelectronics Laboratory, UC Berkeley — We describe the theory of a novel technique for simultaneously and continuously measuring a pair of non-commuting qubit observables, which has until now not been realized experimentally. Our proposed experimental platform consists of a qubit dispersively coupled to two linear cavity modes. Driving the qubit on resonance realizes an effective two-level system with energy splitting given by the Rabi frequency. Non-commuting measurements are performed on this system by application of sideband tones detuned from the cavity resonance frequencies by the Rabi frequency. We show that this realizes cooling and back-action free measurements constituting destructive and QND measurements, respectively, along an arbitrary axis of the Bloch sphere. Simultaneous application of a distinct pair of measurements may then be achieved by choosing a different axis for each cavity mode. We show that existing high quantum efficiency homodyne measurement techniques will enable the reconstruction of quantum trajectories of the qubit. Finally, we describe methods for characterizing the system’s dynamics and verify that the scheme does enable access to incommensurate, competing degrees of freedom.

\(^1\)This research is supported by the ARO.

4:54PM H48.00013 Simultaneous measurement of non-commuting observables in circuit QED: Experiment\(^1\), SHAY HACOHEN-GOURGY, LEIGH MARTIN, EMMANUEL FLURIN, Quantum Nanoelectronics Laboratory, UC Berkeley, BIRGITTA WHALEY, Berkeley Quantum Information Center, UC Berkeley, IRFAN SIDDIQI, Quantum Nanoelectronics Laboratory, UC Berkeley — The existence of incompatible measurements lies at the heart of numerous fundamental concepts in quantum mechanics, such as entanglement, contextuality and measurement-disturbance tradeoffs. We implement a novel technique for simultaneously and continuously measuring a pair of non-commuting observable in a circuit-QED architecture, which features a transmon qubit coupled to two modes of an electromagnetic cavity. By driving the transmon on resonance, we form an effective, low-frequency two-level system on which we perform the non-commuting measurements. To this end, we use microwave tones near the cavity’s resonances to implement cooling and back-action-evading measurements familiar from optomechanics. Control of the relative amplitude and phase of these sideband tones enables qubit state measurement along an arbitrary axis of the Bloch sphere. We apply this technique to both modes of the cavity simultaneously, with distinct axes chosen for each mode. This realizes a continuous and simultaneous measurement of two non-commuting observables. We use high quantum-efficiency parametric amplifiers to track the resulting quantum trajectories of the qubit, enabling a measurement of the mutual disturbance of the two observables.

\(^1\)This research is supported by the ARO

5:06PM H48.00014 Optimized entanglement purification schemes for modular based quantum computers . STEFAN KRASTANOV, LIANG JIANG, Yale University — The choice of entanglement purification scheme strongly depends on the fidelities of quantum gates and measurements, as well as the imperfection of initial entanglement. For instance, the purification scheme optimal at low gate fidelities may not necessarily be the optimal scheme at higher gate fidelities. We employ an evolutionary algorithm that efficiently optimizes the entanglement purification circuit for given system parameters. Such optimized purification schemes will boost the performance of entanglement purification, and consequently enhance the fidelity of teleportation-based non-local coupling gates, which is an indispensable building block for modular-based quantum computers. In addition, we study how these optimized purification schemes affect the resource overhead caused by error correction in modular based quantum computers.
5:18PM H48.00015 Entanglement distillation in circuit quantum electrodynamics . MARKUS OPPLIGER, JOHANNES HEINSOO, YVES SALATHE, ANTON POTOCNIK, MINTU MONDAL, ANDREAS WALLRAFF, ETH Zurich, GHEORGHE SORIN PARAOANU, Aalto University School of Science — Entanglement is an essential resource for quantum information processing, such as quantum error correction, quantum teleportation and quantum communication. Such algorithms perform optimally with maximally entangled states. In practice entangled quantum states are very fragile due to a wide range of decoherence mechanisms. When two parties share degraded entangled states they are still able to generate an entangled state with higher fidelity using local operations and classical communication. This process is commonly referred to as entanglement distillation. Here we demonstrate distillation of highly entangled Bell states from two copies of less entangled states on a four transmon qubit device realized in the circuit-QED architecture. We characterize the output state for different degrees of entanglement at the input with quantum state tomography. A clear improvement of the entanglement measures is observed at the output.

Tuesday, March 15, 2016 5:45PM - 6:45PM
Session J38 GQI: GQI Business Meeting 341 -

5:45PM J38.00001 GQI BUSINESS MEETING —

Wednesday, March 16, 2016 8:00AM - 11:00AM
Session K44 GQI: Quantum Error Correction, Control & Simulation 347 - Todd Brun, University of Southern California

8:00AM K44.00001 Hamiltonian Engineering for High Fidelity Quantum Operations, HUGO RIBEIRO, ALEXANDRE BAKSIC, AAISHISH CLERK, McGill University — High-fidelity gates and operations are crucial to almost every aspect of quantum information processing. In recent experiments [1], fidelity is mostly limited by unwanted couplings with states living out of the logical subspace. This results in both leakage and phase errors. Here, we present a general method to deal simultaneously with both these issues and improve the fidelity of quantum gates and operations. Our method is applicable to a wide variety of systems. As an example, we can correct gates for superconducting qubits [1], improve coherent state transfer between a single NV centre electronic spin and a single nitrogen nuclear spin [2], improve control over a nuclear spin ensemble [3], etc. Our method is intimately linked to the Magnus expansion. By modifying the Magnus expansion of an initially given Hamiltonian $H_1$, we find analytically additional control Hamiltonians $H_{ctrl}$, such that $H_1 + H_{ctrl}$ leads to the desired gate while minimizing both leakage and phase errors.


8:12AM K44.00002 Method for generating all uniform $\pi$-pulse sequences used in deterministic dynamical decoupling, HAOYU QI1, JONATHAN DOWLING3, Department of Physics & Astronomy, Louisiana State University — Dynamical decoupling has been actively investigated since Viola first suggested using a pulse sequence to protect a qubit from decoherence. Since then, many schemes of dynamical decoupling have been proposed to achieve high-order suppression, both analytically and numerically. However, hitherto, there has not been a systematic framework to understand all existing uniform $\pi$-pulse dynamical decoupling schemes. In this report, we use the projection pulse sequences as basic building blocks and concatenation as a way to combine them. We derived a concatenated-projection dynamical decoupling, a framework in which we can systematically construct pulse sequences to achieve arbitrary high suppression order. All previously known uniform dynamical decoupling sequences using $\pi$ pulse can be fit into this framework. Understanding uniform dynamical decoupling as successive projections on the Hamiltonian will also give insights on how to invent new ways to construct better pulse sequences.

1This work is supported by AirForce Office of Scientific Research, the US Army Research Office, and the National Science Foundation
2Quantum Sciences & Technologies Group Horace C. Hearne Jr. Institute for Theoretical Physics
3Quantum Sciences & Technologies Group Horace C. Hearne Jr. Institute for Theoretical Physics

8:24AM K44.00003 Quantum gates with optimal bandwidth in noisy environments, GUANG HAO LOW, YODER THEODORE, ISAAC CHUANG, Massachusetts Inst of Tech-MIT — The traditional approach of open-loop quantum error correction suppresses certain systematic imperfections $\epsilon$ in quantum control to higher orders $\epsilon^O(L)$ by a well-designed sequence of $L$ imperfect quantum gates. However, this philosophy of maximal flatness leads to an $\epsilon$-bandwidth that scales poorly with length and a residual that is easily overwhelmed by unaccounted sources of noise. We advance the paradigm of equiripple compensated gates that directly optimize for bandwidth given the limitations imposed by noise of magnitude $\delta$. By modifying the Magnus expansion of an initially given Hamiltonian $H_1$, we find analytically additional control Hamiltonians $H_{ctrl}$, such that $H_1 + H_{ctrl}$ leads to the desired gate while minimizing both leakage and phase errors.

8:36AM K44.00004 Engineering autonomous error correction in stabilizer codes at finite temperature, C. DANIEL FREEMAN, University of California - Berkeley, CHRIS HERDMAN, University of Waterloo, BIRGITTA WHALEY, University of California - Berkeley — We present an error correcting protocol that enhances the lifetime of stabilizer code based qubits which are susceptible to string-like error modes at finite temperature, such as the toric code. The primary tool employed is dynamic application of the CSWAP operator, a local, unitary operator which exchanges defects and thereby translates quasiparticles. Crucially, the protocol does not require any information about the locations of quasiparticles, and can be used to enhance the lifetime of an encoded qubit in the absence of stabilizer measurement. This work was supported by the NSF grant DGE-1106400.

8:48AM K44.00005 New class of photonic quantum error correction codes, MATTI SILVERI, MARIOS MICHAEL, R. T. BRIERLEY, JUHA SALMILEHTO, VICTOR V. ALBERT, LIANG JIANG, S. M. GIRVIN, Departments of Physics and Applied Physics, Yale University — We present a new class of quantum error correction codes for applications in quantum memories, communication and scalable computation. These codes are constructed from a finite superposition of Fock states and can exactly correct errors that are polynomial up to a specified degree in creation and destruction operators. Equivalently, they can perform approximate quantum error correction to any given order in time step for the continuous-time dissipative evolution under these errors. The codes are related to two-mode photonic codes[1] but offer the advantage of requiring only a single photon mode to correct loss (amplitude damping), as well as the ability to correct other errors, e.g. dephasing. Our codes are also similar in spirit to photonic “cat codes” but have several advantages including smaller mean occupation number and exact rather than approximate orthogonality of the code words. We analyze how the rate of uncorrectable errors scales with the code complexity and discuss the unitary control for the recovery process. These codes are realizable with current superconducting qubit technology[2] and can increase the fidelity of photonic quantum communication and memories. [1] I.Chuang et al., Phys. Rev. A 56, 1114 (1997); [2] R.Heeres et al., Phys. Rev. Lett. 115, 137002 (2015).
9:00AM K44.00006 Non-commuting two-local Hamiltonians for quantum error suppression
ELEANOR RIEFFEL, NASA Ames Research Center, ZHANG JIANG, Stinger Ghaifarian Technologies Inc., NASA Ames Research Center, QUALI TEAM
— Physical constraints make it challenging to implement and control multi-body interactions. Designing quantum information processes with Hamiltonians consisting of only one- and two-local terms is a worthwhile challenge. A common approach to robust storage of quantum information is to encode in the ground subspace of a Hamiltonian. Even allowing particles with high Hilbert-space dimension, it is not possible to protect quantum information from single-site errors by encoding in the ground subspace of any Hamiltonian containing only commuting two-local terms [1]. We demonstrate how to get around this no-go result by encoding in the ground subspace of a Hamiltonian consisting of non-commuting two-local terms arising from the gauge operators of a subsystem code. Specifically, we show how to protect stored quantum information against single-qubit errors using a Hamiltonian consisting of sums of the gauge generators from Bacon-Shor codes [2] and generalized-Bacon-Shor code [3]. Thus, non-commuting two-local Hamiltonians have more error-suppressing power than commuting two-local Hamiltonians. Finally, we comment briefly on the robustness of the whole scheme. [1] I. Marvian and D. A. Lidar, PRL 113, 260504 (2014) [2] D. Bacon, PRA 73, 012340 (2006) [3] S. Bravyi, PRA 83, 012320 (2011)

9:12AM K44.00007 Error threshold for the surface code in a superohmic environment
DANIEL A. LOPEZ-DELGADO, Universidade Estadual de Campinas - Brazil, E. NOVAIS, Universidade Federal do ABC - Brazil, EDUARDO R. MUCCIOLO, University of Central Florida, AMIR Q. G. DEVAIR, Universidade Estadual de Campinas — We evaluate the fidelity of a multi-qubit quantum state protected by the surface code during a single quantum error correction cycle when qubits couple to a gapless bosonic environment. We discuss the protection of the state for different spectral functions and bath temperatures. Analytical results are supported by finite-size scaling analyses based on Monte Carlo and exact numerical calculations. Our results demonstrate a finite threshold that explicitly depends on the bath-mediated qubit-qubit interaction range and bath spectral function and temperature.

9:24AM K44.00008 Fidelity of a quantum state protected by the surface code in the presence of a finite-temperature bosonic bath
E. NOVAIS, Federal University of ABC (SP-BRAZIL), A. J. STANFORTH, EDUARDO R. MUCCIOLO, University of Central Florida — We evaluate the fidelity of a multi-qubit quantum state protected by the surface code during a single quantum error correction cycle when qubits couple to a gapless bosonic environment. We discuss the protection of the state for different spectral functions and bath temperatures. Analytical results are supported by finite-size scaling analyses based on Monte Carlo and exact numerical calculations. Our results demonstrate a finite threshold that explicitly depends on the bath-mediated qubit-qubit interaction range and bath spectral function and temperature.

9:36AM K44.00009 Repeated quantum error correction by real-time feedback on continuously encoded qubits
JULIA CRAMER, NORBERT KALB, M. ADRIAN ROL, BAS HENSEN, MACHIEL S. BLOK, QuTech and Kavli Institute of Nanoscience Delft, MATTHEW MARKHAM, DANIEL J. TWITCHEN, Element Six Innovation, RONALD HANSON, TIM H. TAMINIAU, QuTech and Kavli Institute of Nanoscience Delft, and the National Institute of Standards and Technology, JACOB TAYLOR, Univ. of Maryland, National Institute of Standards and Technology — Advances in single-photon creation, transmission, and detection suggest that sending quantum information over optical fibers may have low enough losses to be overcome using quantum error correction. Such error-corrected communication is equivalent to a novel quantum repeater scheme, but crucial questions regarding implementation and system requirements remain open. In this talk, I will show that long-range entangled bit generation with rates approaching 10^6 entangled bits per second may be possible using a completely serialized protocol, in which photons are generated, entangled, and error corrected via sequential, one-way interactions with as few matter qubits as possible. Provided loss and error rates of the required elements are below the threshold for quantum error correction, this scheme demonstrates improved performance over single photons. We find improvement in entangled bit rates at large distances using this serial protocol and various quantum error correcting codes.

9:48AM K44.00010 Serialized Quantum Error Correction Protocol for High-Bandwidth Quantum Repeaters
ANDREW GLAUDELL, Univ. of Maryland, National Institute of Standards and Technology, EDO WAKS, Univ. of Maryland and the National Institute of Standards and Technology, JACOB TAYLOR, Univ. of Maryland, National Institute of Standards and Technology — Advances in single-photon creation, transmission, and detection suggest that sending quantum information over optical fibers may have low enough losses to be overcome using quantum error correction. Such error-corrected communication is equivalent to a novel quantum repeater scheme, but crucial questions regarding implementation and system requirements remain open. In this talk, I will show that long-range entangled bit generation with rates approaching 10^6 entangled bits per second may be possible using a completely serialized protocol, in which photons are generated, entangled, and error corrected via sequential, one-way interactions with as few matter qubits as possible. Provided loss and error rates of the required elements are below the threshold for quantum error correction, this scheme demonstrates improved performance over single photons. We find improvement in entangled bit rates at large distances using this serial protocol and various quantum error correcting codes.

10:00AM K44.00011 Spectroscopy of cross-correlations of environmental noises with two qubits
LUKASZ CYWINSKI, Institute of Physics, Polish Academy of Sciences, PIOTR SZANKOWSKI, MAREK TRIPPENBACH, Faculty of Physics, University of Warsaw, — A single qubit driven by an appropriate sequence of control pulses can serve as a spectrometer of local noise affecting its energy splitting. We show that by driving and observing two spatially separated qubits, it is possible to reconstruct the spatial spectrum of cross-correlations of noises acting at various locations. When the qubits are driven by the same sequence of pulses, real part of cross-correlation spectrum can be reconstructed, while applying two distinct sequence to the two qubits allows for reconstruction of imaginary part of this spectrum [1]. The latter quantity contains information on either the critical temperature of the spin model. For superohmic baths, we find that time does not affect the error threshold: its value is the same for one or an arbitrary number of quantum error correction cycles.

1Financial support Fapesp, and CNPq (Brazil).

2This work was supported by the NSF grant CCF 1117241 and by Fapesp(Brazil) grant 2014/26356-9.

3This work was supported by funds of Polish National Science Center (NCN) under decision no. DEC-2012/07/B/ST3/03616
10:12AM K44.00012 1D quantum simulation using a solid state platform¹, MEGAN KIRKENDALL, PATRICK IRVIN, MENGCHEN HUANG, JEREMY LEVY, University of Pittsburgh, HYUNGWOO LEE, CHANG-BEOM EOM, University of Wisconsin - Madison — Understanding the properties of large quantum systems can be challenging both theoretically and numerically. One experimental approach–quantum simulation—involves mapping a quantum system of interest onto a physical system that is programmable and experimentally accessible. A tremendous amount of work has been performed with quantum simulators formed from optical lattices; by contrast, solid-state platforms have had only limited success. Our experimental approach to quantum simulation takes advantage of the gate-based structure of a metal-insulator transition at the interface between two insulating complex oxide materials. This system naturally exhibits a wide variety of ground states (e.g., ferromagnetic, superconducting) and can be configured into a variety of complex geometries. We will describe initial experiments that explore the magnetotransport properties of one-dimensional superfamilies with spatial periods as small as 4 nm, comparable to the Fermi wavelength. The results demonstrate the potential of this solid-state quantum simulation approach, and also provide empirical constraints for physical models that describe the underlying oxide material properties.

¹We gratefully acknowledge financial support from AFOSR (FA9550-12-1-0057 (JL), FA9550-10-1-0524 (JL) and FA9550-12-1-0342 (CBE)), ONR N00014-15-1-2847 (JL), and NSF DMR-1234096 (CBE)

10:24AM K44.00013 Classical Emulation of a Two-Qubit Quantum Computer with Analog Electronics¹, BRIAN LA COUR, COREY OSTROVE, GRANVILLE OTT, MICHAEL STARKEY, GARY WILSON, Applied Research Laboratories, The University of Texas at Austin — Abstract: The Hilbert space mathematical structure of a gate-based quantum computer may be reproduced by mapping the computational basis states to corresponding functions in the space of complex exponentials and identifying an inner product between any two such functions. The span of these complex basis exponentials may then identified with the finite-dimensional Hilbert space of a gate-based quantum computer. By using classical analog electronic components, such as four-quadrant multipliers and operational amplifiers, voltage signals representing arbitrary four-dimensional quantum states, along with the equivalent gate and measurement operations of a quantum computer have been physically realized through the corresponding circuitry. The fidelity of the emulation is measured using both a direct evaluation of the signal as well as through an emulation of quantum state tomography to infer the quantum state. We demonstrate that for both state synthesis and gate operations, our quantum emulation device is capable of achieving over 99% fidelity.

¹This work was supported by the Office of Naval Research under Grant No. N00014-14-1-0323.

10:36AM K44.00014 Fourth-order master equation for a charged harmonic oscillator coupled to an electromagnetic field, ARZU KURT¹, RESUL ERYIGIT², Abant Izzet Baysal University — Using Krylov averaging method, we have derived a fourth-order master equation for a charged harmonic oscillator weakly coupled to an electromagnetic field. Interaction is assumed to be of velocity coupling type which also takes into account the diaphragmatic term. Exact analytical expressions have been obtained for the second, the third and the fourth-order corrections to the diffusion and the drift terms of the master equation. We examined the validity range of the second order master equation in terms of the coupling constant and the bath cutoff frequency and found that for the most values of those parameters, the contribution from the third and the fourth order terms have opposite signs and cancel each other. Inclusion of the third and the fourth-order terms is found to not change the structure of the master equation.

¹Boh, Turkey
²Boh, Turkey

10:48AM K44.00015 A Numerical Study of Entanglement Entropy of the Heisenberg Model on a Bethe Cluster, BARRY FRIEDMAN, Physics, Sam Houston State University, GREG LEVINE, Physics and Astronomy, Hofstra University — Numerical evidence is presented for a nearest neighbor Heisenberg spin model on a Bethe cluster, that by bisecting the cluster, the generalized Renyi entropy scales as the number of sites in the cluster. This disagrees with spin wave calculations and a naive application of the area law but agrees with previous results for non interacting fermions on the Bethe cluster. It seems this scaling is not an artifact of non interacting particles. As a consequence, the area law in greater then one dimension is more subtle then generally thought and applications of the density matrix renormalization group to Bethe clusters face difficulties at least as a matter of principle.

Wednesday, March 16, 2016 8:00AM - 11:00AM
Session K45 GQI DAMOP: Hybrid Quantum Systems II

8:00AM K45.00001 Hamiltonian simulation for improved state transfer and readout in cavity QED, FELIX BEAUDOIN, McGill University, ALEXANDRE BLAIS, Université de Sherbrooke, WILLIAM A. COISH, McGill University — Quantum state transfer into a memory, state shuttling over long distances via a quantum bus, and high-fidelity readout are important tasks for quantum technology. Generating the Hamiltonians that realize these tasks is challenging in the presence of realistic couplings to an environment. Here, we use average Hamiltonian theory to design the desired Hamiltonians in cavity QED. In particular, we present a protocol for state transfer between a qubit and a cavity. This approach makes use of a controllable qubit-cavity coupling strength to achieve a high fidelity even in the presence of inhomogeneous broadening that is stronger than the qubit-cavity coupling strength. In addition, we design a time-averaged interaction that allows for an improved quantum nondemolition readout. These ideas can be applied directly to propel novel systems coupling single spins to a microwave cavity into the strong coupling regime [Viennot et al, Science 349, 408 (2015)]. The approach can also be employed to improve quantum operations with spin ensembles.

8:12AM K45.00002 Quantum efficiency of a double quantum dot microwave photon detector¹, CLEMENT WONG, MAXIM VAVILOV, Univ of Wisconsin-Madison — Motivated by recent interest in implementing circuit quantum electrodynamics with semiconducting quantum dots, we study charge transfer through a double quantum dot (DQD) capacitively coupled to a superconducting cavity subject to a microwave field. We analyze the DQD current response using input-output theory and determine the optimal parameter regime for complete absorption of radiation and efficient conversion of microwave photons to electric current. For experimentally available DQD systems, we show that the cavity-coupled DQD operates as a photon-to-charge converter with quantum efficiencies up to 80%.

¹C.W. acknowledges support by the Intelligence Community Postdoctoral Research Fellowship Program
8:24AM K45.00003 Optical-Fiber-Illuminated Response of a Superconducting Microwave Resonator Below 1 K, KRISTEN VOIGT, J. B. HERTZBERG, S. K. DUTTA, J. E. HOFFMAN, J. A. GROVER, J. LEE, P. SOLANO, R. P. BUDOYO, C. BALLARD, J. R. ANDERSON, C. J. LOBB, S. L. ROLSTON, F. C. WELLSTOOD, IQI and CNAM, Dept. of Physics, University of Maryland — As a step towards building a hybrid quantum system that couples superconducting elements to neutral atoms trapped on a tapered optical nanofiber, we have studied how the presence of the fiber dielectric and light scattered from a fiber affect the response of a translatable thin-film lumped-element superconducting Al microwave resonator that is cooled to 15 mK. The resonator has a resonance frequency of about 6 GHz, a quality factor $Q \approx 10^5$, and is mounted inside a 3D Al superconducting cavity. An optical fiber is tapered to a 60 um diameter and passes through two small holes in the 3D cavity such that it sits near the resonator. The 3D cavity is mounted on an x-z piezo-translation stage that allows us to change the relative position of the thin-film resonator and fiber. When the resonator is brought closer to the fiber, the resonance frequency decreases slightly due to the presence of the fiber dielectric. When 200 uW of 780 nm light is sent through the fiber, about 100 pW/mm is Rayleigh-scattered from the fiber. This causes a position-dependent illumination of the resonator, affecting its resonance frequency and $Q$. We compare our results to a model of the resonator response that includes the generation, diffusion, and recombination of quasiparticles in the resonator and find that the frequency response allows us to track the position of the fiber to within 10 um.

8:36AM K45.00004 Connecting trapped ions and quantum dots with photons, MICHAEL KOEHL, University of Bonn — Coupling individual quantum systems lies at the heart of building scalable quantum networks. Here, we report the first direct photonic coupling between a semiconductor quantum dot and a trapped ion and we demonstrate that single photons generated by a quantum dot controllably change the internal state of an Yb$^+$ ion. We ameliorate the effect of the sixty-fold mismatch of the radiative linewidths with coherent photon generation and a high-finesse fiber-based optical cavity enhancing the coupling between the single photon and the ion. The transfer of information presented here via the classical correlations between the $\sigma^z$ projection of the quantum-dot spin and the internal state of the ion provides a promising step towards quantum state-transfer in a hybrid photonic network.

9:12AM K45.00005 Encoding a Qubit into a Cavity Mode in Circuit-QED using Phase Estimation, BARBARA TERRHAL, DANIEL WEIGAND, RWTH - Aachen — Gottesman, Kitaev and Preskill have formulated a way of encoding a qubit into an oscillator such that the qubit is protected against small shifts (translations) in phase space. The idea underlying this encoding is that error processes of low rate can be expanded into small shift errors. The qubit space is defined as an eigenspace of two mutually commuting displacement operators which act as large shifts/translations in phase space. We propose and analyze the approximate creation of these qubit states by coupling the oscillator to a sequence of ancilla qubits realizing the protocol of approximate phase estimation for a displacement operator. We analyze the performance of repeated and adaptive phase estimation as the experimentally most viable schemes given a realistic upper limit on the number of photons in the oscillator. We propose a physical implementation of the protocol using the dispersive coupling between an ancilla transmon qubit and a cavity mode in circuit-QED. We estimate that in a current experimental set-up one can prepare a good code state from a squeezed vacuum state using 8 rounds of adaptive phase estimation lasting in total about 4 microseconds, with at least 80.

9:24AM K45.00006 Long-distance entanglement of spin qubits via quantum Hall edge states, GUANG YANG, CHEN-HSUAN HSU, PETER STANO, RIKEN Center for Emergent Matter Science, Wako, Japan, JELENA KLINOVaja, DANIEL LOSS, Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland — The implementation of a functional quantum computer involves entangling and coherent manipulation of a large number of qubits. For qubits based on electron spins confined in quantum dots, which are among the most investigated solid-state qubits at present, architectural challenges are often encountered in the design of quantum circuits attempting to assemble the qubits within the very limited space available. Here, we provide a solution to such challenges based on an approach to realizing entanglement of spin qubits over long distances. We show that long-range Ruderman-Kittel-Kasuya-Yosida interaction of confined electron spins can be established by quantum Hall edge states, leading to an exchange coupling of spin qubits. The coupling is anisotropic and can be either Ising-type or XY-type, depending on the spin polarization of the edge state. Such a property, combined with the dependence of the electron-spin susceptibility on the chirality of the edge state, can be utilized to gain valuable insights into the topological nature of various quantum Hall states.

9:36AM K45.00007 Entangling distant resonant exchange qubits via circuit quantum electrodynamics, VANITA SRINIVASA, Laboratory for Physical Sciences/University of Maryland, College Park, MD, JACOB M. TAYLOR, Joint Center for Quantum Information and Computer Science/John Quantum Institute/National Institute of Standards and Technology, Gaithersburg, MD, CHARLES TAHAN, Laboratory for Physical Sciences, College Park, MD — Enabling modularity within a quantum information processing device relies on robust entanglement of coherent qubits at macroscopic distances. To address this challenge, we investigate theoretically a hybrid quantum system consisting of spatially separated resonant exchange qubits, defined in three-electron semiconductor triple quantum dots, that are coupled via a superconducting transmission line resonator. By analyzing three specific approaches drawn from circuit quantum electrodynamics and Hartmann-Hahn double resonance techniques for implementing resonator-mediated two-qubit entangling gates in both dispersive and resonant regimes, we show that methods for entangling superconducting qubits map directly to resonant exchange qubits. We also calculate the rate of relaxation via phonons for resonant exchange qubits in silicon triple dots and show that such an implementation is particularly well-suited to achieving the strong coupling regime. Our approach combines the robustness of encoded spin qubits in silicon with the rapid and robust long-range entanglement provided by circuit QED systems.

9:48AM K45.00008 Long distance coupling of resonant exchange qubits, MAXIMILIAN RUSS, GUIDO BURKARD, Department of Physics, University of Konstanz, D-78457 Konstanz, Germany — We investigate the effectiveness of a microwave cavity as a mediator of interactions between two resonant exchange (RX) qubits in semiconductor quantum dots (QDs) over long distances, limited only by the extension of the cavity. Our interaction model includes the orthonormalized Wannier orbitals constructed from Fock-Darwin states under the assumption of a harmonic QD confinement potential. We calculate the qubit-cavity coupling strength $g_\phi$ in a Jaynes Cummings Hamiltonian, and find that dipole transitions between two states with an asymmetric charge configuration constitute the relevant RX qubit-cavity coupling mechanism. The effective coupling between two RX qubits in a shared cavity yields a universal two-qubit ISWAP-gate with gate times on the order of nanoseconds over distances on the order of up to a millimeter. Funded by ARO through grant No. W911NF-15-1-0149.

10:00AM K45.00009 Injection locking of a semiconductor double-quantum-dot micromaser$^1$. 
Y.-Y. LIU, J. STEHLIK, Department of Physics, Princeton University, M. J. GULLANS, J. M. TAYLOR, Joint Quantum Institute/NIST, J. R. PETTA, Department of Physics, Princeton University — Narrow linewidth lasers and masers are desirable for applications such as frequency standards and low-noise amplifiers. Recently we have demonstrated a double-quantum-dot (DQD) micromaser, which generates photons through single electron tunneling events.\cite{1} Charge noise couples to the DQD energy levels and results in a maser linewidth that is 100 times larger than the Schawlow-Townes prediction. We demonstrate linewidth narrowing by more than a factor of 10 using injection locking. The injection locking range is measured as a function of input power and shown to be in excellent agreement with the Adler equation. The position and amplitude of distortion sidebands that appear outside of the injection locking range are quantitatively examined. Our results show that this unconventional maser, which is impacted by strong charge noise and electron-phonon coupling, is well described by standard laser models.\cite{2}

$^1$Supported by the National Science Foundation and the Gordon and Betty Moore Foundation’s EPiQS initiative through grant no. GBMF4535.


10:12AM K45.00010 Real-time tuning of a double quantum dot using a Josephson parametric amplifier$^1$, J. STEHLIK, Y.-Y. LIU, Department of Physics, Princeton University, C. M. QUINTANA, Department of Physics, UC Santa Barbara, C. EICHLER, T. R. HARTKE, J. R. PETTA, Department of Physics, Princeton University — Josephson parametric amplifiers (JPAs)\cite{3} have enabled advances in readout of quantum systems. Here we demonstrate JPA-assisted readout of a cavity-coupled double quantum dot (DQD).\cite{4} Utilizing a JPA we improve the signal-to-noise ratio (SNR) by a factor of 2000 compared to the situation with the parametric amplifier turned off. At an interdot charge transition we achieve a SNR of 76 (19 dB) with an integration time $\tau = 400$ ns, which is limited by the linewidth of our cavity. By measuring the SNR as a function of $\tau$ we extract an equivalent charge sensitivity of $8 \times 10^{-5}$ e/$\sqrt{Hz}$. We develop a dual-gate-voltage rastering scheme that allows us to acquire a DQD charge stability diagram in just 20 ms. Such rapid data acquisition rates enable device tuning in live “video-mode,” where the results of parameter changes are immediately displayed. Live tuning allows the DQD confinement potential to be rapidly tuned, a capability that will become increasingly important as semiconductor spin qubits are scaled to a larger number of dots.

$^3$Research is supported by the Packard Foundation, ARO Grant No. W911NF-15-1-0149, DARPA QuEST Grant No. HR0011-09-1-0007, and the NSF (Grants No. DMR-1409556 and DMR-1420541).


10:24AM K45.00011 Investigating the level broadening of a semiconductor charge qubit in microwave emission measurements, A. STOCKKLAUSER, N. HEDRICH, V. F. MAISI, J. BASSET, K. CUJIA, C. REICHL, W. WEGSCHIEIDER, T. IHN, K. ENSSLIN, A. WALLRAFF, ETH Zurich — We investigate a hybrid circuit quantum electrodynamics architecture in which a double quantum dot charge qubit is coupled to a nearby microwave cavity. The discussed experiments explore the emission of microwave radiation from a voltage-biased GaAs double dot similar to Ref. \cite{1}. We study the dependence of the emission line width on the tunnel rates to the leads and identify this as the dominant contribution to the broadening of the qubit levels. For the explored bias conditions qubit decoherence is low in comparison. We extract the tunnel rates to the leads from the linewidth of the emission signal and compare it with the tunnel rates extracted from current measurements.


10:36AM K45.00012 Observation of magnon number states in a superconducting qubit spectrum, DANY LACHANCE-QUIRION, Université de Sherbrooke, YUTAKA TABUCHI, SEICHIRO ISHINO, ATSUSHI NOGUCHI, TOYOUMI ISHIKAWA, REKISHU YAMAZAKI, KOJI USAMI, RCAST, The University of Tokyo, YASUNOBU NAKAMURA, RCAST, The University of Tokyo, CEMS, RIKEN — A quantum transducer interfacing qubits in the microwave domain to optical light requires a quantum system interacting with photons of both frequency domains. Coherent interaction between collective excitations (magnons) in the ferrimagnetic insulator yttrium iron garnet (YIG) and a superconducting qubit through virtual microwave photons has recently been demonstrated \cite{1}. In this talk, we present results on the observation of magnon number states in a superconducting qubit spectrum when creating a coherent state in a magnetostatic mode of a YIG sphere interacting dispersively with the qubit. The dispersive interaction strength of 1.2 MHz measured in the straddling regime is in good agreement with numerical simulations. Furthermore the probability distribution of magnon number states, recovered from the qubit spectrum, is compared with the Poisson distribution expected for a coherent state. Resolving magnon number states constitutes a first step toward encoding quantum information into a quantum state of a magnetostatic mode \cite{2}.


10:48AM K45.00013 Emergent Curved space induced by adiabatic approximation$^1$, RAN CHENG, XIAOCHUAN WU, DI XIAO, Carnegie Mellon University — Berry curvature, serving as the imaginary part of quantum geometric tensor (QGT), gives rise to an effective Lorentz force to the dynamics of the adiabatic parameter. However, it is not clear whether the real part of QGT, the quantum metric, has any dynamical consequence as the Berry gauge force. We show in a general way that during an adiabatic process, the particle in a hybrid quantum system governed by an equation of motion second order in time is subject to an induced gravitational force. The adiabatic dynamics can be described by a geodesic equation as if the spacetime is curved by the quantum metric. As an example, we demonstrate the above result in a simple toy model.

$^1$This work is supported by DOE BES (No. DE-SC0012509) and AFOSR (No. FA9550-12-1-0479)

Wednesday, March 16, 2016 8:00AM - 11:00AM — Session K48 GQI: Novel Superconducting Qubits & Architectures 349 - John Martinis, Google, Inc.
and eliminate unwanted couplings. We discuss the incorporation of weakly-flux-tunable transmon qubits into such an architecture. Using DC tuning through gates offer simplicity of setup and operation. However, the relative frequencies of adjacent qubits must be carefully arranged in order to optimize gate rates of qubits requires a strong coupling between adjacent qubits and consistently high gate fidelity among them. In such a system, all-microwave cross-resonance of Copenhagen, Denmark — We have developed a superconducting transmon qubit with a semiconductor-based Josephson junction element. The junction is made from an InAs nanowire with in situ molecular beam epitaxy-grown superconducting Al contacts. This gate-controlled transmon, or gatemon, allows simple tuning of the qubit transition frequency using a gate voltage to vary the density of carriers in the superconductor region. In the first generations of devices we have measured coherence times up to ~10 µs. These coherence times, combined with stable qubit operation, permit single qubit rotations with fidelities of ~99.5 % for all gates including voltage-controlled Z rotations. Towards multi-qubit operation we have also implemented a two qubit voltage-controlled cPhase gate. In contrast to flux-tunable transmons, voltage-tunable gatemon may simplify the task of scaling to multi-qubit circuits and enable new means of control for many qubit architectures. In collaboration with T.W. Larsen, L. Casparis, M.S. Olsen, F. Kuenmmeth, T.S. Jespersen, P. Krostrup, J. Nygard and C.M. Marcus. Research was supported by Microsoft Project Q, Danish National Research Foundation and a Marie Curie Fellowship.

8:36AM K48.00002 Progress toward coupled flux qubits with high connectivity and long coherence times . STEVEN WEBER, DAVID HOVER, DANNA ROSENBERG, GABRIEL SAMACH, JONILYN YODER, ANDREW KERMAN, WILLIAM OLIVER, MIT Lincoln Laboratory — The ability to engineer interactions between qubits is essential to all areas of quantum information science. The capability to tune qubit-qubit couplings in situ is desirable for gate-based quantum computing and analog quantum simulation and necessary for quantum annealing. Consequently, tunable coupling has been the subject of several experimental efforts using both transmon qubits and flux qubits. Recently, our group has demonstrated robust and long-lived capacitively shunted (C-shunt) flux qubits. Here, we discuss our efforts to develop architectures for tunably coupling these qubits. In particular, we focus on optimizing the RF SQUID coupler to achieve high connectivity. This research was funded by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA) and by the Assistant Secretary of Defense for Research & Engineering under Air Force Contract No. FA8721-05-C-0002. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of ODNI, IARPA, or the US Government.

8:48AM K48.00003 Three coupled qubits in a single superconducting quantum circuit1, MADDHAI CHAND, SUMAN KUNDU, N. NEHRA, COSMIC RAJ, TANAY ROY, A. RANADIVE, MEGHAN P. PATANKAR, R. VIJAY, Tata Institute of Fundamental Research, Mumbai 400005 — We propose a new design for a 3-qubit system in the 3D circuit QED architecture. Our design exploits the geometrical symmetry of a single superconducting circuit with three degrees of freedom to generate three coupled qubits. However, only one of these is strongly coupled to the environment while the other two are protected from the Purcell effect. Nevertheless, all three qubits can be measured using the standard dispersive technique. We will present preliminary data on this circuit showing evidence of three distinct qubits that retain the essential properties of a 3D transmon, namely insensitivity to charge noise, sufficient anharmonicity and good coherence times. We will also characterize the coupling of the three qubits to each other, to the environment and to a neighboring transmon qubit. Finally, we will compare our design to previous multi-qubit circuits and discuss possible applications in quantum computing and quantum simulations.

1 Funding: Department of Atomic Energy, Govt. of India; Department of Science and Technology, Govt. of India

9:00AM K48.00004 Analog approaches to quantum computation using highly-controllable superconducting qubits . C. NEILL, UCSB, P. ROUSHAN, R. BARENDTS, Google Inc., B. CAMPBELL, UCSB, Y. CHEN, Google Inc., Z. CHEN, B. CHIARO, A. DUNSWORTH, UCSB, A. FOWLER, E. JEFFREY, J. KELLY, E. LUCERO, A. MEGRANT, J. MUTUS, M. NEELEY, Google Inc., P. O’MALLEY, C. QUINTANA, UCSB, D. SANK, Google Inc., J. WENNER, UCSB, T. WHITE, J. MARTINIS, Google Inc. — The first generation of quantum hardware that outperforms classical computers will likely be analog in nature. In an effort to realize such a platform, we have built a one-dimensional chain of 9 superconducting gmon qubits. This device provides individual time-dependent control over all nearest-neighbor couplings and local fields (X, Y, Z) in the multi-qubit Hamiltonian. In this talk, I will focus on open problems in non-equilibrium statistical mechanics where dynamical properties become impossible to compute for only a few 10s of qubits. In particular, I will review device performance and the scaling of analog errors with system size. By studying how errors scale during practical applications, we aim to predict if otherwise-tractable computations could be carried out with 30 to 40 qubits.

9:12AM K48.00005 Concentric transmon qubit featuring fast tunability and site-selective Z coupling . MARTIN WEIDES, JOCHEN BRAUMUELLER, Karlsruhe Institute of Technology, MARTIN SANDBERG, MICHAEL VISSERS, National Institute of Standards and Technology, ANDRE SCHNEIDER, STEFFEN SCHLOER, LUKAS GRUENHAUPT, HANNES ROTZINGER, MICHAEL MARTHALER, ALEXANDER LUKASCHENKO, AMADEUS DIETER, ALEXEY USTINOV, Karlsruhe Institute of Technology, DAVID PAPPAS, National Institute of Standards and Technology — We present a planar qubit design based on a superconducting circuit that we call concentric transmon. While employing a simple fabrication process using Al evaporation and lift-off lithography, we observe qubit lifetimes and coherence times in the order of 10 ßs. We systematically characterize loss channels such as incoherent dielectric loss, Purcell decay and radiative losses. The implementation of a gradiometric SQUID loop allows for a fast tuning of the qubit transition frequency and therefore for full tomographic control of the quantum circuit. The presented qubit design features a passive direct Z coupling between neighboring qubits, being a pending quest in the field of quantum simulation.

9:12AM K48.00005 Concentric transmon qubit featuring fast tunability and site-selective Z coupling . MARTIN WEIDES, JOCHEN BRAUMUELLER, Karlsruhe Institute of Technology, MARTIN SANDBERG, MICHAEL VISSERS, National Institute of Standards and Technology, ANDRE SCHNEIDER, STEFFEN SCHLOER, LUKAS GRUENHAUPT, HANNES ROTZINGER, MICHAEL MARTHALER, ALEXANDER LUKASCHENKO, AMADEUS DIETER, ALEXEY USTINOV, Karlsruhe Institute of Technology, DAVID PAPPAS, National Institute of Standards and Technology — We present a planar qubit design based on a superconducting circuit that we call concentric transmon. While employing a simple fabrication process using Al evaporation and lift-off lithography, we observe qubit lifetimes and coherence times in the order of 10 ßs. We systematically characterize loss channels such as incoherent dielectric loss, Purcell decay and radiative losses. The implementation of a gradiometric SQUID loop allows for a fast tuning of the qubit transition frequency and therefore for full tomographic control of the quantum circuit. The presented qubit design features a passive direct Z coupling between neighboring qubits, being a pending quest in the field of quantum simulation.

9:24AM K48.00006 Blackbox quantization and numerical simulation of a concentric transmon superconducting qubit . ALIREZA NAJAFI-YAZDI, KEVIN LALUMIERE, Anyon Systems Inc., J. BRAUMÜLLER, MARTIN WEIDES, KIT — We present a blackbox quantization [1] and numerical study of a planar concentric transmon superconducting qubit. This architecture has been recently proposed and experimentally investigated by Braumiller et al [2]. The device involves a gradiometric SQUID loop for a fast tuning of the qubit transition frequency. This allows for full tomographic control of the quantum circuit. A fully automated numerical package for quantization of superconducting qubits is developed and used for a study of the concentric transmon. A systematic characterization of loss channels such as Purcell decay and radiative losses are also studied. Numerical results are in close agreement with experimental data and suggest the platform to be a useful tool in the design of superconducting circuits. References: [1] Firat, S., DiVicenzo, D. W., Physical Review B, Vol. 90, No. 13, pp. 134-504, 2014. [2] J. Braumiller et al., arXiv:1509.08014

9:36AM K48.00007 Weakly-tunable transmon qubits in a multi-qubit architecture . JARED HERTZBERG, NICHOLAS BRONN, ANTONIO CORCOLES, MARKUS BRINK, GEORGE KEEFE, MAIKA TAKITA, IBM T J Watson Res Ctr, M. HUTCHINGS, B. L. T. PLOURDE, Syracuse University, JAY GAMBITTA, JERRY CHOW, IBM T J Watson Res Ctr — Quantum error-correction employing a 2D lattice of qubits requires a strong coupling between adjacent qubits and consistently high gate fidelity among them. In such a system, all-microwave cross-resonance gates offer simplicity of setup and operation. However, the relative frequencies of adjacent qubits must be carefully arranged in order to optimize gate rates and eliminate unwanted couplings. We discuss the incorporation of weakly-flux-tunable transmon qubits into such an architecture. Using DC tuning through filtered flux-bias lines, we adjust qubit frequencies while minimizing the effects of flux noise on decoherence. [1] J.M. Chow et al, Nat Comm 5, 4015 (2014). [2] A.D. Corcoles et al, Nat Comm 6, 6979 (2015).
The smallest p-value we observed is 5.9 x 10^{-9}. We propose an encoded qubit approach realizable with state-of-the-art tunable Josephson junction qubits. Our results show that this design philosophy holds promise, enables microwave-free control, and offers a pathway to future qubit designs with new capabilities such as with higher fidelity or, perhaps, operation at higher temperature. The approach is especially suited to qubits based on variable super-semi junctions. [1] Yun-Pil Shim and Charles Tahan, arXiv:1507.07923

10:24AM K48.0009 Coupling a Transmon Qubit to a Superconducting Metamaterial Resonator. HAOZHI WANG, M. HUTCHINGS, SAGER INDRAJEET, FRANCISCO ROUXINOL, MATTHEW LAHAYE, B.L.T. PLOURDE, Syracuse Univ, BRUNO G. TAKETANI, FRANK K. WILHELM, Saarland University — Arrays of lumped circuit elements can be used to form metamaterial resonant structures that exhibit significantly different mode structures compared to resonators made from conventional distributed transmission lines. In particular, it is possible to produce a high density of modes in the microwave regime where a superconducting qubit can be operated and coupled to the various modes. We will present our low-temperature measurements of such a superconducting metamaterial resonator coupled to a tunable transmon qubit. By tuning the magnetic flux biasing the qubit, we observe vacuum Rabi splittings in the modes that the qubit transition passes through. We will also discuss our measurements of an interaction between neighboring modes of the metamaterial system that is mediated by the qubit. Because of the dispersive coupling of the qubit to the various modes of the system, driving a microwave tone near one mode of the system can have a significant influence on the transmission through another mode, with a strong dependence on the bias point of the qubit. We will compare these measurements with a theoretical model of the system.

10:36AM K48.00010 Coplanar waveguide flux qubit suitable for quantum annealing2. CHRIS QUINTANA, UC Santa Barbara, YU CHEN, D. SANK, D. KAFRI, A. MEGRANT, T. C. WHITE, A. SHABANI, R. BARENDTS, Google, Santa Barbara, B. CAMPBELL, Z. CHEN, B. CHIARO, A. DUNSWORTH, UC Santa Barbara, A. FOWLER, E. JEFFREY, J. KELLY, E. LUCERO, J. Y. MUTUS, M. NEELEY, Google, Santa Barbara, C. NEILL, P. J. J. O’MALLEY, UC Santa Barbara, P. ROUSHAN, Google, Santa Barbara, A. VAINSCHER, J. WENNER, UC Santa Barbara, J. M. MARTINIS, University of California and Google, Santa Barbara — We introduce the “fluxmon” flux qubit, designed with the goal of practical quantum annealing. The qubit's capacitance and linear inductance are provided by a coplanar waveguide on a low loss substrate, minimizing dielectric dissipation and in principle allowing for GHz-scale inter-qubit coupling in a highly connected tunable architecture. Utilizing a dispersive microwave readout scheme, we characterize single-qubit noise and dissipation, and present a simple tunable inter-qubit coupler. We discuss tradeoffs between coherence and coupling in a quantum annealing architecture.


11:15AM L44.00001 Quantum Speed Limits, coherence and asymmetry. IMAN MARVIAN, massachusetts institute of technology, ROBERT SPEKSENS, Perimeter Institute for theoretical physics, PAOLO ZANARDI, University of Southern California — The resource theory of asymmetry is a framework for classifying and quantifying the symmetry-breaking properties of both states and operations relative to a given symmetry. In the special case where the symmetry is the set of translations generated by a fixed observable, asymmetry can be interpreted as coherence relative to the observable eigenbasis, and the resource theory of asymmetry provides a framework to study this notion of coherence. We here show that this notion of coherence naturally arises in the context of quantum speed limits. Indeed, the very concept of speed of evolution, i.e., the inverse of the minimum time it takes the system to evolve to another (partially) distinguishable state, is a measure of asymmetry relative to the time translations generated by the system Hamiltonian. Furthermore, the celebrated Mandelstam-Tamm and Margolus-Levitin speed limits can be interpreted as upper bounds on this measure of asymmetry by functions which are themselves measures of asymmetry in the special case of pure states. Using measures of asymmetry that are not restricted to pure states, such as the Wigner-Yanase skew information, we obtain extensions of the Mandelstam-Tamm bound which are significantly tighter in the case of mixed states.

11:27AM L44.00002 A Strong Loophole-Free Test of Local Realism. PETER BIERHORST, LYNDEN SHALM, MARTIN STEVENS, THOMAS GERRITS, SCOTT GLANCY, MICHAEL ALLMAN, KEVIN COAKLEY, SHELLEE DYER, CARSON HODGE, ADRIANA LITA, VARUN VERMA, RICHARD MIRIN, EMANUEL KNILL, SAE WOO NAM. National Institute of Standards and Technology, Boulder, CO — We discuss theoretical and statistical aspects of a recent loophole-free violation of local realism using entangled photon pairs. The experiment ensures that all relevant events in the Bell test are spacelike separated by placing the parties far enough apart and using fast random number generators and high-speed polarization measurements. A high-quality polarization-entangled source of photons, combined with high-efficiency, low-noise, single-photon detectors, allows us to make measurements without requiring any fair-sampling assumptions. We collected six data sets, and for each data set we used a hypothesis test to compute the maximum probability (the p-value) that our experiment, if it had been governed by local realism, would produce a violation as large or larger than we observed. The smallest p-value we observed is 5.9 x 10^{-9}.

1See Phys. Rev. Lett. 115, 250402 for a complete list of authors.
11:39AM L44.00003 Implications of Einstein-Weyl Causality on Quantum Mechanics . DAVID BENDANIEL, Cornell University — A fundamental physical principle that has consequences for the topology of space-time is the principle of Einstein-Weyl causality. This also has quantum mechanical manifestations. Borchers and Sen have rigorously investigated the mathematical implications of Einstein-Weyl causality and shown the denumerable space-time $\mathbb{Q}^2$ would be implied. They were left with important philosophical paradoxes regarding the nature of the physical real line $\mathbb{R}$, e.g., whether $\mathbb{R} = \mathbb{R}$, the real line of mathematics. In order to remove these paradoxes an investigation into a constructible foundation is suggested. We have pursued such a program and find it indeed provides a dense, denumerable space-time and, moreover, an interesting connection with quantum mechanics. We first show that this constructible theory contains polynomial functions which are locally homeomorphic with a dense, denumerable metric space $\mathbb{R}$ and are inherently quantized. Eigenfunctions governing fields can then be effectively obtained by computational iteration. Postulating a Lagrangian for fields in a compactified space-time, we get a general description of which the Schroedinger equation is a special case. From these results we can then also show that this denumerable space-time is relational (in the sense that space is not infinitesimally small if and only if it contains a quantized field) and, since $\mathbb{Q}^2$ is imbedded in $\mathbb{R}^2$, it directly fulfills the strict topological requirements for Einstein-Weyl causality. Therefore, the theory predicts that $\mathbb{E} = \mathbb{R}^4$.

11:51AM L44.00004 Entanglement Entropy and Mutual Information of Circular Entangling Surfaces in 2+1d Quantum Lifshitz Model1, TIANCI ZHOU, XIAO CHEN, EDUARDO FRADKIN, Univ of Illinois - Urbana — We investigate the entanglement entropy (EE) of circular entangling surfaces in the 2+1d quantum Lifshitz model, where the spatially conformal invariant ground state is a Rohsskas-Kivelson state with Gibbs weight of 2d free Boson. We use cut-off independent mutual information regulator[1] to define and calculate the subleading correction in the EE. The subtlety due to the Boson compactification in the replica trick is carefully taken care of. Our results show that for circular entangling surface, the subleading term is a constant on both the sphere of arbitrary radius and infinite plane. For the latter case, it parallels the constancy of disk EE in 2+1d conformal field theory, despite the lack of full space time conformal invariance. In the end, we present the mutual information of two disjoint disks and compare its scaling function in the small parameter regime (radii much smaller than their separation) with Cardy’s general CFT results[2]. 1. H. Casini, M. Huerta, R. Myers, A. Yale, arXiv: 1506.06195 (2015). 2. J. Cardy, J. Phys. A: Math. Theor. 46, 285402 (2013)

12:03PM L44.00005 Monogamy of quantum steering . ANTONY MILNE, DAVID JENNINGS, Imperial College London, SANIA JEVTC, Brunel University, TERRY RUDOLPH, Imperial College London, HOWARD WISEMAN, Griffith University — The quantum steering ellipsoid formalism naturally extends the Bloch vector picture for qubits to provide a visualization of two-qubit systems. If Alice and Bob share a correlated state then a local measurement by Bob steers Alice’s qubit inside the Bloch sphere; given all possible measurements by Bob, the set of states to which Alice can be steered form her steering ellipsoid. We apply the formalism to a three-party scenario and find that steering ellipsoid volumes obey a simple monogamy relation. This gives us a novel derivation of the well-known CKW (Coffman-Kundu-Wootters) inequality for entanglement monogamy. The geometric perspective also identifies new measure of quantum correlation, ‘obesity’, and a set of ‘maximally obese’ states that saturate the steering monogamy bound. These states are found to have extremal quantum correlation properties that are significant in the steering ellipsoid picture and for the study of two-qubit states in general.

12:15PM L44.00006 Conflict between the Uncertainty Principle and wave mechanics . ANTONY BOURDILLON, retied — The traveling wave group that is defined on conserved physical values is the vehicle of transmission for a unidirectional photon or free particle having a wide wave front. As a stable wave packet, it expresses internal periodicity combined with group localization. Heisenberg’s Uncertainty Principle is precisely derived from it. The wave group demonstrates serious conflict between the Principle and wave mechanics. Also derived is the phase velocity beyond the horizon set by the speed of light. In this space occurs the reduction of the wave packet which occurs in measurement and which is represented by comparing phase velocities in the direction of propagation with the transverse plane. The new description of the wavefunction for the stable free particle or antiparticle contains variables that were previously ignored. Deterministic physics must always appear probabilistic when hidden variables are bypassed. Secondary hidden variables always occur in measurement. The wave group turns out to be probabilistic. It is ubiquitous in physics and has many consequences.

12:27PM L44.00007 Coherence-path-information duality relation for N paths . MARK HILLERY, Department of Physics, Hunter College of CUNY, EMILIO BAGAN, Fisica Teorica: Informacio i Fenomens Quantics, Universitat Autonoma de Barcelona, JANOS BERGOU, Department of Physics, Hunter College of CUNY — For an interferometer with two paths, there is a duality relation between the information about which path the particle took and the visibility of the interference pattern at the output. The more path information we have, the smaller the visibility, and vice versa. We generalize this relation to a multi-path interferometer, and we substitute a recently defined measure of quantum coherence for the visibility. The path information is provided by attaching a detector to each path and applying the minimum-error state discrimination procedure to the detector states.

12:39PM L44.00008 Axioms for quantum mechanics: relativistic causality, retrocausality, and the existence of a classical limit1 . DANIEL ROHRLICH2, Physics Department, Ben-Gurion University of the Negev, Beersheba 8410501 — Y. Aharonov and A. Shimony both conjectured that two axioms – relativistic causality (“no superluminal signalling”) and nonlocality – so nearly contradict each other that only quantum mechanics reconciles them. Can we indeed derive quantum mechanics, at least in part, from these two axioms? No: “PR-box” correlations show that quantum correlations are not the most nonlocal correlations consistent with relativistic causality. Here we replace “nonlocality” with “retrocausality” and supplement the axioms of relativistic causality and retrocausality with a natural and minimal third axiom: the existence of a classical limit, in which macroscopic observables commute. That is, just as quantum mechanics has a classical limit, so must any generalization of quantum mechanics. In this limit, PR-box correlations violate relativistic causality. Generalized to all stronger-than-quantum bipartite correlations, this result is a derivation of Tarski’s bound (a theorem of quantum mechanics) from the three axioms of relativistic causality, retrocausality and the existence of a classical limit. Although the derivation does not assume quantum mechanics, it points to the Hilbert space structure that underlies quantum correlations.

1I thank the John Templeton Foundation (Project ID 43297) and the Israel Science Foundation (grant no. 1190/13) for support.

2Keywords: nonlocal correlations, quantum nonlocality, retrocausality, PR boxes, axioms for quantum mechanics, classical limit

12:51PM L44.00009 J-holomorphic maps and the uncertainty principle in geometric quantum mechanics . BARBARA SANBORN, Antioch College — The theory of geometric quantum mechanics describes a quantum system as a Hamiltonian dynamical system, with a complex projective Hilbert space as its phase space. The Kähler structure of the projective space provides quantum mechanics with a Riemannian metric in addition to the symplectic structure characteristic of classical mechanics. By including aspects of the symplectic topology of the quantum phase space, the geometric theory is extended and enriched. In particular, the quantum uncertainty principle is naturally expressed as an inequality from J-holomorphic map theory.
1:03PM L44.00010 A proposed physical analog for a quantum probability amplitude. JEFFREY BOYD, retired — What is the physical analog of a probability amplitude? All quantum mathematics, including quantum information, is built on amplitudes. Every other science uses probabilities; QM alone uses their square root. Why? This question has been asked for a century, but no one previously has proposed an answer. We will present cylindrical helices moving toward a particle source, which particles follow backwards. Consider Feynman’s book QED. He speaks of amplitudes moving through space like the hand of a spinning clock. His hand is a complex vector. It traces a cylindrical helix in Cartesian space. The Theory of Elementary Waves changes direction so Feynman’s clock faces move toward the particle source. Particles follow amplitudes (quantum waves) backwards. This contradicts wave particle duality. We will present empirical evidence that wave particle duality is wrong about the direction of particles versus waves. This involves a paradigm shift; which are always controversial. We believe that our model is the ONLY proposal ever made for the physical foundations of probability amplitudes. We will show that our probability amplitudes in physical nature form a Hilbert vector space with adjoints, an inner product and support both linear algebra and Dirac notation.

1:15PM L44.00011 Quantum enhanced estimation of a multi-dimensional field. ANIMESH DATTA, University of Warwick, TILLMANN BAUMGRATZ, University of Oxford — We present a framework for the quantum-enhanced estimation of multiple parameters corresponding to non-commuting unitary generators. We derive the quantum Fisher information matrix to put a lower bound on the total variance of all the parameters involved. We present the conditions for the attainment of the multi-parameter bound, which is not guaranteed unlike the quantum metrology of single parameters. Our study also reveals that too much quantum entanglement may be detrimental to attaining the Heisenberg scaling in the estimation of unitarily generated parameters. One particular case of our framework is the simultaneous estimation of all three components of a magnetic field. We propose a probe state that demonstrates that the simultaneous estimation of the three components is better than the precision of estimating the three components individually. We provide realistic measurements that come close to attaining the quantum limit, exhibiting the advantage of simultaneous quantum estimation even in the case of non-commuting generators. Our work applies to precision estimation any Hamiltonian, and may be employed in efficient process tomography and verification. Our theoretical proposal can be implement in any finite dimensional quantum system such as trapped ions and nitrogen vacancy centres in diamond.

1:27PM L44.00012 Fisher symmetry and the geometry of quantum states. JONATHAN A. GROSS, HOWARD BARNUM, CARLTON M. CAVES, Univ of New Mexico — The quantum Fisher information (QFI) is a valuable tool on account of the achievable lower bound it provides for single-parameter estimation. Due to the existence of incompatible quantum observables, however, the lower bound provided by the QFI cannot be saturated in the general multi-parameter case. A bound demonstrated by Gill and Massar (GM) captures some of the limitations that incompatibility imposes in the multi-parameter case. We further explore the structure of measurements allowed by quantum mechanics, identifying restrictions beyond those given by the QFI and GM bound. These additional restrictions give insight into the geometry of quantum state space and notions of measurement symmetry related to the QFI.

1:39PM L44.00013 Information Thermodynamics applied to the MERA quantum circuit. VASILIOS PASSIAS, VICTOR CHUA, APOORV TIWARI, SHINSEI RYU, University of Illinois at Urbana-Champaign — We interpret the MERA (Multiscale Entanglement Renormalization Ansatz) tensor network as a unitary quantum circuit to study excited state wavefunctions. Outputs of the quantum computation emanating from the Isometry tensors, which are normally approximate tensor product states, now fluctuate strongly. These “bulk” degrees of freedom in the MERA which act as logical qubits are studied using tools from quantum information theory and information thermodynamics. A local temperature scale based on Landauer’s information erasure principle is defined to measure their degree of fluctuation. We investigate properties of this temperature against the expectations of Luttinger’s theorem which relates weak field gravity to heat flow.

1:51PM L44.00014 The Dimensions of Emergent Spacetime in the Influence Network. KEVIN KNUTH, State Univ of NY - Albany — It has been previously demonstrated that the consistent quantification of a causally ordered set of events (influence network) with respect to observers represented by embedded chains results in a unique consistent quantification scheme that reproduces the Minkowski metric in the case of coordinated chains and Lorentz transformations in the case of linearly-related chains (Knuth and Bahreyni 2014). Here we demonstrate that quantification by multiple coordinated chains can only be consistent in the cases of two and four chains resulting in emergent 1+1 and 3+1 dimensional spacetimes, respectively. Odd numbers of chains are specifically ruled out and numbers of chains greater than four lead to a system that is not closed under chain permutation symmetry in a manner consistent with Galois theory. As a result, the spacetime framework that emerges from the consistent quantification of a causally ordered set of events with respect to embedded observers provides a potential foundation for emergent spacetime as well as an explanation as to the significance and nature of 3+1 spacetime dimensions.

2:03PM L44.00015 Locality and entanglement in bandlimited quantum field theory. JASON PYE, University of Waterloo, WILLIAM DONNELLY, University of California Santa Barbara, ACHIM KEMPF, University of Waterloo — We consider a model for a Planck scale ultraviolet cutoff which is based on Shannon sampling. Shannon sampling originated in information theory, where it expresses the equivalence of continuous and discrete representations of information. When applied to quantum field theory, Shannon sampling expresses a hard ultraviolet cutoff in the form of a bandlimitation. This introduces nonlocality at the cutoff scale in a way that is more subtle than a simple discretization of space: quantum fields can then be represented as either living on continuous space or, equivalently, as living on any one lattice whose average spacing is sufficiently small. We explicitly calculate vacuum entanglement entropies in 1+1 dimensions and we find a transition between logarithmic and linear scaling of the entropy, which is the expected 1+1 dimensional analog of the transition from an area to a volume law. We also use entanglement entropy and mutual information as measures to probe in detail the localizability of the field degrees of freedom. We find that, even though neither translation nor rotation invariance are broken, each field degree of freedom occupies an incompressible volume of space, indicating a finite information density.
discuss the impact of the decoherence on the single/two qubit operations and ways to reduce the gate errors for the addressable semiconductor spin qubit.

In a Si double quantum dot (DQD). In the large detuning regime, where the two qubit gate is operated, we find that the decoherence depends strongly on the Overhauser field fluctuation and improves the fidelity of two-qubit gates under charge noise. Additionally, we perform numerical pulse optimization to fully take the experimentally important imperfections into account, minimizing systematic errors and noise sensitivity. Since transferring the optimal control pulses to an experimental setting will inevitably incur systematic errors, we discuss how these errors can be calibrated on the experiment. [1] J. T. Muhonen, et.al. Nature Nanotechnol. 9, 986 (2014). [2] G. Tosì, et.al. arXiv:1509.08538 (2015).

12:51PM L45.00007 Valley dependent g-factor anisotropy in Silicon quantum dots, RIFAT FERDOUS, Purdue University, ERIKA KAWAKAMI, PASQUALE SCARLINO, MICHAL NOWAK, QuTech and Kavli Institute of Nanoscience, GERHARD KLIMECKE, Purdue University, MARK FRIESEN, SUSAN N. COPPERSMITH, MARK A. ERIKSSON, University of Wisconsin-Madison, LIEVEN M. K. VANDERSYPEN, QuTech and Kavli Institute of Nanoscience, RAJIB RAHMAN, Purdue University — Silicon (Si) quantum dots (QD) provide a promising platform for a spin-based quantum computer, because of the exceptionally long spin coherence times in Si and the existing industrial infrastructure. Due to the presence of an interface and a vertical electric field, the two lowest energy states of a Si QD are primarily composed of two conduction band valleys. Confinement by the interface and the E-field not only affect the charge properties of these states, but also their spin properties through the spin-orbit interaction (SOI), which differs significantly from the SO in bulk Si. Recent experiments have found that the g-factors of these states are different and dependent on the direction of the B-field. Using an atomistic tight-binding model, we investigate the electric and magnetic field dependence of the electron g-factor of the valley states in a Si QD. We find that the g-factors are valley dependent and show 180-degree periodicity as a function of an in-plane magnetic field orientation. However, atomic scale roughness can strongly affect the anisotropic g-factors. Our study helps to reconcile disparate experimental observations and to achieve better external control over electron spins in Si QD, by electric and magnetic fields.

1:03PM L45.00008 Strong spin relaxation anisotropy in a single-electron quantum dot, LIUQI YU, L. C. CAMENZIND, D. E. F. BIESINGER, University of Basel, J. ZIMMERMAN, A. C. GOSSARD, UCSB, D. M. ZUMBHL, University of Basel — Spin coherence and relaxation is of crucial importance in operating spin based qubits. In a magnetic field, spins relax predominantly through spin-phonon coupling mediated by spin-orbit interaction (SOI) [1]. Here we present measurements of the spin relaxation rate anisotropy in a gate defined single-electron GaAs quantum dot. The spin relaxation rate $\tau$ is measured at applied magnetic fields of 4 T in the plane of the 2D electron gas. W exhibits strong anisotropy: a sinusoidal dependence on the B-field angle $\varphi$ with a period of 180 degrees, as reported recently [2]. The extrema are observed at fields pointing nearly along the [110] and [10-1] crystal axes, modulated by a factor of about 14 from minimum to maximum. The periodicity is attributed to the interplay of Rashba and Dresselhaus SOIs. To decipher the role of SOI, we perform pulsed-gate spectroscopy to extract orbital excited-state energies, and obtain very good agreement with theory also for the angular dependence $\tau(m)$, indicating that $\alpha$ and $\beta$, Rashba and Dresselhaus coefficients respectively, have the same relative sign and are within 20% of each other. With controllable manipulations of the dot orbitals by varying gate voltages, it is possible to precisely extract values of $\alpha$ and $\beta$. Meanwhile, top- and back gates have been implemented on the device structure, which allows full electrical control over the Rashba SOI in the 2D electron gas [3]. [1] V. N. Golovach et al., Phys. Rev. Lett. 93, 016601 (2004). [2] P. Scarlino et al., Phys. Rev. Lett. 113, 256802 (2014). [3] F. Dettwiler et al., arXiv:1403.3518 (2014).

1:15PM L45.00009 Electron Spin Resonance Characterization of Damage and Recovery of Si/SiO$_2$ Interfaces from Electron Beam Lithography, JIN-SUNG KIM, ALEXEI TYRYSHKIN, STEPHEN LYON, Department of Electrical Engineering, Princeton University — Electron beam lithography (EBL) is an essential tool for the fabrication of few electron silicon quantum devices. However, high-energy electrons and photons from the EBL process create shallow traps and other defects at the Si/SiO$_2$ interface, inhibiting the control of electron populations through electrostatic gating. To reduce defect densities, high temperature and forming gas anneals are commonly used. We studied the effect of these anneals on the reduction of shallow traps created by EBL by fabricating two sets of large area (~1cm$^2$) MOSFETs and characterizing them using transport and electron spin resonance (ESR) measurements. One set was exposed to a typical EBL dosage (10kV, 40µC/cm$^2$) and the other remained unexposed. All MOSFETs were fabricated from the same commercially grown gate stack (30nm dry thermal oxide, 200nm amorphous silicon gate layer) and were annealed at 900C in N$_2$ and at 435C in forming gas. Our transport data indicate that these annealing steps recover the EBL exposed sample’s low temperature (4.2K) peak mobility to 85% of the unexposed sample’s. Additionally, our ESR data indicate that annealing the EBL exposed sample reduces its density of shallow traps (2-4eV) to the same density as the unexposed sample.

1:27PM L45.00010 Assessing MOS Interface Quality for Silicon Quantum Dot Device Fabrication, RYAN STEIN, Joint Quantum Institute, University of Maryland, JIN-SUNG KIM, STEVE LYON, Department of Electrical Engineering, Princeton University, NEIL M. ZIMMERMAN, M. D. STEWART, JR., National Institute of Standards and Technology — Defects at the Si-SiO$_2$ interface are capable of trapping electrons and degrading the operation of silicon-based quantum dot devices. To improve device performance, we are working to characterize the interface quality in MOSCAPs and MOSFETs fabricated at NIST by comparing industrial standard defect measurements, such as capacitance-voltage (CV), conductance, and mobility, to electron spin resonance (ESR) measurements. This comparison will give insight into the relative role of defects near the band edge and those distributed throughout the gap in degrading device performance. We will discuss our progress toward this goal as well as our latest data and interpretations.

1:39PM L45.00011 First-principles hyperfine tensors for electrons and holes in silicon and GaAs, PERICLES PHILIPPOPOULOS, McGill University, STEFANO CHESI, Beijing Computational Science Research Center, WILLIAM COISH, McGill University — Knowing (and controlling) hyperfine interactions in silicon and III-V semiconductor nanostructures is important for quantum information processing with electron and nuclear spins. We have performed density-functional theory (DFT) calculations that fully account for spin structure of the Bloch states (in contrast with approaches that rely on the density alone). Using this method, we confirm the known value for the contact hyperfine coupling in the conduction band of silicon, but find a significant deviation in the value for the conduction band of GaAs relative to the accepted value, estimated in ref. [1]. Moreover, this method can be used to calculate the full hyperfine tensor for the valence band, where spin-orbit effects may be strong, precluding methods that determine hyperfine couplings from the density alone. This general method can be applied to a broad class of materials with strong combined spin-orbit and hyperfine interactions. [1] D. Paget, G. Lampel, B. Sapoval, and V. I. Safarov Phys. Rev. B 15, 5780 (1977)

1:51PM L45.00012 Quantum quench dynamics of a central-spin system, ALESSANDRO RICOTTONE, WILLIAM COISH, McGill Univ, STEFANO CHESI, YINAN FANG, Beijing Computational Science Research Center — Quantum effects can significantly influence equilibration dynamics. In quantum annealing, a local tunneling mechanism may accelerate the approach to equilibrium. Similarily, long-range quantum coherence can allow for rapid transitions between macroscopically distinct states of a quantum system. An experimentally relevant example of this is given by a ‘central’ electron spin coupled to an ensemble of nuclear spins in a quantum dot. This system admits a superradiance-like burst of current through ferromagnetic leads due to long-range nuclear spin coherence [1] with a simultaneous inversion of the nuclear-spin polarization. Here, we study this system coupled to normal leads. In particular, we study quench dynamics of the nuclear spin polarization after passing through a quantum phase transition controlled by an applied magnetic field. As a function of dephasing controlled by a magnetic field gradient, we find a crossover from rapid equilibration via collective states to slow dynamics described by classical (product-state) spin configurations. This understanding may allow us to better control dynamic nuclear spin polarization processes in quantum dots and to control more general quantum states of nuclear-spin ensembles. [1] S. Chesi and W. A. Coish PRB 91, 245306 (2015)
The low temperature properties of glass are distinct from those of crystals due to the presence of poorly understood low-energy excitations. These are usually thought to be atoms tunneling between nearby equilibria, forming tunneling two level systems (TLSs). We discuss the electronic structure of the electrons bound at the corner, considering the effects due to the anisotropy of the effective mass, the splitting of valleys due to the confinement and the scattering at the interface, generalizing our results to corners of arbitrary angle. Our results indicate the optimal conditions for lifting the valley degeneracy, known to impact quantum coherence and control. We finally mention the expected impacts of this geometry on the tunnel and exchange coupling between dots at opposite corners of a wire.

EDDY COLLIN, Institut Néel, CNRS and Université Grenoble Alpes — The low temperature properties of glass are distinct from those of crystals due to the presence of poorly understood low-energy excitations. These are usually thought to be atoms tunneling between nearby equilibria, forming tunneling two level systems (TLSs). We discuss the electronic structure of the electrons bound at the corner, considering the effects due to the anisotropy of the effective mass, the splitting of valleys due to the confinement and the scattering at the interface, generalizing our results to corners of arbitrary angle. Our results indicate the optimal conditions for lifting the valley degeneracy, known to impact quantum coherence and control. We finally mention the expected impacts of this geometry on the tunnel and exchange coupling between dots at opposite corners of a wire.

ANDREW FEFFERMAN, Institut Néel, CNRS and Université Grenoble Alpes, XIAO LIU, THOMAS METCALF, GLENN JERNIGAN, Naval Research Laboratory, BATTOGTOKH JUGDERSUREN, Sotera Defense Solutions Inc., BRIAN KEARNEY, NRC Postdoctoral Associate, JAMES C. LEE, K. E. KOEHLER, ANDRE SARAIVA, BELITA KOILLER, Universidade Federal do Rio de Janeiro, M. FERNANDO GONZALEZ-ZALBA, Hitachi Cambridge Lab — Nanowire-based transistors, such as FinFETs and Tri-gate FETs, form one and zero dimensional systems at the corners. These corner states may be manipulated for quantum electronic applications, such as tunable quantum dot-based spin qubits. We discuss the electronic structure of the electrons bound at the corner, considering the effects due to the anisotropy of the effective mass, the splitting of valleys due to the confinement and the scattering at the interface, generalizing our results to corners of arbitrary angle. Our results indicate the optimal conditions for lifting the valley degeneracy, known to impact quantum coherence and control. We finally mention the expected impacts of this geometry on the tunnel and exchange coupling between dots at opposite corners of a wire.

1 This work is supported by Google inc.

11:27AM L48.00002 Characterizing and reducing microfabrication-induced loss in superconducting devices, Part II: Xmom qubits ANTHONY MEGRANT, Google, Santa Barbara, A. DUNSWORTH, UC Santa Barbara, J. KELLY, R. BAREND, Google, Santa Barbara, B. CAMPBELL, UC Santa Barbara, Y. CHEN, Google, Santa Barbara, Z. CHEN, B. CHIARO, UC Santa Barbara, A. FOWLER, E. JEFFREY, J. MUTUS, Google, Santa Barbara, C. NEILL, P.J.J. O’MALLEY, UC Santa Barbara, D. SANK, Google, Santa Barbara, A. VAINSENCHER, J. WENNER, UC Santa Barbara, T. WHITE, Google, Santa Barbara, J.M. MARTINIS, University of California and Google, Santa Barbara — Microfabrication-induced loss has previously been shown to limit the coherence times of both planar and 3-D superconducting qubits. Energy loss in these qubits arises from interactions with two-level state defects which are located in thin lossy surface dielectrics. More recently, we have identified a major source of this decoherence in superconducting qubits. Furthermore, we experimentally verified this dominant loss channel using a novel resonator based approach, which we call ‘Hydra’ resonators. We fully characterized and then substantially reduced this loss channel using these Hydra resonators. I will report on these measurements and their implications on improving the coherence of superconducting qubits.

11:39AM L48.00003 Supercritical Fluid Assisted Cleaning of Patterned Aluminum Microstructures for Removal of Post-Processing Residue and Surface Contamination. MARVIN G. WARNER, CHRISTOPHER A. BARRETT, CYNTHIA L. WARNER, Pacific Northwest National Laboratory, CHRISTOPHER J.K. RICHARDSON, NATHAN SIWAK, Laboratory for Physical Sciences, University of Maryland — We report the development of preliminary methods for the supercritical CO2 assisted removal of post-processing residue and surface contamination from delicate aluminum structures, such as those found in superconducting quantum circuits based on Josephson Junctions. These methods show promise for reducing processing time and improving the yield of high quality aluminum microstructures.

11:51AM L48.00004 Low temperature internal friction of amorphous silicon. XIAO LIU, THOMAS METCALF, GLENN JERNIGAN, Naval Research Lab, BATTGO TOKH JUGDERSUREN, Sotera Defense Solutions Inc., BRIAN KEARNEY, NRC Postdoctoral Associate, JAMES CULBERSTON, Naval Research Lab — The ubiquitous low-energy excitations, known as level-tunnelling systems (TLS), are one of the universal phenomena of amorphous solids. These excitations dominate the acoustic, dielectric, and thermal properties of structurally disordered solids. Using the double-paddle oscillator internal friction measurement technique, we have shown that TLS can be made to almost completely disappear in e-beam deposited amorphous silicon (a-Si) as the growth temperature increased to 400°C. However, there is a mysterious broad maximum in internal friction at 2-3K, which we suspect to come from metallic contamination of our oscillators and is not related to a-Si. Our new result of a-Si deposited in a different UVH system and on oscillators with a different type of metallic electrodes, confirms our suspicion. This lowers the upper bound of possible TLS content in a-Si, in terms of tunnelling strength, to below 10^-10 eV.

1 Work supported by the Office of Naval Research

12:03PM L48.00005 Elastic measurements of TLSs in amorphous silicon at mK temperatures. ANDREW FEFFERMAN, Institut Néel, CNRS and Université Grenoble Alpes, XIAO LIU, THOMAS METCALF, GLENN JERNIGAN, Naval Research Laboratory, EDDY COLLIN, Institut Néel, CNRS and Université Grenoble Alpes — The low temperature properties of glass are distinct from those of crystals due to the presence of poorly understood low-energy excitations. These are usually thought to be atoms tunneling between nearby equilibria, forming tunneling two level systems (TLSs). Elastic measurements on amorphous silicon films deposited with e-beam evaporation showed that this material contains a variable density of TLSs that decreases as the growth temperature increases from 45 to 400 deg C. [1]. We will present an analysis of the elastic properties of these films down to the low mK range in the framework of the standard tunneling model. [1] X. Liu, D. R. Queen, T. Metcalf, J. Karel and F. Hellman, Phys. Rev. Lett., 113, 025503 (2014)
TiN samples investigated at 100 mK exhibited no significant changes in linewidth when operated without magnetic shielding. Qubits often minimize TLS effects by choosing optimal device geometries. We have previously investigated methods to electrically sweep the energy of a bath of TLSs and control their excited-state population. Here we discuss a qubit design that incorporates a similar control over the TLSs, and which may prove to minimize TLS decoherence effects. In this device the qubit energy can remain constant while the TLS bath is dynamically controlled. We will discuss experimental progress towards realizing this qubit.

This research was supported by the ARO.

Fabrication and characterization of highly disordered TiN thin films by reactive evaporation for circuit-QED. YEN-HSIANG LIN, RAYMOND MENCIA, BAOLONG NGUYEN, VLADIMIR MANUCHARYAN, University of Maryland - College Park — Titanium nitride (TiN) has been identified as one of the potentially new materials for circuit-QED. In particular, disordered TiN films close to superconductor-insulator transition can be beneficial to greatly enhance kinetic inductance due to low superfluid density. Here we report TiN thin films prepared by e-beam evaporation within a nitrogen rich environment. By controlling nitrogen gas flow rate, the normal sheet resistance of TiN film can be tuned higher than 1kΩ while superconductivity still remains above 2K. Here, we present our characterization results and microwave measurement of quality factor Q and kinetic inductance L.

This work is sponsored in part by the Laboratory for Physical Science, IARPA, and the Assistant Secretary of Defense for Research and Engineering under Air Force Contract FA8721-05-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

Anomalous thickness dependence of quality factor in TiN film resonators grown on functionalized Si substrates. PENG XU, TIM KOHLER, Laboratory for Physical Sciences, EVGENIYA LOCK, Naval Research Laboratory, YANIV ROSEN, ARUNA RAMANAYAKA, SAMARESH GUCHAR, KEVIN OSBORN, Laboratory for Physical Sciences — Various properties affect the quality factor of superconducting resonators at millikelvin temperatures including the presence of nanoscale interfacial dielectric films and residual quasiparticles. Superconducting titanium nitride is polycrystalline such that growth phases may also affect the resonator quality. Here, we functionalize Si substrates in different hydrophobic and hydrophilic plasma environments, sputter titanium nitride on top and pattern the latter films into resonators. For each functionalization we study the quality factor dependence on the superconducting film thickness, where the thicknesses are changed only between 25 and 50 nm. As expected, most functionalizations reveal very little quality factor dependence on superconducting film thickness. However, other functionalizations dramatically, and even anomalously, increase or decrease the quality factor with thickness. For example, oxygen plasma functionalization causes the quality factor to increase by a factor of more than ten at single photon power with increased thickness. We report on the progress towards finding the intrinsic reason for strong quality factor dependences on surface functionalization.

This research was supported by the ARO and IARPA.
logical qubit memory, of the combinations of bit flip and phase flip errors. The presentation will review the experimental progress that recently occurred in the field of superconducting quantum circuits towards the correction, for a full question is the starting point of the main challenges in the construction of a scalable quantum computer, namely the implementation of quantum error correction.

Flammia, University of Sydney

1:39PM L48.00013 Characterizing the performance of waveguide technologies for microwave-frequency quantum communication, PHILIPP KURPIERS, TOBIAS FREY, ANDREAS WALLRAFF, ETH - Zurich — In circuit quantum electrodynamics (QED) systems quantum communication over distances beyond chip-scale requires low-loss waveguides. We measure the loss per unit length and the phase stability of commercially available waveguide technologies down to Millikelvin temperatures and single photon levels. More specifically, we characterize the frequency dependent attenuation and dispersion properties of a range of semi-rigid microwave cables and waveguides. We study the properties of various, commonly used conducting and dielectric materials with high accuracy in resonant structures to extract the internal quality factor which is inversely proportional to the loss per unit length. Furthermore, we compare our data with corresponding loss models. The results of our characterization are relevant to applications in which quantum communication is needed between nodes of a small network, e.g., between quantum circuits realized on different chips within the same or in distinct cryogenic systems.

The theory of quantum error-correcting codes has bolstered our confidence that quantum computing is scalable, deepened our understanding of topological phases of matter, and spawned novel insights into the quantum structure of spacetime.

1:51PM L48.00014 Spectrum of a Resonator Coupled to a Driven Superconducting Qubit in the Strong Dispersive Regime of Circuit Quantum Electrodynamics, YOUNK CHONG, HYUN-GUE HONG, DONG-GWANG HA, Korea Research Institute of Standards and Science — The resonator spectrum in the strong dispersive coupling regime of circuit-QED has been a useful nondestructive indicator of a stationary qubit state. Here we present experimental observation of the further modification of the resonator spectrum as the qubit undergoes the dynamic transition by a resonant driving field. The quartet resonance associated with the polarized qubit is observed for the resonant driving at one-photon as well as the multi-photon transition in a 3D transmon qubit. The evolution of the resonance as a function of the driving power and the detuning of the driving field is well understood by a simple model which is based on the analytic diagonalization of Hamiltonian and described in terms of dressed states, Lamb shift, and AC Stark shift.

2:03PM L48.00015 Characterizing Ensembles of Superconducting Qubits, ADAM SEARS, JEFF BIRENBAUM, DAVID HOVER, DANNA ROSENBERG, STEVEN WEBER, JONILYN L. YODER, JAMIE KERMAN, MIT Lincoln Laboratory, SIMON GUSTAVSSON, ARCHANA KAMAL, FEI YAN, MIT, WILLIAM OLIVER, MIT Lincoln Laboratory — We investigate ensembles of up to 48 superconducting qubits embedded within a superconducting cavity. Such arrays of qubits have been proposed for the experimental study of Ising Hamiltonians, and efficient methods to characterize and calibrate these types of systems are still under development. Here we leverage high qubit coherence (> 70 µs) to characterize individual devices as well as qubit-qubit interactions, utilizing the common resonator mode for a joint readout. This research was funded by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA) under Air Force Contract No. FA8721-05-C-0002. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of ODNI, IARPA, or the US Government.

Wednesday, March 16, 2016 11:15AM - 2:15PM –

11:15AM L55.00001 Stability, topology, holography: The many facets of quantum error correction, JOHN PRESKILL, Caltech — Quantum error correction is a surprising and far-reaching concept, with many implications for science and technology. The theory of quantum error-correcting codes has bolstered our confidence that quantum computing is scalable, deepened our understanding of topological phases of matter, and spawned novel insights into the quantum structure of spacetime.

11:51AM L55.00002 Fault Tolerance in Small Experiments, DANIEL GOTTESMAN, Perimeter Inst for Theo Phys — Experiments are finally reaching the size and level of precise control where we can hope to see a truly fault-tolerant experiment within the next few years. I will give a proposal for a 5-qubit fault-tolerant experiment and discuss how to evaluate if an experiment has successfully demonstrated fault tolerance. I will also consider the possibility of using future fault-tolerant experiments to answer important questions about the interaction of fault-tolerant protocols with real experimental errors.

12:27PM L55.00003 Quantum Error Correction and the Future of Solid State Quantum Computing, DAVID DIVINCENZO, Forschungszentrum Juelich and RWTH Aachen — Quantum error correction (QEC) theory has provided a very challenging but well defined goal for the further development of solid state qubit systems: achieve high enough fidelity so that fault-tolerant, error-corrected quantum computation in networks of these qubits becomes possible. I will begin by touching on some historical points: initial work on QEC is actually more than 20 years old, and the landmark work of Kitaev in 1996 which established 2D lattice structures as a suitable host for effective error correction, has its roots in theoretical work in many-body theory from Wegner in the 1970s. I will give some perspective on current developments in the implementation of small fragments of the surface code. The surface-code concept has driven a number of distinct requirements, beyond the reduction of error rates below the 1/8 range, that are actively considered as experiments are scaled beyond the 10-qubit level.

1Work supported by ARO and YINQE.

1:03PM L55.00004 Quantum error correction with trapped ions, PHILIPP SCHINDLER, University of Innsbruck — Quantum computers promise exponential speed-up compared to their classical counterparts for certain problems. Unfortunately, the states required for quantum computation are fragile and lose their quantum properties with growing system size. In a milestone work, it has been shown that quantum error correction can overcome this problem and enable arbitrary long and arbitrary high quality quantum algorithms. However, current experiments are not able to fulfill the requirements to employ useful quantum error correction procedures. In this talk, I will first review past proof-of-principle experiments in trapped ion quantum information processors. Building on that, I will sketch a way towards a medium-sized trapped ion system that will be capable of running an error correction procedure that outperforms it constituents.

1:39PM L55.00005 Quantum error correction in superconducting circuits, MICHEL DEVORET, Yale University — Can we prolong the coherence of a two-state manifold in a complex quantum system beyond the coherence of its longest-lived component? This question is the starting point of the main challenges in the construction of a scalable quantum computer, namely the implementation of quantum error correction. The presentation will review the experimental progress that recently occurred in the field of superconducting quantum circuits towards the correction, for a full logical qubit memory, of the combinations of bit flip and phase flip errors.
A universal fault-tolerant gate set for the 5-qubit quantum code. THEODORE YODER, RYUJI TAKAGI, ISAAC CHUANG, Massachusetts Institute of Technology — While the smallest single-error correcting classical code encodes one bit in just three, the smallest such quantum code requires five qubits to protect one qubit. Yet, the 5-qubit quantum code is widely regarded as useless when it comes to encoded quantum computation, as it supports just one Pauli transversal gate, the $K = SH$ gate where $H$ is Hadamard and $S$ is the phase gate. However, transversal gates, though convenient, are not all there is to fault-tolerant computation. Here we develop non-transversal, fault-tolerant logical gates for the 5-qubit code of Steane, including logical controlled-$Z$ ($CZ$) and logical controlled-$\text{controlled-}Z$ ($C^2Z$). With $K$, we can then create fault-tolerant CNOT and Toffoli gates. Together, logical Toffoli and $K$ imply that the 5-qubit code is capable of universal, fault-tolerant quantum computation. Moreover, we achieve our results without magic states. Indeed, no ancillary qubits beyond those needed for error-correction are necessary in any of our fault-tolerant constructions. We also report fault-tolerance thresholds for our new gates, calculated by exact computer simulation. In some cases, our logical gates on the 5-qubit code have better thresholds than the analogous constructions on the next smallest quantum code, the 7-qubit code.

2:42PM P44.00002 Quantum fault-tolerant thresholds for universal concatenated schemes. CHRISTOPHER CHAMBERLAND, TOMAS JOCHYM-O’CONNOR, Institute for Quantum Computing, University of Waterloo, RAYMOND LAFLAMME, Institute for Quantum Computing, University of Waterloo, Perimeter Institute — Fault-tolerant quantum computation uses ancillary qubits in order to protect logical data qubits while allowing for the manipulation of the quantum information without severe losses in coherence. While different models for fault-tolerant quantum computation exist, determining the ancillary qubit overhead for competing schemes remains a challenging theoretical problem. In this work, we study the fault-tolerance threshold rates of different models for universal fault-tolerant quantum computation. Namely, we provide different threshold rates for the 105-qubit concatenated coding scheme for universal computation without the need for state distillation. We study two error models: adversarial noise and depolarizing noise and provide lower bounds for the threshold in each of these error regimes. Establishing the threshold rates for the concatenated coding scheme will allow for a physical quantum resource comparison between our fault-tolerant universal quantum computation model and the traditional model using magic state distillation.

2:54PM P44.00003 Critical parameters of a noise model that affect fault tolerant quantum computation on a single qubit. PAVITHRAN IYER, Univ of Sherbrooke, MARCUS P DA SILVA, Raytheon BBN Technologies, DAVID POULIN, Univ of Sherbrooke — In this work, we aim to determine the parameters of a single qubit channel that can tightly bound the logical error rate of the Steane code. We do not assume any a priori structure for the quantum channel, except that it is a CPTP map and we use a concatenated Steane code to encode a single qubit. Unlike the standard Monte Carlo technique that requires many iterations to estimate the logical error rate with sufficient accuracy, we use techniques to compute the complete effect of a physical CPTP map, at the logical level. Using this, we have studied the predictive power of several physical noise metrics on the logical error rate, and show, through numerical simulations with random quantum channels, that, on their own, none of the natural physical metrics lead to accurate predictions about the logical error rate. We then show how machine learning techniques help us to explore which features of a random quantum channel are important in predicting its logical error rate.

3:06PM P44.00004 Doubled Color Codes. SERGEY BRAVYI, IBM Watson Research Center — Combining protection from noise and computational universality is one of the biggest challenges in the fault-tolerant quantum computing. Topological stabilizer codes such as the 2D surface code can tolerate a high level of noise but implementing logical gates, especially non-Clifford ones, requires a prohibitively large overhead due to the need of state distillation. In this talk I will describe a new family of 2D quantum error correcting codes that enable a transversal implementation of all logical gates required for the universal quantum computing. Transversal logical gates (TLG) are encoded operations that can be realized by applying some single-qubit rotation to each physical qubit. TLG are highly desirable since they introduce no overhead and do not spread errors. It has been known before that a quantum code can have only a finite number of TLGs which rules out computational universality. Our scheme circumvents this no-go result by combining TLGs of two different quantum codes using the gauge-fixing method pioneered by Paetznick and Reichardt. The first code, closely related to the 2D color code, enables a transversal implementation of all single-qubit Clifford gates such as the Hadamard gate and the $\pi/2$ phase shift. The second code that we call a doubled color code provides a transversal T-gate, where $T$ is the $\pi/4$ phase shift. The Clifford+T gate set is known to be computationally universal. The two codes can be laid out on the honeycomb lattice with two qubits per site such that the code conversion requires parity measurements for six-qubit Pauli operators supported on faces of the lattice. I will also describe numerical simulations of logical Clifford+T circuits encoded by the distance-3 doubled color code. Based on a joint work with Andrew Cross.

3:42PM P44.00005 Efficiently simulable approximations to realistic incoherent and coherent errors and their application to threshold estimation. MAURICIO GUTIERREZ, KENNETH BROWN, Georgia Institute of Technology — Classical simulations of noisy stabilizer circuits are often used to estimate the threshold of a quantum error-correcting code (QECC). It is not completely clear how sensitive a code’s threshold is to the error model, and whether or not a Pauli channel (PC) is a good approximation for realistic non-stabilizer errors. Within the stabilizer formalism, it has been shown that for a single qubit more accurate approximations can be obtained by expanding the PC. We now examine the feasibility of employing these error approximations at the single-qubit level to obtain better estimates of a QECC’s threshold. We calculate the level-1 pseudo-threshold for the Steane $[[7,1,3]]$ code for several error models. At the logical level, the Pauli twisted channel (PTC) provides an extremely accurate approximation for incoherent channels. However, for coherent channels, the PTC severely underestimates the magnitude of the error. By computing the effective 1-qubit process matrix for the whole circuit at low error rates, it becomes clear that this behavior is due to the stronger persistence of off-diagonal entries in the coherent channels. Therefore, if the main source of error in the quantum system is coherent, reliable stabilizer simulations should employ expanded Clifford channels.

3:54PM P44.00006 Decoder for 3-D color codes. KUNG-CHUAN HSU, TODD BRUN, University of Southern California — Transversal circuits are important components of fault-tolerant quantum computation. Several classes of quantum error-correcting codes are known to have transversal implementations of any logical Clifford operation. However, to achieve universal quantum computation, it would be helpful to have high-performance error-correcting codes that have a transversal implementation of some logical non-Clifford operation. The 3-D color codes are a class of topological codes that permit transversal implementation of the logical $\pi/8$-gate. The decoding problem of a 3-D color code can be understood as a graph-matching problem on a three-dimensional lattice. Whether this class of codes will be useful in terms of performance is still an open question. We investigate the decoding problem of 3-D color codes and analyze the performance of some possible decoders.

4:06PM P44.00007 High-threshold decoding algorithms for the gauge color code, WILLIAM ZENG, Rigetti Computing, BENJAMIN BROWN, Niels Bohr Institute, University of Copenhagen — Gauge color codes are topological quantum error correcting codes on three dimensional lattices. They have garnered recent interest due to two important properties: (1) they admit a universal transversal gate set, and (2) their structure allows reliable error correction using syndrome data obtained from a measurement circuit of constant depth. Both of these properties make gauge color codes intriguing candidates for low overhead fault-tolerant quantum computation. Recent work by Brown et al. calculated a threshold of 0.31% for a particular gauge color code lattice using a simple clustering decoder and phenomenological noise. We show that we can achieve improved threshold error rates using the efficient Wootters and Loss Markov-chain Monte Carlo (MCMC) decoding. In the case of the surface code, the MCMC decoder produced a threshold close to that code’s upper bound. While no upper bound is known for gauge color codes, the thresholds we present here may give a better estimate.

4:18PM P44.00008 ABSTRACT WITHDRAWN —

4:30PM P44.00009 Potts glass reflection of the decoding threshold for qudit quantum error correcting codes1, 2, YI JIANG, University of California, Riverside, ALEXEY A. KOVALEV, University of Nebraska—Lincoln, LEONID P. PRYADKO, University of California, Riverside — We map the maximum likelihood decoding threshold for qudit quantum error correcting codes to the multicritical point in generalized Potts gauge glass models, extending the map constructed previously for qubit codes [1]. An n-qudit quantum LDPC code, where a qudit can be involved in up to m stabilizer generators, corresponds to a Zd Potts model with n interaction terms which can couple up to m spins each. We analyze general properties of the phase diagram of the constructed model, give several bounds on the location of the transitions, bounds on the energy density of extended defects (non-local analogs of domain walls), and discuss the correlation functions which can be used to distinguish different phases in the original and the dual models.

1 A A Kovalev and L P Pryadko, Quant. Inf. & Comp. 15, 0825 (2015).

4:42PM P44.00010 Fault-tolerant quantum computation in multiqubit block codes: performance and overhead1, 2, TODD BRUN, Univ of Southern California — Fault-tolerant quantum computation requires that quantum information remain encoded in a quantum error-correcting code at all times, that a universal set of logical unitary gates and measurements is available; and that the probability of an uncorrectable error is low for the duration of the computation. Quantum computation can in principle be scaled up to unlimited size if the rate of decoherence is below a threshold. The main constructions that have been studied involve encoding each logical qubit in a separate block (either a concatenated code or a block of the surface code), which typically requires thousands of physical qubits per logical qubit, if not more. To reduce this overhead, we consider using multiqubit codes to achieve much higher storage rates. We estimate performance and overhead for certain families of codes, and ask: how large a quantum computation can be done as a function of the decoherence rate for a fixed size code block? Finally, we consider remaining open questions and limitations to this approach.

1 This research was supported in part by the grants: NSF PHY-1415600 (AAK), NSF PHY-1416578 (LPP), and ARO W911NF-14-1-0272 (LPP)

4:54PM P44.00011 Numerical Simulation of Coherent Error Correction, DANIEL CROW, ROBERT JOYNT, MARK SAFFMAN, Univ of Wisconsin, Madison — A major goal in quantum computation is the implementation of error correction to produce a logical qubit with an error rate lower than that of the underlying physical qubits. Recent experimental progress demonstrates physical qubits can achieve error rates sufficiently low for error correction, particularly for codes with relatively high thresholds such as the surface code and color code. Motivated by experimental capabilities of neutral atom systems, we use numerical simulation to investigate whether coherent error correction can be effectively used with the 7-qubit color code. The results indicate that coherent error correction does not work at the 10-qubit level in neutral atom array quantum computers. By adding more qubits there is a possibility of making the encoding circuits fault-tolerant which could improve performance.

5:06PM P44.00012 Noise Estimation and Adaptive Encoding for Asymmetric Quantum Error Correcting Codes1, 2, JAN FLORJANCZYK, TODD BRUN, Univ of Southern California, CENTER FOR QUANTUM INFORMATION SCIENCE AND TECHNOLOGY TEAM — We present a technique that improves the performance of asymmetric quantum error correcting codes in the presence of biased qubit noise channels. Our study is motivated by considering what useful information can be learned from the statistics of syndrome measurements in stabilizer quantum error correcting codes (QECC). We consider the case of a qubit dephasing channel where the dephasing axis is unknown and time-varying. We are able to estimate the dephasing angle from the statistics of the standard syndrome measurements used in stabilizer QECC’s. We use this estimate to rotate the computational basis of the code in such a way that the most likely type of error is covered by the highest distance of the asymmetric code. In particular, we use the [[15, 1, 3]] shortened Reed-Muller code which can correct one phase-flip error but up to three bit-flip errors. In our simulations, we tune the computational basis to match the estimated dephasing axis which in turn leads to a decrease in the probability of a phase-flip error. With a sufficiently accurate estimate of the dephasing axis, our memory’s effective error is dominated by the much lower probability of four bit-flips.

1 ARO MURI Grant No. W911NF-11-1-0268

5:18PM P44.00013 Details of [[7,1,3]] Syndrome Measurements, YAAKOV WEINSTEIN, MITRE — We explore different aspects of syndrome measurements (SM) for the [[7,1,3]] quantum error correction code. This includes determining how often to apply SM, comparing the performance of different SM, rearranging the order in which SM are applied, and exploring the effects of improving SM ancilla state construction. Finally, we attempt to formulate gates and their attached SM as superoperators.

2:30PM P45.00001 Nuclear-driven electron spin rotations in a coupled silicon quantum dot and single donor system, PATRICK HARVEY-COLLARD, Univ of Sherbrooke, NOAH TOBIAS JACOBSON, MARTIN RUDOLPH, GREGORY A. TEN EYEK, JOEL R. WENDT, TAMMY PLUYM, MICHAEL P. LILLY, Sandia National Laboratories, MICHEL PIORO-LADRIERE, Univ of Sherbrooke, MALCOLM S. CARROLL, Sandia National Laboratories — Single donors in silicon are very good qubits. However, a central challenge is to couple them to one another. To achieve this, many proposals rely on using a nearby quantum dot (QD) to mediate an interaction. In this work, we demonstrate the coherent coupling of electron spins between a single $^{31}$P donor and an enriched $^{29}$Si metal-oxide-semiconductor few-electron QD. We show that the electron-nuclear spin interaction can drive coherent rotations between singlet and triplet spin states. Moreover, we are able to tune electrically the exchange interaction between the QD and donor electrons. The combination of single-nucleus-driven rotations and voltage-tunable exchange provides all elements for future all-electrical control of a spin qubit, and requires only a single dot and no additional magnetic field gradients. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U. S. Department of Energy (DOE) Office of Science. 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. DOE’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

2:42PM P45.00002 All-electrical control of a singlet-triplet qubit coupled to a single nuclear spin 1, N. TOBIAS JACOBSON, Sandia National Laboratories, PATRICK HARVEY-COLLARD, Sandia National Laboratories and Université de Sherbrooke, ANDREW BACZEWSKI, JOHN GAMBLE, MARTIN RUDOLPH, ERICK NIELSEN, RICHARD MULLER, MALCOLM CARROLL, Sandia National Laboratories — Donor nuclear spins in isotopically purified silicon have very long coherence times, suggesting that they may form high-quality quantum memories. We propose that coupling these nuclear spins to few-electron quantum dots could enable nuclear spin readout and two-qubit operations of the joint quantum dot and nuclear spin system without the need for electron spin resonance. As a step towards this goal, our group recently demonstrated coherent singlet/triplet electron spin rotations induced by the hyperfine interaction between electronic spin degrees of freedom and a single nuclear spin in isotopically purified silicon. In this talk, I will discuss the feasibility of universal all-electrical control of such a singlet/triplet electron spin qubit and explore the decoherence mechanisms that we expect to dominate. Finally, I will examine the relative merits of AC and pulsed DC gating schemes.

2:54PM P45.00003 Full Controllability of a Singlet-Triplet Qubit Coupled to a Nuclear Spin Qubit, ANDREW D. BACZEWSKI, JOHN KING GAMBLE, N. TOBIAS JACOBSON, RICHARD P. MULLER, ERICK NIELSEN, STEPHEN M. CARR, MALCOLM S. CARROLL, Sandia National Laboratories, MATTHEW CURRY, Sandia National Laboratories and University of New Mexico, PATRICK HARVEY-COLLARD, Sandia National Laboratories and Université de Sherbrooke, RYAN M. JOCK, MARTIN RUDOLPH, Sandia National Laboratories — Recent experimental developments indicate that it is possible to drive coherent singlet-triplet rotations in a MOS quantum dot coupled to a single nearby phosphorus donor through the electron-nuclear hyperfine interaction. With the addition of NMR, we propose that it is possible to achieve universal 2-qubit control spanning i.) an electronic singlet-triplet subspace of the dot, ii.) the spin-1/2 donor nucleus, and iii.) entangling operations between them. We will assess the practicality of such an approach given realistic experimental conditions and constraints, including a comparison of pulsed and RF control of the detuning between the donor and dot. 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.

3:06PM P45.00004 Transport through an impurity tunnel coupled to a Si/SiGe quantum dot, RYAN H. FOOTE, DANIEL R. WARD, University of Wisconsin-Madison, J.R. PRANCE, Lancaster University, JOHN KING GAMBLE, ERICK NIELSEN, Sandia National Laboratories, BRANDUR THORGRIMSSON, D.E. SAVAGE, University of Wisconsin-Madison, A.L. SARAIVA, Universidade Federal do Rio de Janeiro, MARK FRIESEN, S.N. COPPERSMITH, M.A. ERIKSSON, University of Wisconsin-Madison — Here we present measurements of transport through a gate-defined quantum dot formed in a Si/SiGe heterostructure, demonstrating controllable tunnel coupling between the quantum dot and a localized electronic state. Combining experimental stability diagram measurements with 3D capacitive modeling based on the expected electron density profiles, we determine the most likely location of the localized state in the quantum well. This work is supported in part by NSF (DMR-1206915, IIA-1132804), ARO (W911NF-12-1-0607) and the William F. Vilas Estate Trust. Development and maintenance of the growth facilities used for fabricating samples supported by DOE (DE-FG02-03ER46028). This research utilized facilities supported by the NSF (DMR-0832760, DMR-1121288). The work of J.K.G. and E.N. was 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.

3:18PM P45.00005 Silicon quantum dots with counted antimony donor implants, MEENAKSHI SINGH, JOSE PACHECO, DANIEL PERRY, JOEL WENDT, RONALD MANGINEL, JASON DOMINGUEZ, TAMMY PLUYM, DWIGHT LUHMAN, EDWARD BIELEJEJ, MICHAEL LILLY, MALCOLM CARROLL, Sandia National Laboratory — Antimony donor implants next to silicon quantum dots have been detected with integrated solid-state diode detectors with single ion precision. Devices with counted number of donors have been fabricated and low temperature transport measurements have been performed. Charge offsets, indicative of donor ionization and coupling to the quantum dot, have been detected in these devices. The number of offsets corresponds to 10-50% of the number of donors counted. We will report on tunneling time measurements and spin readout measurements on the donor offsets. 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 Sandia National Laboratories Directed Research and Development Program. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U.S. Department of Energy under Contract No. DE-AC04-94AL85000.

3:30PM P45.0006 Detection of ion implanted patterns in silicon using STM, HYUN-SOO KIM, Univ of Maryland-College Park, A.N. RAMANAYAKA, Joint Quantum Institute, Univ of Maryland-College Park, K.J. DWYER, Univ of Maryland-College Park, M.D. STEWART JR., J.M. POMEROY, National Institute of Standards and Technology — Ion implanted regions in silicon are scanned using STM to detect features which will facilitate in-situ overlay and alignment of STM hydrogen patterned nano-devices. STM hydrogen lithography is used to make atomically precise devices such as single electron transistors and single atom qubits. However, with currently available imaging techniques, we are limited to make devices on a single plane using STM lithography. In-situ detection of high local doping concentrations using STM will allow precise alignment between the multiple layers of buried nano-devices and metal electrodes.
Atomic Simulations of negatively charged donor states probed in STMs

3:42PM P45.00007

GERHARD KLIMECK, RAJIB RAHMAN, Purdue University, USA — A single donor in silicon binding two electrons (D−) is important for electron spin readout in two-qubit operations in a donor based silicon (Si) quantum computer, and has recently been probed in Scanning Tunneling Microscope (STM) experiments for sub-surface dopants. In this work, atomistic configuration interaction technique is used to compute the two-electron states of the donor taking into account the geometry of the STM-vacuum-silicon-reservoir device. While 45 meV charging energy is obtained for D− in bulk Si, the electrostatics of the device reduces the charging energy to 30 meVs. It is also shown that the reduced charging energy enables spin triplet states to be bound to the donor. The exchange splitting between the singlet and triplet states can be tuned by an external electric field. The computed wavefunctions of the D− state helps to understand how the contribution of the momentum space valley states change with donor depth and electric field.

Atomic Precision Donor Devices Fabricated on Strained Silicon on Insulator (sSOI) with SiGe

3:54PM P45.00008

ARCHANA TANKASALA, Purdue University, USA, JOE SALFI, SVEN ROGGE, CQCCT, University of New South Wales, Australia, GERHARD KLIMECK, RAJIB RAHMAN, Purdue University, USA — A single donor in silicon binding two electrons (D−) experiments, ARCHANA TANKASALA, Purdue University, USA, JOE SALFI, SVEN ROGGE, CQCCT, University of New South Wales, Australia, GERHARD KLIMECK, RAJIB RAHMAN, Purdue University, USA, are comparable to the values reported using the RF techniques. 10 with a bandwidth of 1 MHz, corresponding to a single-shot time-domain charge-sensitivity of approximately 10−14 e/cm2/√Hz. SET and discrete HBT in an integrated package mounted to the mixing chamber stage of a dilution refrigerator. We experimentally demonstrate a SNR of up to 100 cm2/√Vs (T=4K) similar to results reported relaxed SiI reported elsewhere. Second, we have grown our concept epitaxial SiGe/sSOI stack, evaluated the morphology using STM, and fabricated Hall devices to evaluate low-T transport in our first SiGe/sSOI. Here, we report on these advances in atomic precision donor fab, along with STM analysis our MBE SiGe/sSOI. This work extends STM-based atom precision fab on strained Si toward a vertically gated architecture.

Low-frequency conductance fluctuations in SiP and GeP δ-layers

4:06PM P45.00009

SAQUIB SHAMIM, Department of Physics, Indian Institute of Science, Bangalore 560 012, India, SUDDHASATTA MAHAPATRA, GIORDANO SCAPPUCCI1, W. M. KLESSE, MICHELLE Y. SIMMONS, Centre for Quantum Computation and Communication Technology, University of New South Wales, Sydney NSW 2052, Australia, ARINDAM GHOSH, Department of Physics, Indian Institute of Science, Bangalore 560 012, India — Delta doped Si:P and Ge:P devices offer a formidable platform for application towards quantum computation. The fabrication of single donor devices by STM-lithography takes us forward to address the solid state quantum bits. The atomic scale control however makes the devices extremely sensitive to fluctuations and disorder which affect their long term stability. Hence, a study of low frequency 1/f noise for these devices is desirable. We measure 1/f noise in Si:P and Ge:P δ-layers of varying doping density. Fluctuations in conductivity arise due to fluctuations in mobility and the Hooge parameter scales inversely with mobility as 1/μ3 for all devices. For highly doped Ge:P δ-layer, the noise magnitude in a perpendicular magnetic field (B⊥) reduces by factors of two at the phase breaking field and the Zeeman field indicating universal conductance fluctuations (UCF). The phase breaking length l⊥ extracted by fitting the B⊥ dependence of noise to the crossover function matches well with l⊥ extracted from weak localization (WL) fits to magnetoconductivity indicating that both UCF and WL are governed by same scattering rates.

Weak measurement and quantum steering of spin qubits in silicon

4:18PM P45.00010

ANDREA MORELLO, JUHA MUHONEN1, STEPHANIE SIMMONS2, SOLOMON FREER, JUAN DEHOLLAIN, UNSW Australia, JEFFREY MCCALLUM, DAVID JAMIESON, Univ Melbourne, KOHEI ITOH, Keio University, ANDREW DZURAK, UNSW Australia — Single-shot, projective measurements have been demonstrated with very high fidelities on both the electron [1] and the nuclear [2] spin of single implanted phosphorus (1P) donors in silicon. Here we present a series of experiments where the measurement strength is continuously reduced, giving access to the regime of weak measurement of single spins. For the electron qubit, the measurement strength is set by the measurement time compared to the spin-dependent tunneling time between the 31P donor and a charge reservoir. For the nuclear qubit, the measurement strength is set by the rotation angle of an ESR pulse. We have demonstrated quantum steering of the spin states, with curious and useful applications. We can improve the fidelity of electron qubit initialization by steering it towards the ground state, thus bypassing thermal effects on the initialization process. We can also accurately measure the electron-reservoir tunnel coupling, without the electron ever tunneling away from the 31P atom. Finally, these techniques allow the study of weak values and Leggett-Garg inequalities.

Weak measurement and quantum steering of spin qubits in silicon

1A. Morello et al., Nature 467, 687 (2010)

Single-Shot Charge Readout Using a Cryogenic Heterojunction Bipolar Transistor Preamplifier Inline with a Silicon Single Electron Transistor at Millikelvin Temperatures

4:30PM P45.00011

MATTHEW CURRY, University of New Mexico, TROY ENGLAND, JOEL WENDT, TAMMY PLUYM, MICHAEL LILLY, STEPHEN CARR, MALCOLM CARROLL, Sandia National Laboratories — Single-shot readout is a requirement for many implementations of quantum information processing. The single-shot readout fidelity is dependent on the signal-to-noise-ratio (SNR) and bandwidth of the readout detection technique. Several different approaches are being pursued to enhance read-out including RF-reflectometry, RF-transmission, parametric amplification, and transistor-based cryogenic preamplification. The transistor-based cryogenic preamplifier is attractive in part because of the reduced experimental complexity compared with the RF techniques. Here we present single-shot charge readout using a cryogenic Heterojunction-Bipolar-Transistor (HBT) inline with a silicon SET charge-sensor at millikelvin temperatures. For the relevant range of HBT DC-biasing, the current gain is 100 to 2000 and the power dissipation is 50 nW to 5 μW, with the microfabricated SET and discrete HBT in an integrated package mounted to the mixing chamber stage of a dilution refrigerator. We experimentally demonstrate a SNR of up to 10 with a bandwidth of 1 MHz, corresponding to a single-shot time-domain charge-sensitivity of approximately 10−14 e/√Hz. This measured charge-sensitivity is comparable to the values reported using the RF techniques.

1Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.
A microsecond long. Several example unitary operations addressing the first 8 levels of the resonator are described and characterized. Control methods allow us to manipulate the combined cavity–transmon system on a time-scale of order 1/\chi, the dispersive shift; in practice pulses of about this direction. Due to the linearity of harmonic oscillators it is not directly obvious how to manipulate them. Here we show that pulses designed using optimal be used to encode multiple bits of quantum information. The long lifetime of superconducting cavity resonators make them a suitable candidate to explore a unitary operation on the Hilbert space of our superconducting resonator truncated to 8 levels can be performed using a pulse of around a microsecond. We show that full control of the resonator is possible on a time-scale of order 1/\chi, the dispersive shift. In practice this means that the occupation of the quantum dot system down to the few-electron limit. We measure the change stability of the DQD in DC transport as well as dispersively via in situ gate-based radio frequency (rf) reflectometry, where one top-gate electrode is connected to a resonator. The latter removes the need for external charge sensors in quantum computing architectures and provides a compact way to readout the dispersive shift caused by changes in the quantum capacitance during inter-dot charge transitions. Here, we observe Pauli spin-blockade in the rf response of the circuit at finite magnetic fields between singlet and triplet states. The blockade is lifted at higher magnetic fields when intra-dot triplet states become the ground state configuration. A line shape analysis of the dispersive signal reveals furthermore an intra-dot valley-orbit splitting $\Delta_{kv} \approx 145\mu$eV. Our results open up the possibility to operate compact CMOS technology as a singlet-triplet qubit and make split-gate silicon nanowire architectures an ideal candidate for the study of spin dynamics.

5:06PM P45.00014 Characterization and Monte Carlo simulation of single ion Geiger mode avalanche diodes integrated with a quantum dot nanostructure, J. B. S. ABRAHAM, G. TEN EYCK, K. D. CHILDS, E. BIELEJEC, M. S. CARROLL, Sandia National Laboratories — Detection of single ion implantation within a nanostructure is necessary for the high yield fabrication of implanted donor-based quantum computing architectures. Single ion Geiger mode avalanche (SIGMA) diodes with a laterally integrated nanostructure capable of forming a quantum dot were fabricated and characterized using photon pulses. The detection efficiency of this device was measured as a function of wavelength, lateral position, and for varying delay times between the photon pulse and the orbitas detection window. Monte Carlo simulations based only on the random diffusion of photo-generated carriers and the geometrical placement of the avalanche region agrees qualitatively with device characterization. Based on these results, SIGMA detection efficiency appears to be determined solely by the diffusion of photo-generated electron-hole pairs into a buried avalanche region. Device performance is then highly dependent on the uniformity of the underlying silicon substrate and the proximity of photo-generated carriers to the silicon-silicon dioxide interface, which are the most important limiting factors for reaching the single ion detection limit with SIGMA detectors. 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.

5:18PM P45.00015 Joint measurement of electron spin qubits via proximal conductance, JASON KESTNER, Department of Physics, UMBC — We propose a method to carry out joint measurements on spin qubits that are separated by several microns. Joint measurements, which reveal multi-qubit properties without determining anything about the individual qubits, are a key ingredient to performing quantum error correction and to producing measurement-based entanglement of non-interacting qubits. We presume that the qubits are capacitively coupled to a common conductance channel that are separated by a distance less than the phase coherence length of the semiconductor, and we calculate the tolerance of the procedure to various experimental imperfections. Conditions for carrying out $N$-qubit syndrome measurements are discussed.

Wednesday, March 16, 2016 2:30PM - 5:30PM –
Session P48 GQI: Quantum Control in Superconducting Circuits

2:30PM P48.00001 Quantum Control of Cavity Resonators, Part I: Control Algorithms, PHILIP REINHOLD, REINIER HEERES, NISSIM OFEK, KATRINA SLIWA, Yale University, MICHAEL HATRIDGE, University of Pittsburgh, STEFAN KRASTANOV, LIANG JIANG, LUIGI FRUNZIO, MICHEL DEVORET, ROBERT SCHOELKOPF, Yale University — Harmonic oscillators are linear systems with equally spaced energy levels, which makes them hard to control. We have previously explored a constructive control approach mediated by a far-off-resonantly coupled two-level ancilla. Here we present an extension to that method which relies on optimal control algorithms to allow much more efficient quantum control of a combined resonator ancilla system. We show that full control of the resonator is possible on a time-scale of order 1/\chi, the dispersive shift. In practice this means that a unitary operation on the Hilbert space of our superconducting resonator truncated to 8 levels can be performed using a pulse of around a microsecond.

2:42PM P48.00002 Quantum Control of Cavity Resonators, Part II: Experiment, REINIER HEERES, PHILIP REINHOLD, NISSIM OFEK, KATRINA SLIWA, Yale University, MICHAEL HATRIDGE, University of Pittsburgh, STEFAN KRASTANOV, LIANG JIANG, LUIGI FRUNZIO, MICHEL DEVORET, ROBERT SCHOELKOPF, Yale University — Harmonic oscillators offer a large Hilbert space that can potentially be used to encode multiple bits of quantum information. The long lifetime of superconducting cavity resonators make them a suitable candidate to explore this direction. Due to the linearity of harmonic oscillators it is not directly obvious how to manipulate them. Here we show that pulses designed using optimal control methods allow us to manipulate the combined cavity−transmon system on a time-scale of order 1/\chi, the dispersive shift; in practice pulses of about a microsecond long. Several example unitary operations addressing the first 8 levels of the resonator are described and characterized.
2:54PM P48.00003 Optimal control of single flux quantum (SFQ) pulse sequences, PER LIEBERMANN, FRANK WILHELM, Saarland University — Single flux quantum (SFQ) pulses are a natural candidate for on-chip control of superconducting qubits. High accuracy quantum gates are accessible with quantum optimal control methods. We apply trains of SFQ pulses to operate single qubit gates, under the constraint of fixed amplitude and duration of each pulse. Timing of the control pulses is optimized using genetic algorithms and simulated annealing, decreasing the average fidelity error by several orders of magnitude. Furthermore, we are able to reduce the gate time to the quantum speed limit. Leakage out of the qubit subspace as well as timing errors of the pulses are considered, exploring the robustness of our optimized sequence. This takes us one step further to a scalable quantum processor. [1] R. McDermott and M. G. Vavilov, Phys. Rev. Appl. 2, 014007 (2014)

3:06PM P48.00004 Robust Control of a Two-Qubit Operation in 3D Circuit Quantum Electrodynamics, JOSEPH ALLEN, ATI, University of Surrey, ROBERT KOSUT, SC Solutions, Inc., JAEWOO JOO, ERAN GINOSSAR, ATI, University of Surrey — Superconducting qubits have shown great improvement in coherence times with the introduction of 3D cavities. In order to control the qubits in 3D a microwave drive is usually coupled to the common mode of the cavity, which makes individual addressability a challenge and causes additional unwanted single and two-qubit dynamics when performing two qubit operations. Quantum information processing requires precise control of the system dynamics in the presence of potential uncertainties in the estimated system parameters. We use optimal control theory to develop pulse shapes that are able to implement an all-microwave two-qubit gate, while mitigating extra unwanted interaction terms, with $F = 0.9964$. In addition, we develop pulses which are robust to errors in the two qubit transition frequencies. This is demonstrated with experimentally relevant parameters and includes realistic constraints in the possible pulse shapes, presenting pulses that can be implemented in experiment.

3:18PM P48.00005 Gradient Optimization for Analytic controls - GOAT, ELIE ASSEMEN, Saarland University, SHAI MACHNES, DAVID TANNOR, Weizmann Institute of Science, FRANK WILHELM-MAUCH, Saarland University — Quantum optimal control becomes a necessary step in a number of studies in the quantum realm. Recent experimental advances showed that superconducting qubits can be controlled with an impressive accuracy. However, most of the standard optimal control algorithms are not designed to manage such high accuracy. To tackle this issue, a novel quantum optimal control algorithm has been introduced: the Gradient Optimization for Analytic controls (GOAT). It avoids the piecewise constant approximation of the control pulse used by standard algorithms. This allows an efficient implementation of very high accuracy optimization. It also includes a novel method to compute the gradient that provides many advantages, e.g., the absence of backpropagation or the natural route to optimize the robustness of the control pulses. This talk will present the GOAT algorithm and a few applications to transmon systems.

3:30PM P48.00006 Fast resonator reset in circuit QED using open quantum system optimal control, SAMUEL BOUTIN, Département de Physique, Université de Sherbrooke, CHRISTIAN Kraglund ANDERSEN, Department of Physics and Astronomy, Aarhus University, JAYAMEENKASHI VENKATRAMAN, Department of Physics, Indian Institute of Technology Kanpur, ALEXANDRE BLAIS, Département de Physique, Université de Sherbrooke and Canadian Institute for Advanced Research — Practical implementations of quantum information processing requires repetitive qubit readout. In circuit QED, where readout is performed using a resonator dispersively coupled to the qubits, the measurement repetition rate is limited by the resonator reset time. This rate is usually performed passively by waiting several resonator decay times. Alternatively, it was recently shown that a simple pulse sequence allows to decrease the reset time to twice the resonator decay time [1]. In this work, we show how to further optimize the ring-down pulse sequence by using optimal control theory for open quantum systems. Using a new implementation of the open GRAPE algorithm that is well suited to large Hilbert spaces, we find active resonator reset procedures that are faster than a single resonator decay time. Simple quantum speed limits for this kind of active reset processes will be discussed. [1] McClure et al., arXiv 1503.01456

3:42PM P48.00007 ABSTRACT WITHDRAWN –

3:45PM P48.00008 Analysis of non-adiabatic effects in circuit QED measurement of a transmon, ERIC MILINAR, MOSTAFA KHEZRI, University of California, Riverside, JUSTIN DRESSEL, Chapman University, ALEXANDER N. KOROTKOV, University of California, Riverside — In a circuit QED setup with a transmon qubit dispersively coupled to a driven resonator, we investigate whether rapid resonator ringup will cause nonadiabatic effects that disturb the qubit state. We show that only unrealistically fast high-power pulses will produce significant deviations from adiabatic behavior, while typically the qubit-resonator dynamics is well described by coherent evolution in the joint eigenbasis. Nevertheless, even in typical parameter regimes we show that the qubit nonlinearity still produces a dynamical shearing effect that squeezes the state of the resonator field.

4:06PM P48.00009 A method of extracting operating parameters of a quantum circuit, EYO B A. SETE, MAXWELL BLOCK, MICHAEL SCHEER, CRIS ZANOCI, MEHRNOOSH VAHIDPOUR, DANE THOMPSON, CHAD RIGETTI, Rigetti Quantum Computing, Berkeley, CA — Rigorous simulation-driven design methods are an essential component of traditional integrated circuit design. We adapt these techniques to the design and development of superconducting quantum integrated circuits by combining classical finite element analysis in the microwave domain with Brune circuit synthesis by Solgun [PhD thesis 2014] and BKD Hamiltonian analysis by Burkard et al. [Phys. Rev. B 69, 064503 (2004)]. Using the Hamiltonian of the quantum circuit, constructed using the synthesized equivalent linear circuit and the nonlinear Josephson junctions’ contributions, we extract operating parameters of the quantum circuit such as resonance coupling strength, dispersive shift, qubit anharmonicity, and decoherence rates for single- and multi-port quantum circuits. This approach has been experimentally validated and allows the closed-loop iterative simulation-driven development of quantum information processing devices.

4:18PM P48.00010 Critical fluctuations near excitation threshold of a quantum parametric oscillator, M. I. DYKMAN, Michigan State University, Y. NAKAMURA, The University of Tokyo and CEMS RIKEN, Z. R. LIN, CEMS RIKEN — A weakly damped parametrically driven oscillator has several vibrational states already for weak driving. These are stable and unstable states with twice the modulation period and also the steady state. At the critical point all states merge. We show that this leads to anomalously strong quantum fluctuations. These fluctuations are similar whether the friction, in the classical picture, is linear or nonlinear. The critical region is $\propto h(2n+1)^{1/3}$ along the field frequency axis and $\propto [h(2n+1)]^{2/3}$ along the field amplitude axis, where $n\hbar$ is the Planck number. The correlation time scales as $\propto [h(2n+1)]^{-2/3}$. The number of photons for $\bar{n}=0$ scales as $h^{-2/3}$. It is determined by the oscillator nonlinearity and decay rate. Above the threshold, quantum fluctuations induce transitions between the period-two states over the quasenergy barrier. We find the effective quantum activation energies for such transitions and their scaling with the difference of the driving amplitude from its critical value. We also present the results of relevant experimental observations obtained with a circuit QED system.
Fluctuations of a parametric oscillator: from the semiclassical to a strongly quantum regime. YAXING ZHANG, MARK DYKMAN, Michigan State University — A semiclassical parametric oscillator has two dynamically stable vibrational states with equal amplitudes and with phases differing by \( \pi \). The rate of switching between these states is exponentially small, and the oscillator displays fluctuations with the reciprocal correlation time given by this rate. It also displays critical slowing down near the excitation threshold. The parameter of the “quantumness” is the ratio of the nonequidistance \( h\Gamma \) of the oscillator energy levels due to the nonlinearity and the level width \( h\Gamma' \) due to decay. In the strongly-quantum regime where \( \Gamma'/\Gamma \gg 1 \) and driving is not too strong, the picture of coexisting vibrational states with opposite phases does not apply. An insight into the transition from the semiclassical to strongly-quantum regime can be gained by studying the quasienergy spectrum and the decay of quantum fluctuations. An analogue of the critical slowing down in the strongly-quantum regime is a sharp increase of the fluctuation correlation time that occurs at a hypersurface in the oscillator parameter space. We find that the quasienergy spectrum and the ratio of the level spacing to their width also sensitively depend on the parameters, in particular on \( \Gamma'/\Gamma \).

Robust tomography of microwave resonator arrays for quantum simulation with light. AMAN LACHAPELLE, JOHN C OWENS, RUICHAO MA, JONATHAN SIMON, DAVID SCHUSTER, Univ of Chicago — We are interested in using a bottom-up approach to create topologically non-trivial states of light via Hamiltonian engineering in coupled microwave cavities. Characterization and reduction of disorder is paramount to realizing and studying idealized many-body Hamiltonians. Our tight-binding lattices are made of arrays of evanescently coupled three-dimensional microwave resonators. From the spectroscopic response measured at specific lattice sites, we develop methods to fully map out the underlying tight-binding Hamiltonian, including onsite energies, nearest-neighbor couplings and the local dissipation on all sites. We show that for a 1D system, one reflection measurement off of the site at the end of the chain is sufficient, while for 2D only measurements along one edge of the system is sufficient for complete tomography of the lattice Hamiltonian. The transmission between neighboring sites also reveals the phase of the tunnel coupling, thereby allow direct measurement of the flux in lattices with time-reversal breaking synthetic gauge fields. These methods can be readily applied to many other physical systems for the characterization of quantum processes or the validation of quantum simulators.

Analysis of qubit dynamics under strong resonant pulses using Floquet theory. CHUNQING DENG, FEIRUO SHEN, JEAN-LUC ORGIAZZI, University of Waterloo, SAHEL ASHSAH, Qatar Foundation, ADRIAN LUPASCU, University of Waterloo — Resonant driving is the most common way of implementing single-qubit gates in various quantum systems. Most of the experiments and optimization of such gates are performed in the weak-driving regime, where the qubit dynamics is relatively slow and well described using the rotating wave approximation. However, the implementation of qubit gates with strong driving, which in principle promises a higher speed, has not been studied extensively. In this work, we consider the dynamics of a qubit driven by strong resonant pulses in the framework of Floquet theory. We analyze the role of pulse shaping in the dynamics, as determined by nonadiabatic transitions between the Floquet states. By suppressing the nonadiabatic transitions, we show that high-fidelity single-qubit operations can be achieved in very short times. This work provides the theoretical basis for optimizing strong pulses for single-qubit gates. These results are particularly relevant for the implementation of single-qubit gates in superconducting qubits, where strong driving with shaped pulses has been demonstrated experimentally.

Flexible, low-latency architecture for qubit control and measurement in circuit QED. WOUTER VLOTHIJZEN, D. DEURLOO, QuTech, Delft University of Technology and Netherlands Organisation for Applied Scientific Research (TNO), Delft, The Netherlands, J. DE STERKE, Topic Embedded Systems, Delft, The Netherlands, R. VERMEULEN, R.N. SCHOUTEN, LEO DICARLO, QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands — Increasing qubit numbers in circuit QED requires an extensible architecture for digital waveform generation of qubit control and measurement signals. For quantum error correction, the ability to select from a number of predetermined waveforms based on measurement results will become paramount. We present a room-temperature architecture with very low latency from measurement to waveform output. This modular FPGA-based system can generate both baseband and RF modulated signals using DACs clocked at 1 GHz. A backplane that interconnects several modules allows exchange of (measurement) information between modules and maintains deterministic timing across those modules. We replace the typical line based sequencer used in arbitrary waveform generators by a user programmable processor that treats waveforms and measurements as instructions added to a conventional CPU architecture. This allows for flexible coding of triggering, repetitions, delays and interactions between measurement and signal generation. We acknowledge funding from the Dutch Research Organization (NWO), an ERC Synergy Grant, and European project SCALEQIT.

Fock State Generator. SHAVINDRA PREMARATNE, Department of Physics, University of Maryland; Laboratory for Physical Sciences, F.C. WELLSTOOD, JQI, CNAM, Department of Physics, University of Maryland, B.S. PALMER, Department of Physics, University of Maryland; Laboratory for Physical Sciences — Using a single junction Al/AlO\(_x\)/Al transmon qubit coupled to a superconducting Al cavity (at a temperature 15 mK), we have used a Raman technique to produce a single Fock state in the cavity. The technique requires 3 microwave tones to drive the system from the ground state of the cavity/qubit system. We achieve an experimental fidelity of the final Fock state of around 90%, limited by thermal photons in the cavity and by decay during the operation time. Using this technique, we have also generated an arbitrary superposition of Fock states and a superposition of qubit and cavity states. Results, simulations and applications of this technique will be discussed.

Quantum thermodynamics for arbitrarily small devices. STEPHANIE WEHNER, Delft Univ of Tech — Quantum thermodynamics for arbitrarily small devices.

Exceeding the Carnot efficiency. NELLY HUEI YING NG, Delft Univ of Tech, MISCHA WOODS, University College of London, Department of Physics and Astronomy, London WC1E 6BT, United Kingdom, STEPHANIE WEHNER, Delft Univ of Tech — A suitable way of quantifying work for microscopic quantum systems has been constantly debated in the field of quantum thermodynamics. One natural approach is to measure the average increase in energy of an ancillary system, called the battery, after a work extraction protocol. The quality of work extracted is usually argued to be good by quantifying higher moments of the energy distribution, or by restricting the amount of entropy to be low. This limits the amount of heat contribution to the energy extracted, but does not completely prevent it. We show that if one allows for a definition of work that tolerates a non-negligible entropy increase in the battery, then a small scale heat engine (with a similar set up to that of arXiv:1506.02322) can possibly exceed the Carnot efficiency. This can be done without using any additional resources such as coherence or correlations, and furthermore can be achieved by using finite-size quantum heat baths as well.

Thursday, March 17, 2016 8:00AM - 11:00AM – Session R44 GQI: Quantum Information and Thermodynamics

Quantum thermodynamics for arbitrarily small devices. STEPHANIE WEHNER, Delft Univ of Tech — Quantum thermodynamics for arbitrarily small devices.

Exceeding the Carnot efficiency. NELLY HUEI YING NG, Delft Univ of Tech, MISCHA WOODS, University College of London, Department of Physics and Astronomy, London WC1E 6BT, United Kingdom, STEPHANIE WEHNER, Delft Univ of Tech — A suitable way of quantifying work for microscopic quantum systems has been constantly debated in the field of quantum thermodynamics. One natural approach is to measure the average increase in energy of an ancillary system, called the battery, after a work extraction protocol. The quality of work extracted is usually argued to be good by quantifying higher moments of the energy distribution, or by restricting the amount of entropy to be low. This limits the amount of heat contribution to the energy extracted, but does not completely prevent it. We show that if one allows for a definition of work that tolerates a non-negligible entropy increase in the battery, then a small scale heat engine (with a similar set up to that of arXiv:1506.02322) can possibly exceed the Carnot efficiency. This can be done without using any additional resources such as coherence or correlations, and furthermore can be achieved by using finite-size quantum heat baths as well.
8:48AM R44.00003 The maximum efficiency of nano heat engines depends on more than temperature\(^1\), MISCHA WOODS, Uni Coll London, & TU Delft, Netherlands & National Uni Singapore, NELLY NG, TU Delft, Netherlands & National Uni Singapore, STEPHANIE WEHNER, TU Delft, Netherlands — Sadi Carnots theorem regarding the maximum efficiency of heat engines is considered to be of fundamental importance in the theory of heat engines and thermodynamics. Here, we show that at the nano and quantum scale, this law needs to be revised in the sense that more information about the bath other than its temperature is required to decide whether maximum efficiency can be achieved. In particular, we derive new fundamental limitations of the efficiency of heat engines at the nano and quantum scale that show that the Carnot efficiency can only be achieved under special circumstances, and we derive a new maximum efficiency for others. A preprint can be found here arXiv:1506.02322 [quant-ph]

\(^1\) Singapore MOE Tier 3A Grant & STW, Netherlands

9:00AM R44.00004 Autonomous quantum thermal machines and quantum to classical energy flow\(^1\), MAX FRENZEL, DAVID JENNINGS, TERRY RUDOLPH, Imperial College London — We address the issue of autonomous quantum thermal machines that are tailored to achieve some specific thermodynamic primitive, such as work extraction in the presence of a thermal environment, while having minimal or no control from the macroscopic regime. Beyond experimental implementations, this provides an arena in which to address certain foundational aspects such as the role of coherence in thermodynamics, the use of clock degrees of freedom and the simulation of local time-dependent Hamiltonians in a particular quantum subsystem. For small-scale systems additional issues arise. Firstly, it is not clear to what degree genuine ordered thermodynamic work has been extracted, and secondly non-trivial back-actions on the thermal machine must be accounted for. We find that both these aspects can be resolved through a judicious choice of quantum measurements that magnify thermodynamic properties up the ladder of length-scales, while simultaneously stabilizing the quantum thermal machine.

Within this framework we show that thermodynamic reversibility is obtained in a particular Zeno limit, and finally illustrate these concepts with a concrete example involving spin-systems.

9:12AM R44.00005 Stochastic Independence as a Resource for Small-Scale Thermodynamics, MATTEO LOSTAGLIO, Imperial College London, MARKUS P. MUELLER, Western Ontario University and Perimeter Institute for Theoretical Physics, MICHELE PASTENA, Heidelberg University — It is well-known in thermodynamics that the creation of correlations costs work. It seems then a truism that if a thermodynamic transformation \(A \rightarrow B\) is impossible, so will be any transformation that in sending \(A\) to \(B\) also correlates among them some auxiliary systems \(C\). Surprisingly, we show that this is not the case for non-equilibrium thermodynamics of microscopic systems. On the contrary, the creation of correlations greatly extends the set of accessible states, to the point that we can perform on individual systems and in a single shot any transformation that would otherwise be possible only if the number of systems involved was very large. We also show that one only ever needs to create a vanishingly small amount of correlations (as measured by mutual information) among a small number of auxiliary systems (never more than three). The many, severe constraints of microscopic thermodynamics are reduced to the sole requirement that the non-equilibrium free energy decreases in the transformation. This shows that, in principle, reliable extraction of work equal to the free energy of a system can be performed by microscopic engines.

9:24AM R44.00006 Quantum coherence, time-translation symmetry and thermodynamics, KAMIL KORZEKWA, MATTEO LOSTAGLIO, DAVID JENNINGS, TERRY RUDOLPH, Imperial College London — The first law of thermodynamics imposes not just a constraint on the energy content of systems in extreme quantum regimes but also symmetry constraints related to the thermodynamic processing of quantum coherence. We show that this thermodynamic symmetry decomposes any quantum state into mode operators that quantify the coherence present in the state. We then establish general upper and lower bounds for the evolution of quantum coherence under arbitrary thermal operations, valid for any temperature. We identify primitive coherence manipulations and show that the transfer of coherence between energy levels manifests irreversibility not captured by free energy. Moreover, the recently developed thermomajorization relations on block-diagonal quantum states are observed to be special cases of this symmetry analysis.

9:36AM R44.00007 Quantum work statistics of charged Dirac particles in time-dependent fields\(^1\), SEBASTIAN DEFFNER, AVADH SAXENA, Los Alamos Natl Lab — The quantum Jarzynski equality is an important theorem of modern quantum thermodynamics. We show that the Jarzynski equality readily generalizes to relativistic quantum mechanics described by the Dirac equation. After establishing the conceptual framework we solve a pedagogical, yet experimentally relevant, system analytically. As a main result we obtain the exact quantum work distributions for charged particles traveling through a time-dependent vector potential evolving under Schrödinger as well as under Dirac dynamics, and for which the Jarzynski equality is verified. Special emphasis is put on the conceptual and technical subtleties arising from relativistic quantum mechanics.

\(^1\) SD acknowledges financial support by the U.S. Department of Energy through a LANL Director’s Funded Fellowship.

9:48AM R44.00008 The second law of quantum thermodynamics as an equality, JONATHAN OPPENHEIM, University College London — The traditional second law of thermodynamics says that the average amount of work required to change one state into another while in contact with a heat reservoir, must be at least as large as the change in free energy of the system. Here, we consider a fine-grained notion of the free energy, and show that in terms of it, the second law can be written as an equality. We also obtain a generalisation of the Jarzynski fluctuation theorem which holds for arbitrary initial states, not just the case of an initial thermal state. We derive a generalisation of Gibbs-stochasticity, a condition originally found in the approach to thermodynamics inspired by quantum information theory. This generalisation directly incorporates the case of fluctuating work and serves as a parent equation which can be used to derive the second law equality and the generalisation of the Jarzynski equation. We further show that each of these three generalisations can be seen as the quasi-classical limit of three fully quantum identities. This allows for more general and fully quantum fluctuation relations from the information theoretic approach to quantum thermodynamics.

10:24AM R44.00009 Recoverability in quantum information theory\(^1\), MARK WILDE, Louisiana State Univ - Baton Rouge — The fact that the quantum relative entropy is non-increasing with respect to quantum physical evolutions lies at the core of many optimality theorems in quantum information theory and has applications in other areas of physics. In this work, we establish improvements of this entropy inequality in the form of physically meaningful remainder terms. One of the main results can be summarized informally as follows: if the decrease in quantum relative entropy between two quantum states after a quantum physical evolution is relatively small, then it is possible to perform a recovery operation, such that one can perfectly recover one state while approximately recovering the other. This can be interpreted as quantifying how well one can reverse a quantum physical evolution.

\(^1\) I acknowledge support from startup funds from the Department of Physics and Astronomy at LSU, the NSF under Award No. CCF-1350397, and the DARPA Quiness Program through US Army Research Office award W31P4Q-12-1-0019.
10:36AM R44.00010 Quantum Decoherence at Finite Temperatures: Theory and Computations1, M.A. NOVOTNY, Mississippi State University, FENGPING JIN, Julich Supercomputing Centre, SEIJI MIYASHITA, University of Tokyo, SHENJUN YUAN, Radboud University, HANS DE RAEDT, University of Groningen, KRISTEL MICHIELSEN, Julich Supercomputing Centre — The decoherence of a finite quantum system $S$ coupled to a finite quantum environment $E$ is considered, where the entirety $S + E$ is a closed quantum system. The entirety is prepared in a canonical thermal state at a finite temperature. By applying perturbation theory, we find closed form expressions for measures of decoherence and thermalization of $S$ in terms of the free energies of $S$ and $E$. Hence we have quantified how difficult it is to decohere a particular finite quantum system $S$ at a fixed temperature, the result being a function of the free energy of $S$. We have also quantified how potent a particular finite Hilbert space environment $E$ at a fixed temperature is at decohering a generic quantum system. To test these predictions, we performed both real and imaginary time calculations for the Schrödinger equation for an entirety with up to 40 quantum spins. The large-scale calculations (vectors in Hilbert space with length up to $2^{40\approx10^{12}}$) validate our predictions for all temperatures. Preprint arXiv:1502.03996.

1MAN supported in part by NSF DMR-1206233.

10:48AM R44.00011 Dynamical and thermodynamical control of open quantum Brownian motion, FRANCESCO PETRUCCIONE, University of KwaZulu-Natal, ILYA SINAYSKYI, National Institute for Theoretical Physics — Open quantum Brownian motion was introduced as a new type of quantum Brownian motion for Brownian particles with internal quantum degrees of freedom. Recently, an example of the microscopic derivation of open quantum Brownian motion has been presented [I. Sinayskiy and F. Petruccione, Phys. Scr. T165, 014017 (2015)]. The microscopic derivation allows to relate the dynamical properties of open Quantum Brownian motion and the thermodynamical properties of the environment. In the present work, we study the possibility of control of the external degrees of freedom of the “walker” (position) by manipulating the internal one, e.g., spin, polarization, occupation numbers. In the particular example of the known microscopic derivation the connection between dynamics of the “walker” and thermodynamical parameters of the system is established. For the system of open Brownian walkers coupled to the same environment controllable creation of quantum correlations is investigated.

3This work is based upon research supported by the South African Research Chair Initiative of the Department of Science and Technology and National Research Foundation.

Thursday, March 17, 2016 8:00AM - 10:48AM – Session R45 GQI DAMOP: Hybrid Quantum Systems III — Guido Burkard, University of Konstanz, Germany

8:00AM R45.00001 Investigations of a transmon-coupled nanoresonator in a CPW cavity, YU HAO, Syracuse University, FRANCISCO ROXINAL, University of Campinas, MATT LAHAYE, Syracuse University — In this work, we describe our progress developing a qubit-coupled nanomechanical resonator(nmr), which has potential both for fundamental studies in quantum measurement and quantum thermodynamics and applications in quantum information. The hybrid system is composed of a superconducting charge-type transmon qubit and a ultra-high-frequency flexural nmr; both are embedded in, and measured through, a superconducting coplanar-wave-guide(CPW) resonator. Transmission measurements of the CPW cavity allow us to probe the state of transmon as it interacts resonantly with the NMR. In the talk, we’ll present the latest measurements of this device at low NMR thermal occupation factors and discuss future prospects for developing this system for more advanced quantum measurements.

8:12AM R45.00002 Surface acoustic wave resonators in the quantum regime, RICCARDO MANENTI, MICHAEL PETERER, ANI NERSISYAN, EINAR MAGNUSSON, ANDREW PATTERSON, PETER LEÉK, University of Oxford — Surface acoustic waves (SAWs) are mechanical modes confined to the surface of a piezoelectric crystal that can be excited and detected by electric circuits. These mechanical waves can be trapped between two reflectors producing a SAW resonator. In this talk, I will present an experimental study of SAW resonators at 10 mK [1], in which we find that internal quality factors $Q_i$ approaching 0.5 million can be reached at 0.5 GHz and that $Q_i > 10^4$ is achievable above 4 GHz, making SAW resonators promising devices for integration into quantum circuits. I will discuss the loss mechanisms that may be currently limiting these Q-factors, and report on our progress towards coupling these mechanical resonators to superconducting qubits. [1] R. Manenti et al., arXiv:1510.04965

8:24AM R45.00003 Cavity magnomechanics, XUFENG ZHANG, CHANGLING ZOU, LIANG JIANG, HONG X. TANG, Yale University — Mechanical oscillators have been recently widely utilized to couple with optical and microwave photons in a variety of hybrid quantum systems, but they all lack the tunability. The magnetostriuctive force provides an alternative mechanism to allow phonon to couple with a different type of information carrier. It has been shown that quantum Brownian motion may be controlled by external magnetic fields, which modifies the spin's sensitivity to magnetic fluctuations in a thermally isolated subspace, thus prolonging the Ramsey coherence time from $T_2^\star = 2.7 \pm 0.1 \ \mu s$ to $15 \pm 1 \ \mu s$. We develop a model that quantitatively predicts the relationship between the mechanical Rabi field and the dephasing time. Our model shows that a combination of random magnetic field fluctuations and hyperfine coupling limits the protected coherence time over the range of magnetic dressing fields accessed in our experiment. Finally, we show that amplitude noise in the dressing field will dominate over magnetic noise for larger driving fields.

3We acknowledge research support from the Office of Naval Research.
Towards a highly efficient quantum spin-photon interface for an NV centre based quantum network. Stefan Bogdanovic, Cristian Bonato, Suzanne van Dam, Andreas Reiserer, Anne-Marie Zwerger, Ronald Hanson, Kavli Institute of Nanoscience Delft, Delft University of Technology, Quantum Transport Team — Nitrogen-vacancy (NV) centers in diamond recently emerged as promising candidates for realizing quantum information algorithms due to their remarkable versatility. The spin of these optically active defects can be entangled with their emitted photons, making them an excellent optical interface from the perspective of quantum communication.

Recently, we have demonstrated the first building blocks of such networks, performing kilometer scale entanglement of two NV centers and teleportation of quantum information. (1) However, our current protocols are inefficient due to the low emission of NV centers resonant photons into the zero phonon line (ZPL). Here we present our efforts of coupling a single NV center emitter in a diamond membrane to a fiber-based Fabry-Perot microcavity with high finesse ($F > 10^4$) at cryogenic temperatures. This approach allows spectral tuning of the cavity resonance to the ZPL emission of the NV center, thereby significantly enhancing the resonant photon emission via Purcell effect. Furthermore, the bulk environment of the NV centers protects their spin properties against surface proximity effects, which is of crucial importance for quantum information processing applications.

(1) B. Hensen et al., Nature 526, 682 (2015)

University of Queensland, Jason Twamley, Macquarie University, Warwick P. Bowen, University of Queensland, Michael R. Vanner, University of Oxford — Coupling a single InAs quantum dot to mechanical motion of a photonic crystal membrane. Samuel Carter, Allan Bracker, Naval Research Laboratory, Muin Kim, Sotera Defense Solutions, Inc, Chul Soo Kim, Maxim Zalalutdinov, Brennan Pursley, Naval Research Laboratory, Sophia Economou, Department of Physics, Virginia Tech, Cyprian Czarnecki, Cameron Jennings, Michael Scheibner, School of Natural Sciences, University of California, Merced, Daniel Gammon, Naval Research Laboratory — Coupling quantum mechanical systems to mechanical motion is attractive for fundamental science, quantum information applications, and sensing. Semiconductor quantum dots (QDs) embedded in suspended photonic crystal structures provide a versatile system for advances in this area. Flexible modes of the suspended membrane as well as localized mechanical modes surrounding optical cavities couple to QDs through strain, with the photonic crystal used to maximize collection of photons from QDs. We have performed high resolution spectroscopy of InAs QDs embedded in photonic crystal structures while optically driving mechanical motion. Using time-correlated photon counting, the strain-induced shift of the QD optical transitions is measured as a function of time. For QDs at the center of the membrane (along the growth direction), the strain is minimum, and the optical transitions shift by only a few µeV. For QDs shifted 30 nm from the center, the strain induces larger shifts of 500 µeV. Measurements in a magnetic field are being performed on charged QDs to determine the coupling of mechanical motion to electron and hole spin transitions.

Inductive cooling in quantum magneto-mechanics. Erick Romero-Sanchez, University of Queensland, Jason Twamley, Macquarie University, Warwick P. Bowen, University of Queensland, Michael R. Vanner, University of Oxford — Coupling to light or microwave fields allows quantum control of the motion of a mechanical oscillator, and offers prospects for precision sensing, quantum information systems, and tests of fundamental physics. In cavity electromechanics ground state cooling has been achieved using resolved sideband cooling. Here we present an alternative approach based on a magneto-mechanical system that inductively couples an LC resonator to a mechanical oscillator. The experimental setup consists of a micro cantilever with a pyramidal magnetic tip attached at the end of the beam. The sharp end of the magnetic tip is positioned close to the planar microfabricated inductor of the LC resonator. The displacement in the position of the cantilever generates a change in flux through the coil inducing an electromotive force in the circuit. The current in the LC resonator generates a magnetic field, and then a force between the tip and the coil. When they are strongly coupled and the mechanical resonance frequency $\omega_m$ exceeds the electrical decay rate of the resonator $\gamma_e$, resolved sideband cooling can be used to cool the mechanical. We present estimations for the coupling rates and the experimental parameters required for these experiments.

E. Romero acknowledges to CONACyT.

Strain coupling of a mechanical resonator to a single quantum emitter in diamond. Kenneth Lee, Donghun Lee, Preeti Ovartchaypong, Ania Jayich, University of California Santa Barbara — Hybrid quantum devices are central to the advancement of several emerging quantum technologies, including quantum information science and quantum-assisted sensing. Here, we present a hybrid quantum device in which strain fields associated with resonant vibrations of a diamond cantilever dynamically modulate the energy and polarization dependence of the optical transitions of a single nitrogen-vacancy defect in diamond. With mechanical driving, we observe optomechanical couplings exceeding 100 kHz. Through resonant excitation spectroscopy, we quantitatively characterize the intrinsic strain environment of a single defect, and use this optomechanical coupling to tune the zero-phonon line of the defect. Through stroboscopic measurements, we show that we are able to match the frequency and polarization dependence of the zero-phonon line of two separate NV centers. The experiments demonstrated here mark an important step toward realizing a monolithic hybrid quantum device capable of realizing and probing the dynamics of non-classical states of mechanical resonators, spin-systems, and photons.

This work was supported with grants from the AFOSR, NSF and DARPA.

Microwave-frequency electromechanical resonators incorporating phononic crystals. K. J. Satzinger, G. Pearis, A. Vainsencher, University of California, Santa Barbara, A. N. Cleland, University of Chicago — Piezoelectric micromechanical resonators at gigahertz frequencies have been operated in the quantum limit, with quantum control and measurement achieved using superconducting qubits. However, experiments to date have been limited by mechanical dissipation, due to a combination of internal and radiative losses. In this talk, we explore the incorporation of phononic crystals into resonator designs. In phononic crystals, periodic patterning manipulates the acoustic band structure of the material. Through appropriately chosen geometries, these periodic patterns lead to full acoustic bandgaps which can be used to greatly reduce radiation losses from resonant structures. Alternatively, this crystal geometry can be manipulated to allow isolated modes within the bandgap, giving fine control over the spatial structure of the resonator modes. In this talk, we will describe the design, fabrication, and measurement of resonators with phononic crystals.

Piezoelectric micromechanical resonators at gigahertz frequencies have been operated in the quantum limit, with quantum control and measurement achieved using superconducting qubits. However, experiments to date have been limited by mechanical dissipation, due to a combination of internal and radiative losses. In this talk, we explore the incorporation of phononic crystals into resonator designs. In phononic crystals, periodic patterning manipulates the acoustic band structure of the material. Through appropriately chosen geometries, these periodic patterns lead to full acoustic bandgaps which can be used to greatly reduce radiation losses from resonant structures. Alternatively, this crystal geometry can be manipulated to allow isolated modes within the bandgap, giving fine control over the spatial structure of the resonator modes. In this talk, we will describe the design, fabrication, and measurement of resonators with phononic crystals.
10:00AM R45.00011 Superconducting-circuit quantum heat engine with frequency resolved thermal baths, PATRICK P. HOFER, JEAN-RENÉ SOUQUET, AASHISH A. CLERK, McGill University — The study of quantum heat engines promises to unravel deep, fundamental concepts in quantum thermodynamics. With this in mind, we propose a novel, realistic device that efficiently converts heat into work while maintaining reasonably large output powers. The key concept in our proposal is a highly peaked spectral density in both the thermal baths as well as the working fluid. This allows for a complete separation of the heat current from the working fluid. In our setup, Cooper pairs tunnelling across a Josephson junction serve as the the working fluid, while two resonant cavities coupled to the junction act as frequency-resolved thermal baths. The device is operated such that a heat flux carried entirely by the photons induces an electrical current against a voltage bias, providing work.

10:12AM R45.00012 Strong nonlinearity of mesoscopic vibrational modes induced by electron-phonon coupling, KIRILL MOSKOVITSEV, M. I. DUKYMAN, Michigan State University — We show that the electron-phonon coupling can lead to a strong nonlinearity of vibrational modes in semiconductor nano- and micro-resonators. For typical mode frequencies, the electron distribution adiabatically follows lattice strain. Therefore, strain leads to redistribution of the electron density over the valleys of the conduction band. It also leads to the onset of a spatial charge. The parameter that controls the distribution is the ratio of the deformation potential to the electron chemical potential or temperature. It is \( \sim 10^3 \) for many semiconductors of interest even when they are heavily doped. Therefore the change of the electron distribution is strongly nonlinear in the strain. As a consequence, the stress induced by the electron-phonon coupling is also strongly nonlinear. We have found the vibration nonlinearity parameters for \( n \)-doped Si and calculated the amplitude dependence of the frequencies of several low-lying Si resonator modes with account taken of their spatial structure. The results are compared with the recent experimental data that shows strong effect of doping on the vibration nonlinearity.

10:24AM R45.00013 Novel High Cooperativity Photon-Magnon Cavity QED, MICHAEL TOBAR, JEREMY BOURHILL, NIKITA KOSTYLEV, MAXIM G. DANIEL CREEDON, School of Physics, University of Western Australia, ARC Centre of Excellence for Engineered Quantum Systems — Novel microwave cavities are presented, which couple photons and magnons in YIG spheres in a super- and ultra-strong way at around 20 mK in temperature. Few-single photon couplings (or normal mode splitting, 2g) of more than 6 GHz at microwave frequencies are obtained. Types of cavities include multiple post reentrant cavities, which co-couple photons at different frequencies with a coupling greater that the free spectral range, as well as spherical loaded dielectric cavity resonators. In such cavities we show that the bare dielectric properties can be obtained by polarizing all magnon modes to high energy using a 7 Tesla magnet. We also show that at zero-field, collective effects of the spins significantly perturb the photon modes. Other effects like time-reversal symmetry breaking are observed.

10:36AM R45.00014 Cavity QED with ferromagnetic magnons in a small YIG sphere, DENGKE ZHANG, Beijing Computational Science Research Center, XIN-MING WANG, Research Center of Laser Fusion, CAEP, TIE-FU LI, Institute of Microelectronics, Tsinghua University, XIAO-QING LUO, Beijing Computational Science Research Center, WEIDONG WU, Research Center of Laser Fusion, CAEP, FRANCO NORI, Center for Emergent Matter Science, RIKEN. J. Q. YOU, Beijing Computational Science Research Center — Hybridizing collective spin excitations in ferromagnetic crystals and a cavity with high cooperativity provides a new research subject in the field of cavity quantum electrodynamics and can also have potential applications to quantum information. In contrast to spin ensembles based on dilute paramagnetic impurities, these spins are strongly exchange-coupled and have a much higher density. Here we report a direct observation of the strong coupling between magnons and microwave photons at both cryogenic and room temperatures by using the same yttrium-iron-garnet (YIG) ferromagnetic sphere in a 3D copper cavity. We observed strong couplings of the cavity mode to both ferromagnetic-resonance (FMR, uniform precession) mode and a magnetostatic (MS, non-uniform precession) mode in the quantum limit at 22 mK. Then, at room temperature, we observed a strong coupling of the cavity mode to the FMR mode with slightly increased damping rate. This reveals the robustness of the FMR mode against temperature. However, the coupling to MS mode disappears at room temperature and numerically simulations show that this is due to a drastic increase of the damping rate of the MS mode. Our work unveils quantum-coherence properties of the magnons.

Thursday, March 17, 2016 8:00AM - 11:00AM –
Session R48 GQI: Decoherence in Superconducting Qubits: Junctions and Fluxonium

8:00AM R48.00001 Novel Josephson circuit elements for high magnetic field parity detection, MAJA CASSIDY, Delft University of Technology — Evidence for Majorana modes in semiconductor nanowires to date has relied on DC transport measurements that probe their zero-energy characteristics. However, in order to unambiguously demonstrate the non-Abelian nature of Majoranas, it is necessary to braid them and measure their parity. Superconducting transmon qubits have been shown to be sensitive parity detectors, however traditional designs are incompatible with the strong magnetic fields required for the creation of Majoranas in nanowires. In this talk I will discuss our development of novel superconducting circuit elements such as CPW resonators, tunnel junctions, transmon qubits and on-chip microwave sources that survive magnetic fields in excess of 1T.

8:36AM R48.00002 Decoherence and Decay of Two-level Systems due to Non-equilibrium Quasiparticles, SEBASTIAN ZANKER, MICHAEL MARTHAULER, GERO SCHN, Karlsruhe Institute of Technology, INSTITUT FR THEORETISCHE PHYSIK TEAM — It is frequently observed that even at very low temperatures the number of quasiparticles in superconducting materials is higher than predicted by standard BCS-theory. These quasiparticles can interact with two-level systems, such as superconducting qubits or two-level systems (TLS) in the amorphous oxide layer of a Josephson junction. This interaction leads to decay and decoherence of the TLS, with specific results, such as the time dependence, depending on the distribution of quasiparticles and the form of the interaction. We study the resulting decay laws for different experimentally relevant protocols.

This work was supported by the German-Israeli Foundation for Scientific Research and Development (GIF).

8:48AM R48.00003 Superconducting resonators with trapped vortices under direct injection of quasiparticles, IBRAHIM NSANZINEZA, Syracuse University, UMESH PATEL, University of Wisconsin, K. R. DODGE, Syracuse University, R. F. MCDERMOTT, University of Wisconsin, B. L. T. PLOURDE, Syracuse University — Nonequilibrium quasiparticles and trapped magnetic flux vortices can significantly impact the performance of superconducting microwave resonant circuits and qubits at millikelvin temperatures. Quasiparticles result in excess loss, reducing resonator quality factors and qubit lifetimes. Vortices trapped near regions of large microwave currents also contribute excess loss. However, vortices located in current-free areas in the resonator or in the ground plane of a device can actually trap quasiparticles and lead to a reduction in the quasiparticle loss. We will describe experiments involving the controlled trapping of vortices in superconducting resonators with direct injection of quasiparticles using Normal-metal-Insulator-Superconductor (NIS)-tunnel junctions.
9:00 AM R48.00004 Robustness of superconducting quantum modes against direct quasiparticle injection. U. PATEL, Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, I. NSANZINEZA, Department of Physics, Syracuse University, Syracuse, New York 13244, M. G. VAVILOV, Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, B. L. T. PLOURDE, Department of Physics, Syracuse University, Syracuse, New York 13244, R. MCDERMOTT, Department of Physics, University of Wisconsin, Madison, Wisconsin 53706 — Classical Josephson digital logic based on Single Flux Quantum (SFQ) pulses offers a path to high-fidelity coherent control of large-scale superconducting quantum machines. However, an SFQ pulse driver generates nonequilibrium quasiparticles that contribute to qubit relaxation, and steps must be taken to protect the qubit from this decoherence channel. Here we describe experiments to characterize the robustness of high-Q superconducting linear resonators and qubits against direct quasiparticle injection. We use NIS junctions and SFQ elements to controllably inject quasiparticles into the groundplane of superconducting resonator and qubit chips, and we characterize the quasiparticle contribution to dissipation. We examine the effectiveness of groundplane cuts, normal metal quasiparticle traps, and spatially-varying superconducting gaps at protecting the quantum modes against quasiparticle loss. Finally, we discuss strategies for the integration of multiqubit circuits with on-chip SFQ control elements.

9:12 AM R48.00005 Normal Metal Quasiparticle Traps in 3D-Transmon Qubits1. LUKE D. BURKHART, YVONNE Y. GAO, CHEN WANG, KYLE SERNIAK, GIUS DE LANGE, YIWEN CHU, URI VOOL, LUIGI FRUNZIO, MICHEL H. DEVORET, Department of Applied Physics and Physics, Yale University, GIANLUIGI CATELANI; Peter Grunberg Institut (PGI-2), Forschungszentrum Jülich, LEONID I. GLAZMAN, ROBERT J. SCHOELKOPF, Department of Applied Physics and Physics, Yale University — Quasiparticles are a known source of decoherence in Josephson-junction based superconducting qubits. While equilibrium quasiparticles should not be present in devices operated at dilution refrigeration temperatures well below the superconducting energy gap, non-thermal quasiparticles have been observed in many different superconducting qubits, including 3D-transmons and fluxonium qubits. Vortices induced by applied magnetic fields have been shown to improve non-equilibrium quasiparticle decay rates and improve coherence times by creating regions of the superconductor with vanishing energy gap, which act as quasiparticle traps. We aim to further mitigate quasiparticle-induced limits on coherence by engineering strong trapping via the introduction of normal metal to the superconducting qubit. In this talk, we present recent results regarding normal metal quasiparticle traps in 3D-transmon qubits.

1Work supported by ARO, A*STAR

9:24 AM R48.00006 Gap-engineered quasiparticle traps in the fluxonium artificial atom1. K. SERNIAK, G. DE LANGE, U. VOOL, M. HAYS, L.D. BURKHART, Y.Y. GAO, C. WANG, K.M. SLIWA, Department of Applied Physics, Yale University, I.M. POP, Department of Applied Physics, Yale University, and Physikalischcs Institut, Karlsruhe Institute of Technology, L. FRUNZIO, I.I. GLAZMAN, R.J. SCHOELKOPF, M.H. DEVORET, Department of Applied Physics, Yale University — Recent experiments have shown that the density of quasiparticles in superconducting quantum circuits exceeds the expected thermal density. In Josephson junction based superconducting qubits, these non-equilibrium quasiparticles can tunnel through the junctions of the circuit, causing decoherence. Quasiparticle traps aim to reduce the density of quasiparticles near the junctions, and therefore the rate of energy loss and dephasing due to tunneling events. These traps must be designed to not introduce any additional losses in the qubit. In this talk we will discuss recent progress in the design and implementation of quasiparticle traps in the fluxonium artificial atom.

1Work supported by ARO, ONR, YINQE, and the European Union

9:36 AM R48.00007 Spectroscopy and decoherence of plasmons and fluxons in superconducting fluxonium qubit. LONG NGUYEN, YEN-HSIANG LIN, NICHOLAS GRABON, NATALYA SOLOVYEVA, VLADIMIR MANUCHARYAN, Univ of Maryland-College Park, SUPERCONDUCTING CIRCUITS LAB TEAM — Transition spectrum of a fluxonium circuit changes drastically with respect to the p=EJ/EC parameter of the small junction, remaining charge-insensitive at all values of p. At larger values of p, the spectrum consists of exponentially decoupled fluxon and plasmon transitions. At smaller values, fluxons no longer exist, and plasmons reside mostly in the array inductance. We present spectroscopy of tunable fluxonics and discuss our findings from the decoherence measurements of various transitions.

9:48 AM R48.00008 The fluxonium as a lambda system1. U. VOOL, A. KOU, W.C. SMITH, K. SERNIAK, S. SHANKAR, S.M. GIRVIN, M.H. DEVORET, Department of Applied Physics, Yale University — A lambda system is a 3-level system in which two low-energy states can transition to a third higher-energy state by a coherent drive but not to each other. Lambda systems are commonly implemented in systems relying on atomic transitions. In the field of superconducting quantum circuits, the fluxonium qubit, an artificial atom consisting of a Josephson junction shunted by a super- inductance, is a unique artificial atom with highly non-linear energy levels. At half-flux quantum it has two low-energy states with a long energy lifetime, but it is difficult to perform fast quantum gates in this manifold. Employing the higher 2nd excited state as an intermediate level would be much more efficient. However, selection rules in the fluxonium qubit prohibit transitions between low-energy states and higher-energy states of the same parity. In this talk, we will introduce a way to create formerly forbidden transitions between levels of the fluxonium qubit - thus creating a more interesting artificial atom and a useful tool for future superconducting quantum circuits.

1Work supported by ARO, ONR, AFSOR and YINQE

10:00 AM R48.00009 Simultaneous monitoring of fluxonium qubits in a waveguide1. A. KOU, W.C. SMITH, U. VOOL, I.M. POP, K.M. SLIWA, M. HATRIDGE, R.J. SCHOELKOPF, M.H. DEVORET, Department of Applied Physics, Yale University — Building quantum computers and quantum simulators requires separate control and readout of multiple qubits. We present an architecture for multiplexed readout of fluxonium qubits. We measured efficiencies in excess of 100% for such artificial atoms placed in a wide-bandwidth electromagnetic environment. We use cascaded Josephson parametric converters to measure the quantum jumps of two fluxonium qubits simultaneously. Our method can access correlations between different qubits and can easily be scaled to read out larger numbers of qubits.

1Work supported by: ARO, AFSOR, and YINQE

10:12 AM R48.00010 A disordered kinetic superinductor1. M. HAYS, G. DE LANGE, K. SERNIAK, Z. WANG, U. VOOL, L. FRUNZIO, M.H. DEVORET, Department of Applied Physics, Yale University — The superinductance is a superconducting circuit element whose reactance exceeds the resistance quantum at the relevant microwave operation frequencies of quantum circuits. It must also be as non-dissipative as possible. Such an element is key to the fluxonium artificial atom, a highly anharmonic, charge insensitive superconducting qubit that has been proposed as the detection circuit for Majorana Fermions. So far fluxonium qubits are made exclusively from arrays of Al-AlOx-Al Josephson junctions. However, aluminium is difficult to employ in conjunction with the strong magnetic fields required in Majorana Fermion experiments. The large kinetic inductance of highly resistive disordered superconducting alloys, such as NbTiN, is currently explored as an alternative material for superinductance in quantum electronic circuits. We report the results of measurement of quality factors and phase-slip rates of high-impedance resonators made from thin-film NbTiN.

1Work supported by: ARO, ONR, AFSOR and YINQE
dependence of the current in semiconductor double quantum dots (DQDs) and highlighted the important role of electron-phonon coupling in inelastic transport.

Our theoretical findings constitute the first quantum memristor in a superconducting circuit and act as the starting point for designing further circuit elements of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain — Memristors, resistive elements that retain information of their past, have garnered particular interest due to their paradigm-changing potential in information processing and electronics. The emergent hysteretic behaviour allows for novel architectural applications and has recently been classically demonstrated in a simplified superconducting setup using the phase-dependent conductance in the tunnel-junction- microscopic model[1]. In this contribution, we present a truly quantum model for a memristor constructed using established elements and techniques in superconducting nanoelectronics, and explore the parameters for feasible operation as well as refine the methods for quantifying the memory retention. In particular, the memristive behaviour is shown to arise from quasiparticle-induced tunneling in the full dissipative model and can be observed in the phase-driven superconducting nanoelectronics. The emergent hysteretic behaviour allows for novel architectural applications and has recently been classically demonstrated in a simplified superconducting setup using the phase-dependent conductance in the tunnel-junction- microscopic model[1]. In this contribution, we present a truly quantum model for a memristor constructed using established elements and techniques in superconducting nanoelectronics, and explore the parameters for feasible operation as well as refine the methods for quantifying the memory retention. In particular, the memristive behaviour is shown to arise from quasiparticle-induced tunneling in the full dissipative model and can be observed in the phase-driven superconducting nanoelectronics. The emergent hysteretic behaviour allows for novel architectural applications and has recently been classically demonstrated in a simplified superconducting setup using the phase-dependent conductance in the tunnel-junction- microscopic model[1]. 

The authors acknowledge support from the CCQED EU project and the Finnish Cultural Foundation.

Thursday, March 17, 2016 11:15AM - 2:15PM — Session S4 GQI DCMP: Quantum Dot-Cavity Hybrid Systems — Guido Burkard, University of Konstanz

11:15AM S4.00001 Probing light-matter interactions at the level of single photons and electrons[3], JASON R. PETTET, Department of Physics, Princeton University — Pioneering experiments by Fujisawa et al. examined the detuning dependence of the current in semiconductor double quantum dots (DQDs) and highlighted the important role of electron-phonon coupling in inelastic transport. Later experiments by the same group directly measured orbital relaxation rates, which were consistent with a phonon-mediated relaxation process. By placing semiconductor DQDs inside of high quality factor microwave cavities it is now feasible to achieve charge-cavity coupling rates that are comparable to the phonon emission rate. I will describe recent experiments that examine masing in cavity-coupled semiconductor DQDs. The application of a source-drain bias results in single electron tunneling and population inversion. The interdot tunneling process generates photons and leads to gain in the cavity transmission. We measure the detuning dependence of the gain and find that the gain feature is very broad compared to the cavity linewidth. Recent theory accounts for the broad gain feature by considering a second-order process that involves the simultaneous emission of a cavity photon and a phonon. With sufficient cavity driving, it is feasible to achieve above-threshold maser action, which is verified by comparing the statistics of the emitted microwave field above and below the maser threshold. In collaboration with Y.-Y. Liu, J. Stehlik, C. Eichler, M. J. Gullans, and J. M. Taylor. Supported by the Packard Foundation, the NSF (DMR-1409556 and DMR-120541), and the Gordon and Betty Moore Foundation’s EPiQS Initiative through Grant No. GBMF4535.

References

12:27PM S4.00003 Theory of strongly driven cavity coupled quantum dots: from micromasers to BECs of light, MICHAEL GULLANS, NIST - Natl Inst of Stds & Tech — Embedding a double quantum dot (DQD) in a low loss microwave resonator results in a large electric dipole interaction between the charge states of the DQD and single microwave photons in the resonator. In the regime of a few electrons and photons, this system is reminiscent of well-known models of cavity quantum electrodynamics from atomic physics; however, there are important deviations due to the strong coupling of the DQD to the electronic reservoirs in the leads, as well as phonons in the lattice. In this talk, we explore how external control and driving of this unique hybrid system can be used to induce non-equilibrium states of light in the resonator.
1:03PM S4.00004 Cavity quantum electrodynamics with carbon nanotube quantum dots, TAKIS KONTOS, Laboratoire Pierre Aigrain, Ecole Normale Supérieure, CNRS — Cavity quantum electrodynamics techniques have turned out to be instrumental to probe or manipulate the electronic states of nanoscale circuits. Recently, cavity QED architectures have been extended to quantum dot circuits. These circuits are appealing since other degrees of freedom than the traditional ones (e.g., those of superconducting circuits) can be investigated. I will show how one can use carbon nanotube based quantum dots in that context. In particular, I will focus on the coherent coupling of a single spin [1] or non-local Cooper pairs to cavity photons. Quantum dots also exhibit a wide variety of many body phenomena. The cQED architecture could also be instrumental for understanding them. One of the most paradigmatic phenomenon is the Kondo effect which is at the heart of many electron correlation effects. I will show that a cQED architecture has allowed us to observe the decoupling of spin and charge excitations in a Kondo system. [1] J. J. Viennot, M. C. Dartiailh, A. Cottet and T. Kontos Science 349 408 (2015).

1:39PM S4.00005 Microwave emission from double quantum dots into cavities, ANDREAS WALLRAFF, ETH - Zurich — No abstract available.

Thursday, March 17, 2016 11:15AM - 2:03PM – Session S44 GQI: Quantum Architectures and Control 347 - Ryan Babbush, Google

11:15AM S44.00001 A universal scheme for indirect quantum control1, DAVID LAYDEN, University of Waterloo (Department of Applied Mathematics), Institute for Quantum Computing, EDUARDO MARTIN-MARTINEZ, ACHIM KEMPF, University of Waterloo (Department of Applied Mathematics), Institute for Quantum Computing, Perimeter Institute for Theoretical Physics — The goal of indirect quantum control is to coherently steer a quantum system solely by acting on a quantum actuator to which it is coupled. This approach to quantum control is convenient in many physical settings, as it allows one to avoid direct addressing of the system—and any associated difficulties—altogether. While it is known in principle that control of the actuator typically yields universal control of the system, the practical details of how such indirect control can be achieved are less clear. This deficiency has led to a number of implementation- and model-specific indirect control schemes, in lieu of a general recipe applicable to any physical setting. Here, we present such a recipe, in the form of an open-loop control scheme which implements arbitrary unitary operations on the system by exploiting open dynamics in the actuator.

1arXiv:1506.06749

11:27AM S44.00002 Symmetry-protected topologically ordered states for universal quantum computation1, HENDRIK POULSEN NAUTRUP, Department of Physics and Astronomy, Stony Brook University, Tzu-Chieh Wei, C. N. Yang Institute for Theoretical Physics, Stony Brook University — Measurement-based quantum computation (MBQC) is a model for quantum information processing utilizing only local measurements on suitably entangled resource states for the implementation of quantum gates. A complete characterization for universal resource states is still missing. It has been shown that symmetry-protected topological order (SPTO) in one dimension can be exploited for the protection of certain quantum gates in MBQC. Here we investigate whether any 2D nontrivial SPTO states can serve as resource for MBQC. In particular, we show that the nontrivial SPTO ground state of the CZX model on the square lattice by Chen et al. [Phys. Rev. B 84, 235141 (2011)] can be reduced to a 2D cluster state by local measurement, hence a universal resource state. Such ground states have been generalized to qudits with symmetry action described by three cocycles of a finite group G of order d and shown to exhibit nontrivial SPTO. We also extend these to arbitrary lattices and show that the generalized two-dimensional plaquette states on arbitrary lattices exhibit nontrivial SPTO in terms of symmetry fractionalization and that they are universal resource states for quantum computation. SPTO states therefore can provide a new playground for measurement-based quantum computation.

1This work was supported in part by the National Science Foundation.

11:39AM S44.00003 Two-dimensional quantum walk under artificial magnetic field, ISKENDER YALCINKAYA, ZAFER GEDIK, Sabanci University — We introduce the Peierls substitution to a two-dimensional discrete-time quantum walk on a square lattice to examine the spreading dynamics and the coin-position entanglement in the presence of an artificial gauge field [1]. We use the ratio of the magnetic flux through the unit cell to the flux quantum as a control parameter. For a given flux ratio, we obtain faster spreading for a small number of steps and the walker tends to be highly localized around the origin. Moreover, the spreading of the walk can be suppressed and decreased within a limited time interval for specific rational values of flux ratio. When the flux ratio is an irrational number, even for a large number of steps, the spreading exhibit difusive behavior rather than the well-known ballistic one as in the classical random walk and there is a significant probability of finding the walker at the origin. We also analyze the coin-position entanglement and show that the asymptotic behavior vanishes when the flux ratio is different from zero and the coin-position entanglement become nearly maximal in a periodic manner in a long time range.


11:51AM S44.00004 Quantum Ultra-Walks: Walks on a Line with Spatial Disorder1, STEFAN BOETTCHER2, STEFAN FALKNER3, Physics Department, Emory University — We discuss the model of a heterogeneous discrete-time walk on a line with spatial disorder in the form of a set of ultrametric barriers. Simulations show that such an quantum ultra-walk spreads with a walk exponent d that ranges from ballistic (dω = 1) to complete confinement (dω = ∞) for increasing separation 1 ≤ 1/ε < ∞ in barrier heights. We develop a formalism by which the classical random walk as well as the quantum walk can be treated in parallel using a coined walk with internal degrees of freedom. For the random walk, this amounts to a 2nd-order Markov process with a stochastic coin, better know as an (anti-)persistent walk. The exact analysis, based on the real-space renormalization group (RG), reproduces the results of the well-known model of “ultradiffusion,” dω = 1 − log2 ε for 0 < ε < 1/2. However, while the evaluation of the RG fixed-points proceeds virtually identical, for the corresponding quantum walk with a unitary coin it fails to reproduce the numerical results. A new way to analyze the RG is indicated.

1supported by NSF-DMR 1207431
2http://www.physics.emory.edu/faculty/boettcher/
3now U. of Freiburg.
http://aad.informatik.uni-freiburg.de/people/falkner/
Reconfigurable Circuit

Optical Quantum Logic, author Chris Sparrow.

If possible schedule directly before Universal Linear Optics: A Testbed for ensembles of tens of thousands of realizations of disordered and noisy systems. In addition, low loss makes this nanophotonic processor a promising platform for localization, environment-assisted quantum transport, ballistic transport, and a number of intermediate quantum transport regimes. Rapid programmability.

Recent experimental and theoretical work has revealed emergent, counter-intuitive quantum transport effects in a range of physical media including solid-state thermoelectric devices, and in disordered and noisy nanophotonic systems.

TOM BAEHR-JONES, MICHAEL HOCHBERG, Coriant Advanced Technology, SETH LLOYD, DIRK ENGLUND, Massachusetts Institute of Technology — I conducted simulations of proof-of-principle experiments using a fabrication model of realistic errors in silicon-based photonic integrated devices. The results indicate high-fidelity performance in the circuits for 2-qubit and 3-qubit quantum Fourier transforms, and for quantum search on 4-item and 8-item databases.

NOEL TABIA, Univ of Tartu — Inductive linear optical networks have significantly improved the functionality and scalability of linear optical devices [1]. In this talk, I present recursive schemes based on linear optics employing few-photon interferometry. A geometric approach to state separation, submitted to NJP (2015). I conducted simulations of proof-of-principle experiments using a fabrication model of realistic errors in silicon-based photonic integrated devices. The results indicate high-fidelity performance in the circuits for 2-qubit and 3-qubit quantum Fourier transforms, and for quantum search on 4-item and 8-item databases.


3 This work was funded by institutional research grant IUT2-1 from the Estonian Research Council and by the European Union through the European Regional Development Fund.

12:03PM S44.00005 Quantum walks outside of boolean domain as a gate for one, two, or three qubits. THOMAS CAVIN, DMITRY SOLENOV, Department of Physics, Saint Louis University, St. Louis, MO 63103 — Quantum computing needs entangling quantum gates to perform computation and error correction. We will discuss a novel way to implement quantum gates, such as CNOT, using quantum walks that are directed through a network of states outside of the boolean domain. In such implementations it is important to investigate walks on networks of different connectivities. Specifically, we will discuss solutions to non-symmetric linear chain networks and demonstrate how solutions to more complex networks that have branching, such as cubes, can be expressed in terms of linear chain solutions. We then show examples of implementing single qubit and two-qubit entangling gates.

12:15PM S44.00006 Duality quantum computer and the efficient quantum simulations. SHIJIE WANG, GUILU LONG, Tsinghua Univ, TSINGHUA NATIONAL LABORATORY FOR INFORMATION SCIENCE AND TECHNOLOGY COLLABORATION, COLLABORATIVE INNOVATION CENTER OF QUANTUM MATTER COLLABORATION, Department of Physics, Tsinghua University, Beijing, China — Duality quantum computer is a new kind of quantum computer which is able to perform an arbitrary sum of unitaries, and therefore a general quantum operator. This gives more computational power than a normal quantum computer. All linear bounded operators can be realized in a duality quantum computer, and unitary operators are just the extreme points of the set of all quantum operators. Duality quantum computer can provide flexibility and clear physical picture in designing quantum algorithms, serving as a useful bridge between quantum and classical algorithms. In this report, we will firstly briefly review the theory of duality quantum computer. Then we will introduce the application of duality quantum computer in Hamiltonian simulation. We will show that duality quantum computer can simulate quantum systems more efficiently than ordinary quantum computer by providing descriptions of the recent efficient quantum simulation algorithms.

12:27PM S44.00007 Optimized probabilistic quantum processors: A unified geometric approach. KERNING CHAN, JANOS BERGOU, CUNY Hunter College, EMILIO BAGAN, Fisica Teorica: Informacio i Fenomens Quantics, Universitat Autonoma de Barcelona, EDGAR FELDMAN, Department of Mathematics, Graduate Center of the City University of New York — Using probabilistic [1] and deterministic quantum cloning [2], and quantum state separation [3] as illustrative examples we develop a complete geometric solution for finding their optimal success probabilities. The method is related to the approach that we introduced earlier for the unambiguous discrimination of more than two states [4]. In some cases the method delivers analytical results, in others it leads to intuitive and straightforward numerical solutions. We also present implementations of the schemes based on linear optics employing few-photon interferometry. A geometric approach to state separation, submitted to NJP (2015).

12:39PM S44.00008 Three step implementation of any unitary matrix with complete graph of n qubits. AMARA KATABARWA, MICHAEL GELLER, Univ of Georgia — The use of programmable array of superconducting qubits for general purpose quantum computation has been continuously proposed, and applications to amplitude amplification, phase estimation and simulation of realistic molecular collisions.

This Single Excitation Subspace (SES) approach does not require error correction and is practical now. We show that any element in the unitary group U(n) can be generated in three steps, for any n. This allows for implementation of highly complex operations in constant time.

12:51PM S44.00009 Recursive linear optical networks for realizing quantum algorithms.

NOEL TABIA, Univ of Tartu — Linear optics has played a leading role in the development of practical quantum technologies. In recent years, advances in integrated quantum photonic systems have significantly improved the functionality and scalability of linear optical devices [1]. In this talk, I present recursive schemes for implementing quantum Fourier transforms and inversion about the mean in Grover’s algorithm with photonic integrated circuits [2]. By recursive, I mean that two copies of a d-dimensional unitary operation is used to build the corresponding unitary operation on 2d modes. The linear optical networks operate on path-encoded qubits and realize d-dimensional unitary operations using O(d2) elements. To demonstrate that the recursive circuits are viable in practice, I conducted simulations of proof-of-principle experiments using a fabrication model of realistic errors in silicon-based photonic integrated devices. The results indicate high-fidelity performance in the circuits for 2-qubit and 3-qubit quantum Fourier transforms, and for quantum search on 4-item and 8-item databases.

the Departamento Administrativo de Ciencia, Tecnologia e Innovacion (COLCIENCIAS) of Colombia under grant number

birth as the number of photons increase. We furthermore propose an experiment called quantum discord gates where discord is zero or non-zero depending on experimental purposes such as: Robust states against change of manifold or dissipation, tunable entanglement states and states with a counterintuitive sudden information about correlations at a certain time. Depending on the initial conditions, this model exhibits a fascinating range of phenomena that can be used for distinguishable from the point of view of quantum discord, states where the two quantifiers give opposite information and states where they give roughly the same and quantum discord are far from being trivial or intuitive. In this context, we find states that are indistinguishable from the point of view of entanglement and to the choice of initial conditions. Through a comprehensive analysis, supported by explicit analytical calculations, we find that the dynamics of entanglement

1:27PM S44.00012 Universal Linear Optics: A Testbed for Optical Quantum Logic . CHRIS SPARRROW, Centre for Quantum Photonics, University of Bristol, UK and Department of Physics, Imperial College London, UK, JACQUES CAROLAN, CHRISTOPHER HARROLD, NICHOLAS RUSSELL, GRAHAM MARSHALL, JOSHUA SILVERSTONE, MARK THOMPSON, JONATHAN MATTHEWS, JEREMY O'BRIEN, ANTHONY LAING, Centre for Quantum Photonics, University of Bristol, UK, ENRIQUE MARTIN-LOPEZ, Nokia Technologies, Cambridge, UK, PETER SHADBOLT, Department of Physics, Imperial College London, UK, NOBUYUKI MATSUDA, NTT Basic Research Laboratories, NTT Corporation, Japan, MANABU OGUMA, MIKIYUKI ITOH, TOSHIZUKU HASHIMOTO, NTT Device Technology Laboratories, NTT Corporation, Japan — Linear optics is a promising platform for scalable quantum information processing. We demonstrate a single reprogrammable optical circuit that is sufficient to implement all possible linear optical protocols up the size of the circuit [Carolan et al., Science, 349, (2015)]. The system is an ideal testbed for rapidly prototyping new linear optical quantum gates, and testing known protocols in experimentally realistic scenarios. We use the device to perform a series of postselected and heralded quantum logic gates including a new scheme for heralded bell state generation, a key primitive in measurement-based linear optical quantum computation. We propose and demonstrate techniques for efficiently and accurately characterising and verifying these gates operation. The ability to rapidly reprogram linear optical devices promises to replace a multitude of existing and future prototype systems, pointing the way to applications across quantum technologies.

1:39PM S44.00013 Entanglement Dynamics in Heisenberg spin systems coupled to a dissipative environment , GEHAD SADIEK, Department of Applied Physics, University of Sharjah, Sharjah 27272, UAE, SAMAHER ALMALKI, Department of Physics, King Saud University, Riyadh 11451, Saudi Arabia — Heisenberg Spin chains and lattices have been intensively used to represent many of the physical systems that are considered as promising candidates for quantum computing and quantum information processing. The main obstacle toward realizing the ultimate goals in these fields is decoherence caused by the surrounding dissipative and thermal environments. We are studying spin relaxation and entanglement dynamics in one and two-dimensional XYZ Heisenberg spin systems under coupling with a dissipative Lindblad environment at finite temperature. We investigate the effect of the anisotropy of the coupling between the spins on the asymptotic steady state of the system and the spin relaxation rates at different temperatures of the environment. We demonstrate the role played by the initial system setup on the entanglement and spin dynamics and steady state properties. Also we examine the effect of the long range interaction between the spins on the asymptotic behavior of the system.

1:51PM S44.00014 Geometrical, response, and gap properties of Lindbladians , VICTOR V. ALBERT, Yale University, BARRY BRADLYN, Princeton University, MARTIN FRAAS, University of Munich, LIANG JIANG, Yale University — We study Lindbladians admitting multi-dimensional steady-state subspaces (SSS) which can be used to store, protect, and process quantum information. We derive an analytical formula for the left eigenmatrices of such Lindbladians corresponding to purely imaginary eigenvalues. This formula resolves how Lindbladian evolution affects perturbative response and geometrical features of the SSS and allows us to generalize recent work to all types of SSS. We show that Hamiltonian and certain jump operator perturbations induce, to first order, exclusively unitary evolution on the SSS. Similarly, the holonomy (generalization of geometric phase) induced on the SSS after adiabatic traversal of a closed path in parameter space is unitary. We derive a new Riemannian metric tensor in parameter space induced by one-type of SSS, generalizing the Fubini-Study metric to Lindbladians possessing one or more mixed steady states. We derive a Kubo formula governing linear response of the SSS to Hamiltonian perturbations. Finally, we show that the energy scale governing leakage out of the SSS is different from the conventional Lindbladian dissipative gap.

Thursday, March 17, 2016 11:15AM - 2:03PM –

Session S45 GQ1 DAMOP: Atomic, Molecular and Optical Quantum Information and Metrology

348 - Jonathan Home, ETH

11:15AM S45.00001 Quantum Rabi Model in Quantum Technologies , JULIEN PEDERNALES, URTZI LAS HERAS, LUCAS LAMATA, University of the Basque Country, Spain, ENRIQUE SOLANO, University of the Basque Country and IKERBASQUE, Spain — We will discuss how to simulate a wide range of regimes of the Quantum Rabi Model (QRM) in quantum platforms as trapped ions and circuit QED. Directly accesible regimes of the QRM correspond to a very narrow set of values of the ratio between the coupling strength and the characteristic frequencies of the system, typically in the strong coupling regime or in the perturbative zone of the ultrastrong coupling regime. However, with analog and digital quantum simulation techniques we can access the most elusive regimes of the QRM. Recent theoretical developments have disclosed a plethora of physical phenomena appearing at these previously unexplored regimes of the QRM, making its experimental implementation timely and of high interest.

11:27AM S45.00002 What can we learn from the dynamics of entanglement and quantum discord in the Tavis-Cummings model?1 , JULIANA RESTREPO, Universidad Antonio Nario, BORIS A. RODRIGUEZ, Universidad de Antioquia — We revisit the problem of the dynamics of quantum correlations in the exact Tavis-Cummings model. We show that many of the dynamical features of quantum discord attributed to dissipation are already present in the exact framework and are due to the well known non-linearities in the model and to the choice of initial conditions. Through a comprehensive analysis, supported by explicit analytical calculations, we find that the dynamics of entanglement and quantum discord are far from being trivial or intuitive. In this context, we find states that are indistinguishable from the point of view of entanglement and distinguishable from the point of view of quantum discord, states where the two quantities give opposite information and states where they give roughly the same information about correlations at a certain time. Depending on the initial conditions, this model exhibits a fascinating range of phenomena that can be used for experimental purposes such as: Robust states against change of manifold or dissipation, tunable entanglement states and states with a counterintuitive sudden birth as the number of photons increase. We furthermore propose an experiment called quantum discord gates where discord is zero or non-zero depending on the number of photons.

1This work was supported by the Vicerrectoría de Investigación of the Universidad Antonio Nario, Colombia under project number 20141031 and by the Departamento Administrativo de Ciencia, Tecnología e Innovacion (COLCIENCIAS) of Colombia under grant number

11:39AM S45.00003 ABSTRACT WITHDRAWN

11:51AM S45.00004 Robust quantum state transfer with suppressed parametric noise , MENGZHEN ZHANG, CHANGLING ZOU, LIANG JIANG, Yale University — For opto-electro-mechanical transducers, there are undesirable parametric processes that introduce parametric noise, which will limit the fidelity of the transferred quantum state[1]. To overcome this imperfection, we propose a quantum state transfer scheme with squeezed input states and measurement dependent compensation to eliminate the parametric noise from the quantum state transfer. Besides parametric noise, we also investigate the sensitivity of our scheme to thermal noise, signal frequency detuning and imperfect impedance matching, and show a good quantum state fidelity and applicability to quantum state transfer.

in the bit density could be achieved with the aid of super resolution microscopy techniques already employed to discriminate between NVs with sub-diffraction, preserves information written on different planes of the diamond crystal and thus serves as a platform for three-dimensional storage. Substantial enhancement allows us to transition from binary to multi-valued encoding, which translates into a significant storage capacity boost. Finally, we show that our technique with 2-D binary bit density comparable to present DVD-ROM technology. The strong fluorescence signal originating from the diffraction-limited bit volume diamond to demonstrate fluorescence-encoded long-term storage of classical information. As a proof of principle, we write, reset, and rewrite various patterns initialize the NV charge state, which has an immediate impact on the center's light emission properties. Here, we use two-color microscopy in NV-rich, type-1b nanoscale metrology. Of interest in these applications is the manipulation of the NV charge state, which can be attained by optical illumination. Here we use 12:39PM S45.00009 Optical patterning of trapped charge in nitrogen-doped diamond1. SIDDHART DHOMKAR, HARISHANKAR JAYAKUMAR, DANIELA PAGLIERO, ABDELGHANI LARAOU, REMUS ALBU, City College of New York-CUNY, Graduate Center-CUNY, SIDDHART DHOMKAR, City College of New York-CUNY, CARLOS MERILES, City College of New York-CUNY, Graduate Center-CUNY, HARISHANKAR JAYAKUMAR, City College of New York- CUNY — The nitrogen-vacancy (NV) center in diamond is the best-known and most-studied defect center, and has proven to be a good proof-of-principle structure for demonstrating the use of such defects in quantum technologies. Increasingly, however, there is an interest in exploring deep defects in alternative semiconductors such as SiC. This is due to the challenges posed by diamond as host material for defects, as well as the attractive properties of SiC. In this density functional theory work, we study the spin-1 structure of the negatively charged NV-center in two polytypes: 3C-SiC and 4H-SiC. The calculated zero phonon line for the excited state of 3C-SiC is in telecom range (0.90 eV), making it a very good candidate for quantum technologies. This work provides basic ingredients required to understand the physics of this color center at a quantitative and qualitative level. We also design quantum information applications, such as a spin-photon interface and multi-photon entanglement.

Towards High Density 3-D Memory in Diamond1. JACOB HENSHAW, City College of New York- CUNY, Graduate Center-CUNY, SIDDHARTH DHOMKAR, City College of New York-CUNY, CARLOS MERILES, City College of New York-CUNY, Graduate Center-CUNY, HARISHANKAR JAYAKUMAR, City College of New York- CUNY — The nitrogen-vacancy (NV) center in diamond is presently the focus of widespread attention for applications ranging from quantum information processing to nanoscale metrology. Of great utility is the ability to optically initialize the NV charge state, which has an immediate impact on the center's light emission properties. Here, we use two-color optical microscopy to investigate the dynamics of NV photo-ionization, charge diffusion, and trapping in type-1b diamond. We combine fixed-point laser excitation and scanning fluorescence imaging to locally alter the concentration of negatively charged NVs and to subsequently probe the corresponding redistribution of charge. We uncover the formation of various spatial patterns of trapped charge, which we semi-quantitatively reproduce via a model of the interplay between photo-excited carriers and atomic defects in the diamond lattice. Further, by using the NV as a local probe, we map the relative fraction of positively charged nitrogen upon localized optical excitation. These observations may prove important to various technologies, including the transport of quantum information between remote NVs and the development of three-dimensional, charge-based memories.

We acknowledge support from the National Science Foundation through grant NSF-1314205.

12:15PM S45.00006 Maximal adaptive-decision speedups in quantum-state readout1, BENJAMIN D’ANJOU, LOUTFI KURET, LILIAN CHILDRESS, WILLIAM A. COISH, McGill University — The average time $T$ required for high-fidelity readout of quantum states can be significantly reduced via a real-time adaptive decision rule. An adaptive decision rule stops the readout as soon as a desired level of confidence has been achieved, as opposed to setting a fixed readout time $t_f$. The performance of the adaptive decision is characterized by the “adaptive-decision speedup” $t_{f}/T$. In this work, we reformulate this readout problem in terms of the first-passage time of a particle undergoing stochastic motion. This formalism allows us to theoretically establish the maximum achievable adaptive-decision speedups for several physical two-state readout implementations. We show that for two common readout schemes (the Gaussian latching readout and a readout relying on state-dependent decay), the speedup is bounded by 4 and 2, respectively, in the limit of high single-shot readout fidelity. We experimentally study the achievable speedup in a real-world scenario by applying the adaptive decision rule to a readout of the nitrogen-vacancy-center (NV-center) charge state. We find a speedup of $\approx 2$ with our experimental parameters. Our results should lead to immediate improvements in nano-scale magnetometry based on spin-to-charge conversion of the NV-center spin.

1We acknowledge support from NSERC, INTRIQ, CIFAR and the Walter C. Sumner Foundation.

12:03PM S45.00005 High efficiency in Mode Selective Frequency Conversion for Optical Quantum Information Processing, NICOLAS QUESADA, Universite de Sherbrooke, J.E. SIPE, University of Toronto — Mode selective Frequency conversion (FC) is an enabling process in many quantum information protocols. Recently, it has been observed that upconversion efficiencies in single-photon, mode-selective FC are limited to around 80%. In this contribution we show that these limits can be understood as time ordering corrections (TOCs) that modify the joint conversion amplitude of the process. Furthermore we show, using a simple scaling argument, that recently proposed cascaded FC protocols that overcome the aforementioned limitations act as “attenuators” of the TOCs. This observation allows us to argue that very similar cascaded architectures can be used to attenuate TOCs in photon generation via spontaneous parametric down-conversion. Finally, by using the Magnus expansion, we argue that the TOCs, which are usually considered detrimental for FC efficiency, can also be used to increase the efficiency of conversion in partially mode selective FC.

Quantum memory enhanced nuclear magnetic resonance of nanometer-scale samples with a single spin in diamond, NABEEL ASLAM, MATTHIAS PFENDER, SEBASTIAN ZAISER, FELIPE FAVARO DE OLIVEIRA, ÁLI MOMENZADEH, ANDREJ DENISENKO, 3 rd Physics Institute, University of Stuttgart, JUNICHI ISOYA, Research Center for Knowledge Communities, University of Tsukuba, PHILIPP NEUMANN, JOERG WRACHERTRUP, 3 rd Physics Institute, University of Stuttgart — Recently nuclear magnetic resonance (NMR) of nanoscale samples at ambient conditions has been achieved with nitrogen-vacancy (NV) centers in diamond. So far the spectral resolution in the NV NMR experiments was limited by the sensor’s coherence time, which in turn prohibited revealing the chemical composition and dynamics of the system under investigation. By entangling the NV electron spin sensor with a long-lived memory spin qubit we increase the spectral resolution of NMR measurement sequences for the detection of external nuclear spins. Applying the latter sensor-memory couple it is particularly easy to track diffusion processes, to identify the molecules under study and to deduce the actual NV center depth inside the diamond. We performed nanoscale NMR on several liquid and solid samples exhibiting unique NMR response. Our method paves the way for nanoscale identification of molecule and protein structures and dynamics of conformational changes.

Single molecule spin resonance spectroscopy and imaging by diamond-sensor, JIANGFENG DU, University of Science and Technology of China — Single-molecule magnetic resonance spectroscopy and imaging is one of the ultimate goals of nanoscale biophysical science and will have great applications in a broad range of scientific areas, from life science to physics and chemistry. The spin of a single nitrogen vacancy (NV) center in diamond is a highly sensitive magnetic-field sensor, which has been proposed for detection of single molecules or nanoscale targets. We and co-workers have successfully obtained the first single-protein spin resonance spectroscopy under ambient conditions [1], high-resolution vector microwave imaging [2], and realized atomic-scale structure analysis of single nuclear-spin clusters in diamond [3]. Moreover, we have tried to improve the quantum control technique and succeed to achieve fault-tolerant universal quantum gates [4]. As the last part, I will briefly introduce our most recently work on single protein imaging in situ in cell. References: [1] Fazhan Shi, et al., Science, 347, 1135 (2015) [2] Pengfei Wang, et al., Nature Comm.,6, 6631 (2015) [3] Fazhan Shi, et al., Nature Physics, 10, 21 (2014) [4] Xing Rong, et al., Nature Comm., In press (2015)

Beating the Shot-Noise Limit with Partially-Distinguishable Photons, PATRICK M. BIRCHALL, JAVIER SABINES-CHESTERKING, JEREMY L. OBRHEN, HUGO CABLE, JONATHAN C. F. MATTHEWS C. F. MATTHEWS, Centre for Quantum Photonics, University of Bristol — Quantum metrology promises high-precision measurements beyond the capability of any classical techniques. This has the potential to be an integral part of investigative techniques, utilised across all areas of science and technology. However, all sensors must be able to operate despite imperfections to be of practical use. Proposals for photonic quantum sensors typically exploit quantum interference between photons which are perfectly indistinguishable, but achieving this indistinguishability can be a major technical challenge in practice, in particular with immature but promising approaches to photon sources. Here we show that highly indistinguishable photons are not required for quantum-enhanced measurements, nor do partially distinguishable photons have to be engineered to mitigate the effects of distinguishability. We conduct an experiment to verify the utility of two- and four-photon states containing partially distinguishable particles by performing quantum-enhanced measurements with low-sensitivity quantum interference. This demonstrates that sources producing spectrally-mixed single photons can be readily applied in quantum metrology systems.

How zero light intensity can exert a nonzero force on a charged particle, JUSTIN DRESSEL, JEFF TOLLAKSEN, Chapman University, YAKIR AHARONOV, Chapman University, Tel Aviv University — A classical electromagnetic field is deterministic and fully specified by a single temporal boundary condition. In contrast, a quantum electromagnetic field is irreducibly stochastic, such that only its average corresponds to a classical field for large ensembles of measurements. Such a field-average may be further refined by a second temporal boundary condition, which can expose fundamentally different classical fields in the same classical averaging limit. To demonstrate this, we consider an ensemble of coherent laser pulses that interact with identically prepared test charges before being collected at an intensity meter. Isolating only the pulses with zero collected intensity reveals a nonzero average classical force on the charge from those pulses. The charge is affected with no light collected.

Sub-Cycle Quantum Optics: Direct Access to Electric Field Vacuum Fluctuations, DENIS SELETSKY, CLAUDIUS RIEK, ANDREY MOSKALENKO, JAN SCHMIDT, PHILIPP KRAUSPE, SEBASTIAN ECKART, STEFAN EGGERT, GUIDO BURKARD, ALFRED LEITENSTORFER, University of Konstanz — Vacuum fluctuations are fundamental to a variety of physical aspects ranging from spontaneous photon emission to the Casimir force and will have great applications in a broad range of scientific areas, from life science to physics and chemistry. In common approaches, such as for example homodyne detection, the information is averaged over multiple cycles of light and amplification to finite intensity is mandatory. Usually, ultrashort pulses are applied for quantum measurements within a slowly-varying envelope approximation. We demonstrate direct detection of the vacuum fluctuations of the local electric field amplitude in free space. Broadband electro-optic sampling with sub-6 femtosecond gate pulses enables quantum-statistic readout [1]. Distinction from the detector shot noise is achieved by modification of the sampled space-time volume. Measuring with a bandwidth matching the 70 THz center frequency maximizes the vacuum amplitude since the ground-state energy approaches half a photon per optical cycle. Our findings open up a new avenue to quantum analysis and manipulation of light working in the time domain and with sub-cycle access to the electric field quadrature.

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a recently developed impedance matching technique. This is achieved by introducing a positive linear slope in the imaginary component of the input impedance seen by the JPA using a

parameterized design to enhance the bandwidth of a resonator based Josephson Parametric Amplifier (JPA) beyond the standard gain-bandwidth product. This is achieved by introducing a controlled reactance in the signal chain. The design was based on a \( \lambda/2 \) transformer. Our theoretical model predicts an extremely flat gain profile with a bandwidth enhancement proportional to the square root of the amplitude of the input signal. Experimentally, we achieved a nearly flat 20 dB gain profile over a 640 MHz band, with a mean 1-dB compression point of -110 dBm along with nearly quantum-limited noise performance. The results are in excellent agreement with our theoretical model. We will then discuss strategies to further enhance the performance in terms of bandwidth and dynamic range of the JPA. Finally, we will consider the applicability of our technique to different parametric pumping methods and other parametric amplifier designs as well.
12:51PM S48.00009 Microwave response and photon emission of a voltage based Josephson junction. SALHA JEBARI, ALEXANDER GRIMM, DIBYENDU HAZRA, MAX HOFHEINZ, CEA Grenoble — The readout of superconducting qubits requires amplifiers combining noise close to the quantum limit, high gain, large bandwidth, and sufficient dynamic range. Josephson parametric amplifiers using Josephson junctions in the 0-voltage state, driven by a large microwave signals, begin to perform sufficiently well in all 4 of these aspects to be of practical use, but remain difficult to optimize and use. Recent experiments with superconducting circuits consisting of a DC voltage-biased Josephson junction in series with a resonator, showed that a tunneling Cooper pair can emit one or several photons with a total energy of 2e times the applied voltage. We present microwave reflection measurements on this device indicating that amplification is possible with a simple DC voltage-biased Josephson junction. We compare these measurements with the noise power emitted by the junction and show that, for low Josephson energy, transmission and noise emission can be explained within the framework of P(E) theory of inelastic Cooper pair tunneling. Combined with a theoretical model, our results indicate that voltage-biased Josephson junctions might be useful for amplification near the quantum limit, offering simpler design and a different trade-off between gain, bandwidth and dynamic range.

1:03PM S48.00010 Estimation of the projection error of a qubit readout by quantum Zeno effect. KOSUKE KAKUYANAGI, YUICHIRO MATSUZAKI, HAYATO NAKANO, NTT Basic Research Laboratories, KOUCHI SEMBA, National Institute of Information and Communications Technology, SHIRO SAITO, NTT Basic Research Laboratories — In a quantum system, frequent projection operations can suppress a specific kind of time evolutions that show quadratic behavior in a time domain. This phenomenon is known as quantum Zeno effect (QZE). Normally, projection operations freeze the qubit state so that the qubit remains in the initially prepared state such as a ground state or an excited state. However, if a projection error occurs, qubit state is flipped. In this case, frequent projection operations do not keep qubit state. This means that, by investigating the efficiency of the QZE, we can in principle estimate the projection error rate of the qubit readout system. A Josephson bifurcation amplifier (JBA) readout method provides us a way to perform fast and low back-action superconducting qubit readout. We fabricate a sample that has a JBA resonator coupled to the superconducting flux qubit. By using this sample, we demonstrated QZE by applying multiple readout pulses during Rabi oscillations. Because of the multiple readout pulses, Rabi oscillation was suppressed and the qubit was kept in its initial state. From the holding time of the state via the QZE, we concluded that the projection error of the JBA readout is less than 2%.

1:15PM S48.00011 Single-shot Readout of a Superconducting Qubit using a Josephson Parametric Oscillator. PHILIP KRANTZ, ANDREAS BENGTSSON, MICHAEL SIMOEN, Chalmers, SIMON GUSTAVSSON, MIT, VITALY SHUMEIKO, Chalmers, W. D. OLIVER, MIT, MIT Lincoln Laboratory, C. M. WILSON, Waterloo, PER DELSING, JONAS BYLANDER, Chalmers — We propose and demonstrate a new read-out technique for a superconducting qubit by dispersively coupling it to a Josephson parametric oscillator. We employ a tunable quarter-wavelength superconducting resonator and modulate its resonant frequency at twice its value with an amplitude surpassing the threshold for parametric instability. We map the qubit states onto two distinct states of classical parametric oscillation: one oscillating state, with 185 photons in the resonator, and one with zero oscillation amplitude. This high contrast obviates a following quantum-limited amplifier. We demonstrate proof-of-principle, single-shot readout performance, and present an error budget indicating that this method can surpass the fidelity threshold required for quantum computing.

1:27PM S48.00012 SLUG Microwave Amplifier as a Nonreciprocal Gain Element for Scalable Qubit Readout. TED THORBECK, EDWARD LEONARD, SHAOJIANG ZHU, ROBERT MCDERMOTT, University of Wisconsin - Madison — Josephson parametric amplifiers for superconducting qubits require several stages of cryogenic isolation to protect the qubit from strong microwave pump tones and downstream noise. But isolators and circulators are large, expensive and magnetic, so they are an obstacle to scaling up a superconducting quantum computer. In contrast, the SLUG (Superconducting Low-inductance Undulatory Galvanometer) is a high gain, broadband, low noise microwave amplifier that provides built-in reverse isolation. Here, we describe the dependence of the SLUG reverse isolation on signal frequency and device operating point. We show that the reverse isolation of the SLUG can be as large as or larger than that of a bulk commercial isolator. Finally, we discuss the use of the SLUG to read out a transmon qubit without isolators or circulators.

1:39PM S48.00013 Noise Characteristics of the Josephson Amplifiers by Stochastic Calculus. WENSHUO LIU, ROBERT MCDERMOTT, MAXIM VAVILOV, University of Wisconsin, Madison — We present theoretical studies of the noise performance of non-reciprocal gain elements based on Josephson junctions including the SQUID and the SLUG. We develop a perturbative approach by means of stochastic calculus which combines both analytical and numerical methods, and calculate the noise characteristics of the amplifiers in the thermal regime. We show that noise in the amplifiers originates mainly from the dispersive behavior of phase slips. This new method could help with the optimization of Josephson amplifiers for high-fidelity multiplexed qubit readout.

1:51PM S48.00014 Qubit Readout with the Josephson Photomultiplier. IVAN PECHENEZHISKII, GUILHEM RIBEIL, University of Wisconsin, Madison, M. HUTCHINGS, CALEB HOWINGTON, Syracuse University, MAXIM VAVILOV, University of Wisconsin, Madison, FRANK WILHELM, Saarland University, B.L.T. PLOURDE, Syracuse University, ROBERT MCDERMOTT, University of Wisconsin, Madison — The realization of a large-scale fault-tolerant quantum processor will require scalable high-fidelity readout of multiqubit parity operators. Here we describe development of a scalable qubit measurement approach based on microwave photon counting. The measurement protocol involves mapping the qubit state to photon occupation of bright and dark cavity pointer states, followed by photodetection using the Josephson photomultiplier (JPM). We discuss use of the qubit as a calibrated source of photons to measure JPM quantum efficiency, and we describe global optimization of the measurement protocol. Finally, we discuss prospects for interfacing the JPM output to single flux quantum circuits to allow low-latency classical postprocessing of the qubit measurement result.

2:03PM S48.00015 Multi-qubit measurements with a Josephson Photomultiplier. CALEB HOWINGTON, M HUTCHINGS, Syracuse University, GUILHEM RIBEIL, IVAN PECHENEZHISKII, MAXIM G. VAVILOV, University of Wisconsin, FRANK K. WILHELM, Saarland University, R. MCDERMOTT, University of Wisconsin, BLT PLOURDE, Syracuse University — The ability to measure multi-qubit parity is critical for the realization of a fault-tolerant quantum information processor. For a system of transmon qubits coupled to a superconducting cavity, a threshold photon detector can provide an efficient path towards the digital readout of qubit parity after the parity information is mapped onto the cavity photon occupation. We will describe progress towards the implementation of such a scheme for measuring the parity of two transmon qubits. On-chip flux bias lines allow us to tune the dispersive cavity shifts related to the state of the two qubits and an appropriately shaped pulse driven to the cavity results in a bright state for one parity but not the other. A Josephson Photomultiplier then serves as a phase-insensitive digital detector of the microwave photons that leak out of the cavity. Future improvements and various technical difficulties will be discussed.

3We acknowledge support from ARO under Contract W911NF-14-1-0080.
2:30PM V44.00001 Second-Order Asymptotics for the Classical Capacity of Image-Additive Quantum Channels, MARCO TOMAMICHEL, University of Sydney — We study non-asymptotic fundamental limits for transmitting classical information over memoryless quantum channels, i.e., we investigate the amount of classical information that can be transmitted when a quantum channel is used a finite number of times and a fixed, non-vanishing average error is permissible. Specifically, we consider the classical capacity of quantum channels that are image-additive, including all classical to quantum channels, as well as the product state capacity of arbitrary quantum channels. In both cases, we show that the non-asymptotic fundamental limit admits a second-order approximation that illustrates the speed at which the rate of optimal codes converges to the Holevo capacity as the blocklength tends to infinity. The behavior is governed by a new channel parameter, called channel dispersion, for which we provide a geometrical interpretation.

3:06PM V44.00002 Quantum Coding with Finite Resources, MARIO BERTA, Caltech — The quantum capacity of a memoryless channel determines the maximal rate at which we can code reliably over asymptotically many uses of the channel. Here we argue that this asymptotic characterization is often insufficient in practice where decoherence severely limits our ability to manipulate large quantum systems in the encoder and decoder. For all practical purposes, we should instead focus on the optimal trade-off between three parameters: the rate of the code, the size of the quantum devices at the encoder and decoder, and the fidelity of the transmission. Towards this goal, we find approximate and exact characterizations of this trade-off for various channels, including dephasing, depolarizing and erasure channels. In each case, the trade-off is parameterized by the capacity and a second channel parameter, the quantum channel dispersion. In the process, we develop several general bounds that are valid for all finite-dimensional quantum channels and can be computed efficiently.

3:42PM V44.00003 Experimental loophole-free Bell inequality violation using electron spins separated by 1.3 km, B HENSEN, H BERNIEN, A E DRAEU, A REISERER, N KALB, M S BLOK, J RUITENBERG, R F L VERMEULEN, R N SCHOUTEN, QuTech & Kavli Inst. of Nanoscience, Delft Univ. of Tech., The Netherlands, C ABELLAN, W AMAYA, V PRUNERI, M W MITCHELL, ICFO-Institut de Ciencies Fotoniques, The Barcelona Inst. of Sc. and Tech., Spain, M MARKHAM, D J TWITCHEN, Element Six Innovation, Didcot, Oxfordshire, UK, D EIKOUS, S WEHNER, QuTech, Delft Univ. of Tech., The Netherlands, T H TAMINIAU, R HANSON, QuTech & Kavli Inst. of Nanoscience, Delft Univ. of Tech., The Netherlands — 50 years ago [1], John Bell proved that no theory of nature that obeys locality and realism can reproduce all the predictions of quantum theory. Numerous Bell inequality tests have been reported, however, all experiments reported so far required additional assumptions to obtain a contradiction with local realism, resulting in loopholes. Here we will present [2] a Bell experiment that is free of any such additional assumption. We use an event-ready scheme that enables the generation of robust entanglement between distant electron spins. Efficient spin read-out avoids the fair-sampling assumption, while the use of fast random-basis selection and spin read-out combined with a spatial separation of 1.3 km ensure the required locality conditions. We performed 245 trials that tested the CHSH–Bell inequality $S \leq 2$ and found $S = 2.42 \pm 0.20$. A null-hypothesis test yields a probability of $P < 0.039$ that a local-realistic model for space-like separated sites could produce data with a violation at least as large as we observe, even when allowing for memory in the devices. [1] J.S. Bell, Physics 1, 195-200, (1964) [2] Hensen et al. Nature 526, 682 (2015)

3:54PM V44.00004 Beating the Classical Limits of Information Transmission using a Quantum Decoder, AKIB KARIM, ZIXIN HUANG, ROB CHAPMAN, University of Sydney, RMIT University, MARCO TOMAMICHEL, STEVE FLAMMIA, University of Sydney, ALBERTO PERUZZO, University of Sydney, RMIT University — Reliable transmission of information over a noisy channel is a fundamental challenge in communication theory. The emergence of quantum technologies has created a new class of strategies that allow for message recovery greater than purely classical methods. Despite this, for many uses of the channel, finding such schemes remains a challenge. We investigate the amplitude damping channel, which describes physical systems that suffer energy loss such as in cavity quantum electrodynamics or spin chain excitations. We derive and experimentally demonstrate the fundamental limit for message recovery possible with only classical methods. We then propose a quantum decoder and experimentally demonstrate message recovery past this classical limit. We use polarisation-encoded photonic qubits. The post-amplitude damping states are generated by an unbalanced Mach–Zehnder interferometer and entanglement is accomplished with a linear optical probabilistic controlled z gate. Our quantum decoder uses a single entangling gate at the receiver where other similar schemes rely on both the sender and the receiver having quantum devices. Our results present an advance in discovering the quantum capabilities of finite resource communications, with specific regard to the amplitude damping channel.

4:06PM V44.00005 Quantum Key Distribution based on Silicon Integrated Photonic Devices, DARUJS BUNANDAR, NICHOLAS HARRIS, ZHESHEN ZHANG, Massachusetts Inst of Tech-MIT, RAN DING, TOM BAEHR-JONES, MICHAEL HOCHBERG, Coriant Advanced Technology Group, JEFFREY SHAPIRO, FRANCO WONG, DIRK ENGLUND, Massachusetts Inst of Tech-MIT — We present a compact quantum key distribution (QKD) transmitter near a 1550-nm wavelength using microring modulators implemented on a silicon-on-insulator photonics platform. The transmitter generates time-bin based qubits with a temporal FWHM of 940 ps and an extinction ratio beyond 16 dB. We prove the feasibility of the transmitter with a coherent one-way QKD protocol, where the bit string is encoded in the arrival time of the time-bin qubits and possible eavesdropping is monitored via the interference visibility of neighboring time-bin qubits. The receiver consists of an asymmetric beamsplitter, which provides a random choice of measurement basis, followed by either a superconducting nanowire single-photon detector (SNPD) or an unbalanced Michelson interferometer with SNSPDs. This experiment demonstrates the feasibility of high-speed QKD based on CMOS-compatible silicon photonics integrated circuits.

4:18PM V44.00006 Quantum Versus Classical Advantages in Secret Key Distillation (and Their Links to Quantum Entanglement), ERIC CHITAMBAR, BENJAMIN FORTESCUE, Southern Illinois University Carbondale, MIN-HSIU HSIEH, University of Technology Sydney — We consider the extraction of shared secret key from correlations that are generated by either a classical or quantum source. In the classical setting, two honest parties (Alice and Bob) use public discussion and local operations to distill secret key from some information of common source. In the quantum setting, the correlations are generated incoherently in the quantum setting. For coherent sources, we next show that the rates are incomparable, and in fact, their difference can be arbitrarily large in either direction. However, we identify a large class of non-trivial distributions that possess the following properties: (i) Eve’s advantage is always greater in the quantum source than classically, and (ii) for the entanglement shared in the coherent source, the so-called entanglement cost/squashed entanglement/relative entropy of entanglement can all be computed. We thus present a rare instance in which various entropic entanglement measures of a quantum state can be explicitly computed.
4:30PM V44.00007 Unstructured quantum key distribution, PATRICK COLES, ERIC METODIEV, NORBERT LUTKENHAUS, University of Waterloo — Quantum key distribution (QKD) allows for communication with security guaranteed by quantum theory. The main theoretical problem in QKD is to calculate the secret key rate for a given protocol. Analytical formulas are known for protocols with high degree of symmetry, since symmetry simplifies the analysis. However, experimental imperfections break symmetries, hence the effect of imperfections on key rates is difficult to estimate. Furthermore, it is an interesting question whether (intentionally) asymmetric protocols could outperform symmetric ones. In this work, we develop a robust numerical approach for calculating the key rate for arbitrary discrete-variable QKD protocols. Ultimately this will allow researchers to study “unstructured” protocols, i.e., those that lack symmetry. Our approach relies on transforming the key rate calculation to the dual optimization problem, which dramatically reduces the number of parameters and hence the calculation time. We illustrate our method by investigating some unstructured protocols for which the key rate was previously unknown.

4:42PM V44.00008 A Contextuality Based Quantum Key Distribution Protocol, JAMES TROUPE, The University of Texas at Austin — In 2005 Spekkens presented a generalization of noncontextuality that applies to imperfect measurements (POVMs) by allowing the underlying hidden variable model to be indeterministic. In addition, unlike traditional Bell-Kochen-Specker noncontextuality, HV models of a single qubit were shown to be context under this definition. Thus, not all single qubit POVM measurement outcomes can be modeled classically. Recently M. Pusey showed that, under certain conditions, exhibiting an anomalous weak value (i.e. values outside the eigenspectrum of the observable) implies contextuality. We will present a new single qubit prepare and measure QKD protocol that uses observation of anomalous weak values of particular observables to estimate the quantum channel error rate and certify the security of the channel. We also argue that it is the “degree” of contextuality of the noisy qubits exiting the channel that fundamentally determine the secure key rate. A benefit of this approach is that the security does not depend on the fair sampling assumption, and so is not compromised by Eve controlling Bob’s measurement devices. Thus, it retains much of the benefit of “Measurement Device Independent” QKD protocols while only using single photon preparations and measurements.

5:06PM V44.00010 Long distance quantum communication using continuous variable encoding, LINSHU LI, VICTOR V. ALBERT, Yale University, MARIOS MICHAEL, Cambridge University, SRERAMAN MURALIDHARAN, CHANG-LING ZOU, LIANG JIANG, Yale University — Quantum communication enables faithful quantum state transfer between different parties and protocols for cryptographic purposes. However, quantum communication over long distances (>1000km) remains challenging due to optical channel attenuation. This calls for investigation on developing novel encoding schemes that correct photon loss errors efficiently. In this talk, we introduce the generalization of multi-component Schrödinger cat states [1] and propose to encode quantum information in these cat states for ultrafast quantum repeaters [2][3]. We detail the quantum error correction procedures at each repeater station and characterize the performance of this novel encoding scheme given practical imperfections, such as coupling loss. A comparison with other quantum error correcting codes for bosonic modes will be discussed. [1] M. Mirrahimi, Z. Leghtas, V. V. Albert, S. Touzard, R. J. Schoelkopf, L. Jiang, and M. H. Devoret, New J. Phys. 16, 045014 (2014). [2] S. Muralidharan, J. Kim, N. Lütkenhaus, M. D. Lukin, and L. Jiang, Phys. Rev. Lett. 112, 250501 (2014). [3] S. Muralidharan, L. Li, J. Kim, N. Lütkenhaus, M. D. Lukin, and L. Jiang, arXiv:1509.08435

5:18PM V44.00011 Quantum Secure Direct Communication in a noisy environment: Theory and Experiment, GUI LU LONG, Tsinghua University — Quantum communication holds promise for absolutely security in secret message transmission. Quantum secure direct communication (QSDC) is an important branch of the quantum communication in which secret messages are sent directly over a quantum channel with security[Phys. Rev. A 65 , 032302 (2002)]. QSDC offers higher security and is instantaneous in communication, and is a great improvement to the classical communication mode. It is also a powerful basic quantum communication primitive for constructing many other quantum communication tasks such as quantum bidding, quantum signature and quantum dialogue and so on. Since the first QSDC protocol proposed in 2000, it has become one of the extensive research focuses. In this talk, the basic ideas of QSDC will be reviewed, and major QSDC protocols will be described, such as the efficient-QSDC protocol, the two-step QSDC protocol, the one-time-pad QSDC protocol, the high-dimensional QSDC protocol and so on. Experimental progress is also developing steadily, and will also be reviewed. In particular, the quantum one-time-pad QSDC protocol has recently been successfully demonstrated experimentally[arXiv:1503.00451].

Thursday, March 17, 2016 2:30PM - 5:42PM —
Session V45 GQI: Semiconductor Qubits: Optical and Microwave Control
2:30PM V45.00001 Generation of heralded entanglement between distant quantum dot hole spins, AYMERIC DELTEIL, Institute of Quantum Electronics, ETH Zurich — Entanglement plays a central role in fundamental tests of quantum mechanics as well as in the burgeoning field of quantum information processing. Particularly in the context of quantum networks and communication, some of the major challenges are the efficient generation of entanglement between stationary (spin) and propagating (photon) qubits, the transfer of information from flying to stationary qubits, and the efficient generation of entanglement between distant stationary (spin) qubits. In this talk, I will present such experimental implementations achieved in our team with semiconductor self-assembled quantum dots. Not only are self-assembled quantum dots good single-photon emitters, but they can host an electron or a hole whose spin serves as a quantum memory, and then present spin-dependent optical selection rules leading to an efficient spin-photon quantum interface. Moreover, InAs quantum dots grown on GaAs substrate can profit from the maturity of III-V semiconductor technology and can be embedded in semiconductor structures like photonic cavities and Schottky diodes. I will report on the realization of heralded quantum entanglement between two semiconductor quantum dot hole spins separated by more than five meters. The entanglement generation scheme relies on single photon interference of Raman scattered light from both dots. A single photon detection projects the system into one of the two possible entangled states. We developed a delayed twin-photon interference scheme that allows for efficient verification of quantum correlations. Moreover the efficient spin-photon interface provided by self-assembled quantum dots allows us to reach an unprecedented rate of 2300 entangled spin pairs per second, which represents an improvement of four orders of magnitude as compared to prior experiments carried out in other systems. Our results extend previous demonstrations in single trapped ions or neutral atoms, in atom ensembles and nitrogen vacancy centers to the domain of artificial atoms, nanocircuit nanostructures that allow for on-chip integration of electronic and photonic elements. This work lays the groundwork for the realization of quantum repeaters and quantum networks on a chip.

3:06PM V45.00002 Polarisation singularities in disordered photonic crystal waveguides for on-chip spin-photon entanglement. DARYL BEGGS, BEN LANG, ANDREW YOUNG, RUTH OULTON, University of Bristol — A polarisation singularity occurs at a position in a vector field where one of the parameters of the local polarisation ellipse (handedness, eccentricity or orientation) becomes singular. With the vector nature of electromagnetic fields, optics is an obvious place for the study of polarisation singularities, and they can be found in systems ranging from tightly focused beams to speckle fields. Here we demonstrate that photonic crystal waveguides support on-chip polarisation singularities. As Bloch waves, the eigenmodes of photonic crystal waveguides possess a strong longitudinal, as well as transverse, component of their electric field. The spatial dependence of both these components and the phase between them ensures a rich and complex polarisation landscape in the waveguide. Recently, the use of polarisation singularities found in photonic crystal waveguides is generating much interest for integrated quantum information applications, as they can couple the spin-states of electrons confined to quantum dots to the optical modes of the waveguide. For example, at a circular-point (C-point), the sign of the local helicity is governed by the propagation direction of the optical mode, which allows for spin-photon coupling to one direction only. However, any real system will inevitably contain imperfections, and it is not obvious that the polarisation singularities will persist in the disordered waveguides. Here, we use calculations of the eigenmodes of disordered waveguides to demonstrate that the polarisation singularities persist far beyond realistically expected levels of disorder.

3:18PM V45.00003 Optical control of Berry phase in a diamond spin qubit1. CHRISTOPHER G. YALE, F. JOSEPH HEREMANS, BRIAN B. ZHOU, DAVID D. AWSCHALOM, Institute for Molecular Engineering, University of Chicago, ADRIAN AUER, GUIDO BURKARD, Department of Physics, University of Konstanz — Geometric phase, a fascinating quantum mechanical phenomenon that arises from cyclic state evolution, is a promising avenue to realize fault-tolerant quantum information processing. Here, we demonstrate an all-optical approach to accumulate a geometric phase, or Berry phase, within a solid-state spin qubit, the nitrogen-vacancy center in diamond. With stimulated Raman adiabatic passage (STIRAP), we evolve two light fields to cycle the resulting dark state of a low temperature lambda system in a ‘tangerine slice’ trajectory that we examine through time-resolved tomography. This type of trajectory acquires a Berry phase which we then measure through phase comparison to a reference state. We then probe the limits of this control as a result of adiabatic breakdown for short timescales and unintended excitation driven by far-detuned optical fields that accumulate for long timescales. We also investigate the intrinsic resilience of this Berry phase to noise introduced into the system, which is the focus of the following talk. As an all-optical approach, this geometric control represents a pathway to the development of optical geometric gates in the solid state.

3:30PM V45.00004 Robustness of optically-controlled Berry phase in a diamond spin qubit. BRIAN B. ZHOU, CHRISTOPHER G. YALE, F. JOSEPH HEREMANS, DAVID D. AWSCHALOM, Institute for Molecular Engineering, University of Chicago, Chicago, IL 60637, ADRIAN AUER, GUIDO BURKARD, Department of Physics, University of Konstanz, D-78457 Konstanz, Germany — The intrinsic noise resilience of geometric phases has motivated their application as an alternative protocol for realizing high fidelity quantum operations. Using stimulated Raman adiabatic passage (STIRAP) to cyclically evolve the dark state of a lambda system, we demonstrate all-optical control over Berry phase for a single spin in the solid state, the nitrogen vacancy center in diamond [1]. Here we introduce both phase and amplitude noise into the optical control fields for a class of ‘tangerine slice’ trajectories on the Bloch sphere. We examine the response of Berry phase to scaling of the noise amplitude and adiabatic cycle time, finding Berry phase to be unaffected by deviations parallel to the trajectory and to increase in robustness for long cycle times. Moreover, our noise resilience is independent of the value of the accumulated Berry phase, a property that differs from the behavior of circular trajectories investigated by prior microwave techniques. We also discuss potential improvements to our work.

3:42PM V45.00005 Quantum nanophotonics: Controlling a photon with a single spin1. EDO WAKS, Univ of Maryland-College Park — The implementation of quantum network and distributive quantum computation relies on strong interactions between stationary qubits and flying photons. The spin of a single electron confined in a quantum dot is considered as a promising matter qubit as it possesses macroscopic coherence time and allows picosecond timescale control using optical pulses. The quantum dot spin can also interact with a photon by controlling the optical response of a strongly coupled cavity. In this talk I will discuss our recent work on an experimental realization of a spin-photon quantum phase switch using a single spin in a quantum dot strongly coupled to a photonic crystal cavity. We show large modulation of the cavity reflection spectrum by manipulating the spin states of the quantum dot, which enables us to control the quantum state of a reflected photon. We also show the complementary effect where the presence of a single photon switches the quantum state of the spin. The reported spin-photon quantum phase operation can switch spin or photon states in picoseconds timescale, representing an important step towards GHz semiconductor based quantum logic devices on-a-chip and solid-state implementations of quantum networks.

1 Shuo Sun, Hyochul Kim, Glenn Solomon, co-authors

This work is supported by the AFOSR, NSF, and the German Research Foundation.
A quantum phase switch between a solid state spin and a photon.

SHOU SUN, HYOCHUL KIM, University of Maryland College Park, GLENN SOLOMON, National Institute of Standards and Technology, EDO WAKS, University of Maryland College Park — The implementation of quantum network and distributed quantum computation relies on strong interactions between stationary matter qubits and flying photons. The spin of a single electron confined in a quantum dot is considered as a promising matter qubit as it possesses microsecond coherence time and allows picosecond timescale control using optical pulses. The quantum dot spin can also interact with a photon by controlling the optical response of a strongly coupled cavity. In this talk I will discuss our recent work on an experimental realization of a spin-photon quantum phase switch using a single spin in a quantum dot strongly coupled to a photonic crystal cavity. We show large modulation of the cavity reflection spectrum by manipulating the spin states of the quantum dot, which enables us to control the quantum state of a reflected photon. We also show the complementary effect where the presence of a single photon switches the quantum state of the spin. The reported spin-photon quantum phase operation can switch spin or photon states in picoseconds timescale, representing an important step towards GHz semiconductor based quantum logic devices on-a-chip and solid-state implementations of quantum networks.

Efficient generation of indistinguishable single photons on-demand at telecom wavelengths.

JEHYUNG KIM, TAO CAI, Univ of Maryland-College Park, CHRISTOPHER RICHARDSON, RICHARD LEAVITT, Laboratory for Physical Science, EDO WAKS, Univ of Maryland-College Park — Highly efficient single photon sources are important building blocks for optical information processing. For practical use and long-distance quantum communication, single photons should have fiber-compatible telecom wavelengths. In addition, most quantum communication applications require high degree of indistinguishability of single photons, such that they exhibit interference on a beam splitter. However, deterministic generation of indistinguishable single photons with high brightness remains a challenging problem in particular at telecom wavelengths. We demonstrate a telecom wavelength source of indistinguishable single photons using an InAs/InP quantum dot in a nanophotonic cavity. To obtain the efficient single quantum dot emission, we employ the higher order mode in a L3 photonic crystal cavity that shows a nearly Gaussian transverse mode profile and results in out-coupling efficiency exceeding 46 % and unusual bright single quantum dot emission exceeding 1.5 million counts per second at a detector. We also observe Purcell enhanced spontaneous emission rate as large as 4 and high linear polarization ratio of 0.96 for the coupled dots. Using this source, we generate high purity single photons at 1.3 μm wavelength and demonstrate the indistinguishable nature of the emission using a two-photon interference measurement.

Quantum Dot Device Design Optimization for Resonator Coupling.

CAMERON KING, S. N. COPPERSMITH, MARK FRIESEN, University of Wisconsin, Madison — Coupling a semiconductor quantum dot qubit to a superconducting resonator broadens the possibilities for interqubit communication and potentially allows integration of quantum dots with other qubit systems. The major technological hurdle that must be overcome is reaching the strong coupling limit, where the coupling frequency between the resonator and the qubit is larger than both the qubit decoherence rate and the photon loss rate of the resonator. In this work, we examine optimization of the quantum dot device design. Using the Thomas-Fermi approximation in conjunction with a metallic dot capacitive model, we focus on improving the capacitive coupling between a resonator gate and a quantum dot while decreasing the cross-coupling to nearby dots. Through these simulations, we find that the optimization follows an intuitive geometric relation.

A dressed spin qubit in Silicon.

ARNIE LAUGHT, RACHPON KALRA, JUAN DEHOLLAIN, STEPHANIE SIMMONS, JUHA MUHONEN, FAHD MOHIYADDIN, SOLOMON FREER, FAY HUDSON, UNSW Australia, KOHEI ITOH, Keio University, DAVID JAMIESON, JEFF MCCALLUM, University of Melbourne, ANDREW DZURAK, ANDREA MORELLO, UNSW Australia — Coherent dressing of a quantum two-level system has been demonstrated on a variety of systems, including atoms, self-assembled quantum dots, and superconductor quantum bits, and can be demonstrated by measuring Rabi oscillations, or a Mollow triplet in the spectrum. It can be used to gain access to a new quantum system with improved properties - a different and tunable level splitting, faster and easier control, and longer coherence times. In our work we investigate the properties of the dressed, donor-bound electron spin in silicon, and probe its potential for the use as quantum bit in scalable architectures. Here, the two dressed spin-polaron levels constitute the quantum bit. The dressed qubit can be coherently driven with an oscillating magnetic field, an oscillating electric field, by frequency modulating the driving field, or by a simple detuning pulse. We measure coherence times of $T_2^*$ = 2.4 ms and $T_2$ = 9 ms (Hahn echo), one order of magnitude longer than those of the undressed qubit.

Gate sensing coherent charge oscillations in a silicon field-effect transistor.

M. FERNANDO GONZALEZ-ZALBA, Hitachi Cambridge Laboratory, UK, SERGEY SHEVCHENKO, B. Verkin Institute for Low Temperature Physics and Engineering, Ukraine, SYLVAIN BARRAUD, CEA-LETI, France, J. ROBERT JOHANSSON, CEMS, RIKEN, Japan, ANDREW FERGUSON, Cavendish Laboratory, UK, FRANCO NORI, CEMS, RIKEN, Japan, ANDREAS BETZ, Hitachi Cambridge Laboratory, UK — We report the observation of coherent charge oscillations in a double quantum dot formed in a silicon nanowire transistor detected via its dispersive interaction with a radio-frequency resonant circuit coupled via the gate. Differential capacitance changes at the inter-dot charge transitions allow us to monitor the state of the system in the strong-driving regime where we observe the emergence of Landau-Zener-Stückelberg-Majarana interference on the phase response of the resonator. A theoretical analysis of the dispersive signal demonstrates that quantum and tunneling capacitance changes must be included to describe the qubit-resonator interaction. Furthermore, a Fourier analysis of the interference pattern reveals a charge coherence time, $T_2 = 100$ ps. Our results demonstrate charge coherent control and readout in a simple silicon transistor and open up the possibility to implement charge and spin qubits in existing complementary metal-oxide-semiconductor technology.

Coplanar photonic bandgap resonators for low temperature electron and nuclear magnetic resonance spectroscopy.

A. J. SIGILLITO, A. M. TVRYSHKIN, S. A. LYN, Department of Electrical Engineering, Princeton University — In recent years, superconducting coplanar waveguide (CPW) resonators have become a useful tool for low temperature pulsed electron spin resonance (ESR), even at dilution refrigerator temperatures. Their small mode volumes make CPW resonators particularly well suited to measuring small numbers of spins near the resonator surface, since in this region the spin sensitivity is very high. While these resonators have proven useful for ESR at single microwave frequencies, it is difficult to also manipulate nuclear spins in electron-nuclear-double resonance (ENDOR) experiments, since manipulation of nuclear spins requires radio frequency (RF) magnetic fields. Ideally one would simply generate these fields by passing RF currents through the CPW, but because conventional CPW resonators are capacitively coupled, they will not transmit low frequency RF currents. In this talk, we discuss the use of one dimensional photonic bandgap (PBG) resonators to overcome this challenge. PBG resonators are a promising alternative to conventional CPW resonators since they offer high quality factors at microwave frequencies, while simultaneously allowing transmission of nonresonant RF currents below the photonic bandgap. Here, we will discuss PBG resonator designs and present data showing their use for low temperature ESR of donors in 28Si. Initial ENDOR results will also be presented.
resonators and nonlinear readout modes in a waveguide. We experimentally investigate this effect for transmon qubits coupled to different realizations of the readout mode: 3-dimensional microwave cavities, strip-line...circuit QED experiments, microwave drives are applied to the readout mode for qubit measurement, control and to realize various multi-photon processes. These...qubits uses the interaction between the qubit and a harmonic oscillator. In the dispersive limit of the interaction, the coupling operator \( n \sigma \) commutes with the qubit Hamiltonian and should be perfectly QND. However, previous experiments have indicated that sufficiently high resonator drive power causes unwanted qubit state transitions, producing errors. We investigate these errors in detail, connect the results with theory, and comment on the implications for quantum computer design.

**Thursday, March 17, 2016 2:30PM - 5:30PM – Session V48 GQI: Readout and Trajectories in Superconducting Circuits**

**2:30PM V48.00001 Probing the Speed Limits of Transmon Dispersive Readout.** Theo Walter, Philipp Kurpiers, Minitu Mondal, Marek Pechal, Andreas Wallraff, S. Gasparinetti, ETH Zurich — In circuit QED, faster and more accurate measurement of a qubit’s state is necessary to achieve better feedback control, to accomplish more complex quantum algorithms and simulations, and to cross the threshold for fault tolerant quantum computing. In this talk, we discuss our experimental progress to minimize the time needed to readout the state of a dispersively coupled transmon qubit with high fidelity. We outline a signal-to-noise ratio model, illuminate the constraints and find optimal parameters for maximizing measurement speed, while maintaining high readout fidelity. Utilizing a Purcell Filter increases the generality of our results as it becomes possible to reach these speeds with a broader set of system parameters.

**2:42PM V48.00002 Fast Quantum Nondemolition Readout by Parametric Modulation of Longitudinal Qubit-Oscillator Interaction.** Jerome Bourassa, Cegep de Granby, Nicolas Didier, McGill University and Universite de Sherbrooke, Alexandre Blais, Universite de Sherbrooke and Canadian Institute for Advanced Research — For quantum information processing, qubit readout must be fast, of high-fidelity and ideally quantum non-demolition (QND). To rapidly reuse the measured qubit, fast reset of the measurement pointer states is also needed. Combining these characteristics is essential to meet the stringent requirements of fault-tolerant quantum computation. For superconducting qubits, a common strategy is the dispersive readout where the qubit is coupled to an oscillator acting as pointer. In this talk, we present an alternative strategy based on parametric modulation of longitudinal qubit-oscillator interaction. We show that compared to dispersive readout it leads to a faster, high-fidelity and ideally QND qubit readout with a simple reset mechanism [1]. We moreover show how to exponentially improve the signal-to-noise ratio (SNR) of this measurement with the help of single-mode squeezed input state on the oscillator. We present an implementation of this longitudinal parametric readout in circuit quantum electrodynamics along with results using realistic experimental parameters. [1] N. Didier, J. Bourassa and A. Blais, Phys. Rev. Lett., In Print (2015)

1 Now at Quantic team, INRIA Paris

**2:54PM V48.00003 Non-QNDDness of Dispersive Measurement in Superconducting Qubits, Part I: Theory.** Mostafa Khezri, University of California, Riverside, Daniel Sank, Google, ZiJUN Chen, University of California, Santa Barbara, Rami Barends, YU Chen, Austin Fowler, Robert Graff, Evan Jeffrey, Julian Kelly, Erik Lucero, Anthony Megrant, Josh Mutus, Pedram Roushan, TEO White, Matthew Neeley, Google, Brooks Campbell, Benjamin Chiaro, Andrew Dunsworth, Charles Neill, Peter O’Malley, Christopher Quintana, Amit Vainsencher, James Wenner, University of California, Santa Barbara, John M. Martinis, Google, University of California, Santa Barbara, Alexander N. Korotkov, University of California, Riverside — We theoretically analyze the dispersive measurement of an Xmon qubit in the circuit QED setup at moderately high power, so that the number of photons in the resonator exceeds the so-called critical number by up to an order of magnitude. Our results show an abrupt change of the qubit state when the number of photons reaches a certain threshold, which depends on the detuning between the qubit and the resonator. The simulation results are in agreement with experimental findings for Xmon measurement at moderately high power. We will discuss the physical mechanism causing an abrupt deterioration of the measurement QNDness at the threshold.

**3:06PM V48.00004 Non-QNDDness of Dispersive Measurement in Superconducting Qubits, Part II: Experiment.** Daniel Sank, Google Inc - Santa Barbara, Z. Chen, UC Santa Barbara, M. Khezri, UC Riverside, R. Barends, Google Inc - Santa Barbara, B. Campbell, UC Santa Barbara, Y. Chen, Google Inc - Santa Barbara, B. Chiaro, A. Dunsworth, UC Santa Barbara, A. Fowler, R. Graff, E. Jeffrey, J. Kelly, E. Lucero, A. Megrant, J. Mutus, M. Neeley, Google Inc - Santa Barbara, C.Neill, P. J. J. O’Malley, UC Santa Barbara, C. Quintana, P. Roushan, Google Inc - Santa Barbara, A. Vainsencher, J. Wenner, UC Santa Barbara, T. White, Google Inc - Santa Barbara, A. Korotkov, UC Riverside, J. M. Martinis, Google Inc - Santa Barbara — Modern quantum state measurement in transmon qubits uses the interaction between the qubit and a harmonic oscillator. In the dispersive limit of the interaction, the coupling operator \( n \sigma_x \) commutes with the qubit Hamiltonian and should be perfectly QND. However, previous experiments have indicated that sufficiently high resonator drive power causes unwanted qubit state transitions, producing errors. We investigate these errors in detail, connect the results with theory, and comment on the implications for quantum computer design.

**3:18PM V48.00005 Dependence of transmon qubit relaxation rate on readout drive power.** S.O. Mundhada, S. Shankar, A. Narla, E. Zalys-Geller, S.M. Girvin, M.H. Devoret, Department of Applied Physics, Yale University — In circuit QED experiments, microwave drives are applied to the readout mode for qubit measurement, control and to realize various multi-photon processes. These microwave drives have been observed to detrimentally affect the qubit mode by increasing the qubit relaxation rates for both upward and downward transitions. These transitions demolish the qubit state during a measurement, limiting the maximum measurement strength and thus the readout fidelity and speed. Here, we experimentally investigate this effect for transmon qubits coupled to different realizations of the readout mode: 3-dimensional microwave cavities, strip-line resonators and nonlinear readout modes in a waveguide.
3:30PM V48.00006 A balanced, superconducting multiplexer circuit for fast-switching and multiplexed qubit readout: Design and modeling, ERIC I. ROSENTHAL, BENJAMIN J. CHAPMAN, BRAD A. MOORES, JILA, University of Colorado, Boulder, JOSEPH KERCKHOFF, HRL Laboratories, JILA, University of Colorado, Boulder, K. W. LEHNERT, JILA, University of Colorado, Boulder, National Institute of Standards and Technology, Boulder — Superconducting qubits hold great promise for the development of new quantum-information technology. Coherence times of individual transmon qubits in microwave cavities are consistently improving. While qubits are becoming well developed tools, scaling qubit readout for many-qubit architectures remains prohibitively complex and expensive. Here, we present a concept for a multipurpose device that enables time or code domain multiplexing of qubit readout. It is a two-port, microwave device that can be switched rapidly between three modes of operation: transmission, reflection and inversion. The design is based on a Wheatstone bridge-like structure of tunable inductors, which we realize as the qubit evolves from its excited to ground state, revealing rich dynamics that occur in the process of spontaneous emission.

σ phase of amplification, we execute weak measurements in the...
Linear feedback. Action principle to investigate the global dynamics of its most likely paths, and finding that qubit state stabilization at any desired pure state is possible with such methods. Multi-time correlation functions for quantum state variables, can be derived by applying functional methods and a perturbative approach to the stochastic evolution, such as the most likely paths, can be obtained by extremizing the action of the stochastic path integral. We also show that any statistical information, of Rochester, Chapman University — We study stochastic behaviour and optimal dynamics of quantum systems under weak continuous measurement. Using stochastic path integral formalism, AREEYA CHANTASRI, University of Rochester, ANDREW JORDAN, University of Rochester, Chapman University — The physics of quantum measurement still continues to puzzle with no resolution in sight between competing interpretations, in particular because no interpretation has so far produced predictions that would be falsifiable by experiment. Here we present an analysis of consecutive projective measurements performed on a quantum state using quantum information theory, where the entanglement between the quantum system and a measuring device is explicitly taken into account, and where the consecutive measurements increase the joint Hilbert space while the wavefunction of the joint system never collapses. Using this relative-state formalism we rederive well-known results for the pairwise correlation between any two measurement schemes. Recently, within the field of superconducting qubits, many experiments have shown tremendous progress towards high fidelity quantum feedback schemes. Some experiments work by traditional measurement based schemes where the classical output is processed on a classical "computer" before a signal is fed back to the qubits. Other approaches are working in a continuous coherent manner, where the full quantum description of the system creates an effective bath that relaxes the system into the desired state. This talk will present a different approach that aims to close a measurement based feedback loop inside a cryostat, and, thus, the scheme works completely autonomous. This approach sidesteps many of the inefficiencies inherent in two-way communication between temperature stages in typical systems with room temperature controllers, and avoids increasing the cryogenic heat load. This controller may find a broad range of uses in multi-qubit systems, but here I analyze two specific demonstrative cases in single qubit-control and show simulations of the time evolution for the full system dynamics.

Friday, March 18, 2016 8:00AM - 10:12AM – Session X44 GQI: Measurement, Characterization, and Emulation 347 - Ken Brown, Georgia Institute of Technology

8:00AM X44.00001 Consecutive Measurements in Quantum Mechanics1. JENNIFER R. GLICK, CHRISTOPH ADAMI, Michigan State University — The physics of quantum measurement still continues to puzzle with no resolution in sight between competing interpretations, in particular because no interpretation has so far produced predictions that would be falsifiable by experiment. Here we present an analysis of consecutive projective measurements performed on a quantum state using quantum information theory, where the entanglement between the quantum system and a measuring device is explicitly taken into account, and where the consecutive measurements increase the joint Hilbert space while the wavefunction of the joint system never collapses. Using this relative-state formalism we rederive well-known results for the pairwise correlation between any two measurement devices, but show that considering the joint as well as conditional entropy of three devices reveals a difference between the collapse and no-collapse pictures of quantum measurement that is experimentally testable.

1 This research was funded by a Michigan State University Enrichment Fellowship.

8:12AM X44.00002 Hidden Variables Theorems with Fewer Measurements. JAY LAWRENCE, Dartmouth College and University of Chicago — A Greenberger-Horne-Zeilinger (GHZ) contradiction may be thought of as a sequence of measurements on a system of N particles, for which each may be duplicated by local hidden variables up to, but not including the last of an irreducible set. Each measurement consists of N spatially separated local measurements on individual particles. Existing contradictions require more such measurements than there are particles, the minimum number being N + 1. By allowing successive measurements to impose incremental local constraints on the hidden variables (as opposed to global constraints associated with products of hidden variables), we derive contradictions that require fewer measurements. We have found protocols for which the number of measurements, N_m, grows more slowly than linearly with the number of particles: Asymptotically, N_m ∼ √N for large N if the particles are qubits, and a similar relation holds for particles of higher spins.

8:24AM X44.00003 Statistical and optimal behaviours of weak continuous quantum measurement using stochastic path integral formalism, AREEYA CHANTASRI, University of Rochester, ANDREW JORDAN, University of Rochester, Chapman University — We study stochastic behaviour and optimal dynamics of quantum systems under weak continuous measurement. Using the stochastic path integral formalism and action principle introduced in [Phys. Rev. A 78, 042110 (2013) and Phys. Rev. A 92, 032125 (2015)], the optimal evolution, such as the most likely paths, can be obtained by extremizing the action of the stochastic path integral. We also show that any statistical information, such as multi-time correlation functions for quantum state variables, can be derived by applying functional methods and a perturbative approach to the stochastic path integral. Examples are given in one-qubit and two-qubit case. Moreover, we consider an example of qubit measurement with feedback control, using the action principle to investigate the global dynamics of its most likely paths, and finding that qubit state stabilization at any desired pure state is possible with linear feedback.
8:36AM X44.00004 Localizing and observing Kochen-Specker quantum contextuality using weak measurements. 1  MORDECAI WAEGELL, JEFF TOLLAKSEN, Institute for Quantum Studies, Chapman University, YUJI HASEGAWA, STEPHAN SPONAR, TOBIAS DENKMAYR, HERMANN GEPPERT, Atom-institute, TU-Wien, INSTITUTE FOR QUANTUM STUDIES COLLABORATION, RESEARCH GROUP OF DR. YUJI HASEGAWA COLLABORATION — Experimental tests of the Kochen-Specker (KS) theorem conventionally require a set of different measurement settings, and the test can furthermore be applied to an arbitrary prepared state. These experiments show that nature is contextual, but they do not indicate which specific observables must behave nonclassically. We show that, using pre- and post-selected states from within a set of projectors that prove the KS theorem, it is possible to identify another specific projector in the set that behaves nonclassically, in this case because it has an anomalous weak value. We explore specific KS sets that give rise to the Quantum Pigeonhole Effect (QPE), and use weak measurements on a large ensemble of identically pre- and post-selected neutrons to verify the QPE, and also to measure the anomalous weak value of the nonclassical projector. We construct a new contextuality inequality based on the recent result of Pusey showing that any projector with a negative weak value is a proof of contextuality, and show that our measured weak value is many standard deviations below zero.

1Fetzer-Franklin Fund

8:48AM X44.00005 Direct Characterization of Quantum Dynamics with Noisy Ancilla1, EUGENE DUMITRESCU, TRAVIS HUMBLE, Oak Ridge National Laboratory, University of Tennessee — We present methods for the direct characterization of quantum dynamics (DCQD) in which both the principal and ancilla systems undergo noisy processes. Using a concatenated error detection code, we discriminate between located and unlocated errors on the principal system in what amounts to filtering of ancilla noise. The example of composite noise involving amplitude damping and depolarizing channels is used to demonstrate the method, while we find the rate of noise filtering is more generally dependent on code distance. Our results indicate the accuracy of quantum process characterization can be greatly improved while remaining within reach of current experimental capabilities.

3We acknowledge support from the IC postdoctoral research program.

9:00AM X44.00006 Realizing quantum advantage without entanglement in single-photon states, ALEJANDRA MALDONADO-TRAPP, PABLO SOLANO, Joint Quantum Institute, ANZI HU, American University, CHARLES W. CLARK, Joint Quantum Institute — Correlations allow us to measure, and quantitatively study, the properties of physical systems, their evolution and their interactions. Quantum discord expresses quantum correlations beyond those associated with entanglement. However, discord has not yet been adopted as a standard subject of study by the experimental community. Here we propose a feasible optical setup to generate symmetric two-qubit λ-states with controllable coherences, where the two qubits correspond to the spin and path of a photon. With these states we show how a classical random variable K can be encoded by Alice and decoded by Bob. Using our previous results we study the correlations between the spin and path qubits and its relation with the information about K that can be decoded by Bob using local measurements with or without two-qubit gate operations. Discord is the mutual information contained in the coherences of the system, and it is possible to exploit it for quantum advantage even in the absence of entanglement.

1K Modi, et al., Rev. Mod. Phys. 84, 1655 (2012)

9:12AM X44.00007 A novel computational approach towards the certification of large-scale boson sampling1, JOONSUH HUH, Pohang University of Science and Technology — Recent proposals of boson sampling and the corresponding experiments exhibit the possible disproof of extended Church-Turing Thesis. Furthermore, the application of boson sampling to molecular computation has been suggested theoretically [1]. Till now, however, only small-scale experiments with a few photons have been successfully performed. The boson sampling experiments of 20-30 photons are expected to reveal the computational superiority of the quantum device. A novel theoretical proposal for the large-scale boson sampling using microwave photons is highly promising due to the deterministic photon sources and the scalability [2]. Therefore, the certification protocol of large-scale boson sampling experiments should be presented to complete the exciting story. We propose, in this presentation, a computational protocol towards the certification of large-scale boson sampling. The correlations of paired photon modes and the time-dependent characteristic functional with its Fourier component can show the fingerprint of large-scale boson sampling. [1] J. Huh, G. G. Guerreschi, B. Peropadre, J. R. McClean, and A. Aspuru-Guzik. Nature Photon. 9 (2015): pp 615-620. [2] B. Peropadre, G. G. Guerreschi, J. Huh, and A. Aspuru-Guzik. Preprint: arXiv:1510.08064.

This work was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology(NRF-2015R1A6A3A04059773), the ICT RD program of MSIP/IITP [2015-019, Fundamental Research Toward Secure Quantum Communication] and Mueunjae Institute for Chemistry (MIC) postdoctoral fellowship.

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9:24AM X44.00008 Occupation number entanglement in mesoscopic conductors, DAVID DASENBROOK, University of Geneva, Switzerland, CHRISTIAN FLINDT, Aalto University, Finland — The controlled entanglement of electrons in mesoscopic conductors has been theoretically investigated before using the spin- and orbital degrees of freedom. By contrast, entanglement of two spatially separated electronic channels using the fermionic occupation number has mostly been considered inaccessible due to the charge superselection rule. However, using non-local measurements or combining several copies of occupation number entangled states, the superselection rules can be lifted and the entanglement can be detected using current and noise measurements. We present the theory for an interferometric setup to detect entanglement in the electron-hole degree of freedom of electronic excitations [1] as well as a mesoscopic setup that demonstrates entanglement and non-locality of a single electron. [1] D. Dasenbrook and C. Flindt, Phys. Rev. B 92, 161412(R) (2015)
9:36AM X44.00009 Neutron interferometry for precise characterization of quantum systems
DUSAN SARENAC, Institute for Quantum Computing, CHANDRA SHAHI, Tulane University, TAISIYA MINEEVA, CHRISTOPHER J. WOOD, Institute for Quantum Computing, MICHAEL G. HUBER, MUHAMMAD ARIF, National Institute of Standards and Technology, CHARLES W. CLARK, Joint Quantum Institute, DAVID G. CORY, DMITRY A. PUSHIN, Institute for Quantum Computing — Neutron interferometry (NI) is among the most precise techniques used to test the postulates of quantum mechanics. It has demonstrated coherent spinor rotation and superposition, gravitationally induced quantum interference, the Alcubierre-Casher effect, violation of a Bell inequality and generation of a single-neutron entangled state. As massive, penetrating and neutral particles neutrons now provide unique capabilities in classical imaging applications that we seek to extend to the quantum domain. We present recent results on NI measurements of quantum discord in a bipartite quantum system and neutron orbital angular momentum multiplexing and review progress on our commissioning of a decoherence-free-subspace NI user facility at the NIST Center for Neutron Research.

9:48AM X44.00010 Recovering the ideal results of a perturbed quantum emulator
MICHAEL MARTHAUSER, Karlsruhe Institute of Technology, LIN TIAN, University of California, Merced, IRIS SCHWENK, Karlsruhe Institute of Technology — We consider a quantum emulator which is a model of an ideal Hamiltonian of interest $H$. However, inevitably the system is perturbed by coupling to additional degrees of freedom. We study the case where we are interested in extracted a correlator from the emulated system in equilibrium. We show that it is possible to extract the ideal correlator from a perturbed system under certain conditions. The ideal correlator can be reconstructed if any n-time correlator of the ideal system can be written as a product of two-time correlators.

10:00AM X44.00011 Experimental observation of melting of the effective Minkowski spacetime
IGOR SMOLYANINOV, University of Maryland, VERA SMOLYANINOVA, Towson University — Cobalt nanoparticle-based ferrofluid in the presence of an external magnetic field forms a self-assembled hyperbolic metamaterial, which may be described as an effective 3D Minkowski spacetime for extraordinary photons. Moreover, such extraordinary photons perceive thermal gradients in the ferrofluid as an effective gravitational field, which obeys the Newton law. If the magnetic field is not strong enough, the effective Minkowski spacetime gradually melts under the influence of thermal fluctuations. On the other hand, it may restore itself if the magnetic field is increased back to its original value. Here we present direct microscopic visualization of such a Minkowski spacetime melting/crystallization, which is somewhat similar to hypothesized formation of the Minkowski spacetime in loop quantum cosmology [1].

Friday, March 18, 2016 8:00AM - 11:00AM –
Session X48 GQI: Scalable Hardware for Superconducting Qubits
349 - William Oliver, Massachusetts Institute of Technology, Lincoln Laboratory

8:00AM X48.00001 High-Q 3D coaxial resonators for cavity QED
TAEKWAN YOON, JOHN C OWENS, RAVI NAIK, AMAN LACHAPELLE, RUICHAO MA, JONATHAN SIMON, DAVID I SCHUSTER, Univ of Chicago — Three-dimensional microwave resonators provide an alternative approach to transmission-line resonators used in most current circuit QED experiments [1]. Their large mode volume greatly reduces the surface dielectric losses that limits the coherence of superconducting circuits, and the well-isolated and controlled cavity modes further suppress coupling to the environment. In this work, we focus on unibody 3D coaxial cavities which are only evanescently coupled and free from losses due to metal-metal interfaces, allowing us to reach extremely high quality-factors. We achieve quality-factor of up to 170 million using 4N6 Aluminum at superconducting temperatures, corresponding to an energy ringdown time of ~4ms. We extend our methods to other materials including Niobium, NbTi, and copper coated with Ti-In-Lead solder. These cavities can be further explored to study their properties under magnetic field or upon coupling to superconducting Josephson junction qubits, e.g. 3D transmon qubits. Such 3D cavity QED system can be used for quantum information applications, or quantum simulation in coupled cavity arrays. References: [1] Matthew Reagor et al., A quantum memory with near-millisecond coherence in circuit QED. arXiv: 1508.05882 (2015)

8:12AM X48.00002 Three-Dimensional Architecture at Chip Level for Large-Scale-Integration of Superconducting Quantum Electronic Devices
MARTIN GÖPPFL, Sensiron AG, PHILIPP KURPIERS, ANDREAS WALLRAFF, ETH Zurich — We propose a novel way to realize three-dimensional circuit QED systems at chip level. System components such as qubits, transmission lines, capacitors, inductors or cross-overs can be implemented as suspended, electromagnetically shielded and optionally, as hermetically sealed structures. Compared to known state-of-the-art devices, volumes of dielectrics penetrated by electromagnetic fields can be drastically reduced. Our intention is to harness process technologies for very-large-scale-integration, reliably applied and improved over decades in micro-sensor- and semiconductor industry, for the realization of highly integrated circuit QED systems. Process capabilities are demonstrated by fabricating first exploratory devices using the back-end-of-line part of a commercial 180 nm CMOS foundry process in conjunction with HF vapor phase etching.

8:24AM X48.00003 3D Integration for Superconducting Qubits
DANNA ROSENBERG, DONNA-RUTH YOST, RABINDRA DAS, DAVID HOVER, LIVIA RACZ, STEVEN WEBER, JONILYN YODER, ANDREW KERMAN, MIT Lincoln Laboratory, WILLIAM OLIVER, MIT Lincoln Laboratory; Research Laboratory of Electronics, MIT — As the field of superconducting quantum computing advances from the few-qubit stage to large-scale fault-tolerant devices, scalability requirements will necessitate the use of standard 3D packaging and integration processes. While the field of 3D integration is well-developed, relatively little work has been performed to determine the compatibility of the associated processes with superconducting qubits. Qubit coherence time could potentially be affected by required process steps or by the proximity of an interposer that could introduce extra sources of charge or flux noise. As a first step towards a large-scale quantum information processor, we have used a flip-chip process to bond a chip with flux qubits to an interposer containing structures for qubit readout and control. We will present data on the effect of the presence of the interposer on qubit coherence time for various qubit-chip-interposer spacings and discuss the implications for integrated multi-qubit devices. This research was funded by the ODNI and IARPA under Air Force Contract No. FA8721-05-C-0002. The views and conclusions contained herein are those of the authors and should not be interpreted as representing the official policies or endorsements, either expressed or implied, of ODNI, IARPA, or the US Government.
8:36 AM X48.00004 Extensible circuit QED processor architecture with vertical I/O1. ALESSANDRO BRUNO, STEFANO POLETTI, QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands, NADIA HAIDER, QuTech, Delft University of Technology, and Netherlands Organisation for Applied Scientific Research (TNO), Delft, The Netherlands, LEONARDO DICARLO, QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands — Achieving quantum fault tolerance in an extensible architecture is an outstanding challenge across experimental quantum computing platforms today. Traditionally, circuit QED processors have millimeter dimensions and lateral coupling for all input/output (I/O) signals, precluding the increase in qubit numbers beyond ~10. We present a scalable footprint for circuit QED processors with vertically coupled I/O. Our demonstration using centimeter scale chips can accommodate the ~50 qubits needed in next-generation processors targeting the experimental demonstration of quantum fault tolerance.

1We acknowledge funding from FOM, NWO and the EU FP7 Project SCALEQIT

8:48 AM X48.00005 The Quantum Socket: Wiring for Superconducting Qubits - Part 1. T.G. MCконек, J.H. БЕЖАНИН, J.R. РИНЕХАРТ, J.D. БАТЕМАН, C.T. ЭРНСТ, C.H. МКРЕЙ, Y. РОХАНИЗАДеган, D. СИРИ, M. МАРИАНТОНИ, University of Waterloo, B. ПЕНАВА, P. БРЕУЛ, S. РОЯК, M. ЗАПАТКА, Ingun, A.G. ФОУЛЕР, Google Inc. — Quantum systems with ten superconducting quantum bits (qubits) have been realized, making it possible to show basic quantum error correction (QEC) algorithms. However, a truly scalable architecture has not been developed yet. QEC requires a two-dimensional array of qubits, restricting any interconnection to external classical systems to the third axis. In this talk, we introduce an interconnect solution for solid-state qubits: The quantum socket. The quantum socket employs three-dimensional wires and makes it possible to connect classical electronics with quantum circuits more densely and accurately than methods based on wire bonding. The three-dimensional wires are based on spring-loaded pins engineered to insure compatibility with quantum computing applications. Extensive design work and machining was required, with focus on material quality to prevent magnetic impurities. Microwave simulations were undertaken to optimize the design, focusing on the interface between the micro-connector and an on-chip coplanar waveguide pad. Simulations revealed good performance from DC to 10 GHz and were later confirmed against experimental measurements.

9:00 AM X48.00006 The Quantum Socket: Wiring for Superconducting Qubits - Part 2. J.H. БЕЖАНИН, T.G. MCконек, J.R. РИНЕХАРТ, J.D. БАТЕМАН, C.T. ЭРНСТ, C.H. МКРЕЙ, Y. РОХАНИЗАДеган, D. СИРИ, M. МАРИАНТОНИ, University of Waterloo, B. ПЕНАВА, P. БРЕУЛ, S. РОЯК, M. ЗАПАТКА, Ingun, A.G. ФОУЛЕР, Google Inc. — Quantum computing research has reached a level of maturity where quantum error correction (QEC) codes can be executed on linear arrays of superconducting quantum bits (qubits). A truly scalable quantum computing architecture, however, based on practical QEC algorithms, requires nearest neighbor interaction between qubits on a two-dimensional array. Such an arrangement is not possible with techniques that rely on wire bonding. To address this issue, we have developed the quantum socket, a device based on three-dimensional wires that enables the control of superconducting qubits on a two-dimensional grid. In this talk, we present experimental results characterizing this type of wiring. We will show that the quantum socket performs exceptionally well for the transmission and reflection of microwave signals up to 10 GHz, while minimizing crosstalk between adjacent wires. Under realistic conditions, we measured an S21 of ~5 dB at 6 GHz and an average crosstalk of ~60 dB. We also describe time domain reflectometry results and arbitrary pulse transmission tests, showing that the quantum socket can be used to control superconducting qubits.

9:12 AM X48.00007 The Quantum Socket: Wiring for Superconducting Qubits - Part 3. M. МАРИАНТОНИ, J.H. БЕЖАНИН, T.G. MCконек, J.R. РИНЕХАРТ, J.D. БАТЕМАН, C.T. ЭРНСТ, C.H. МКРЕЙ, Y. РОХАНИЗАДеган, D. СИРИ, University of Waterloo, B. ПЕНАВА, P. БРЕУЛ, S. РОЯК, M. ЗАПАТКА, Ingun, A.G. ФОУЛЕР, Google Inc. — The implementation of a quantum computer requires quantum error correction codes, which allow to correct errors occurring on physical quantum bits (qubits). Ensemble of physical qubits will be grouped to form a logical qubit with a lower error rate. Reaching low error rates will necessitate a large number of physical qubits. Thus, a scalable qubit architecture must be developed. Superconducting qubits have been used to realize error correction. However, a truly scalable qubit architecture has yet to be demonstrated. A critical step towards scalability is the realization of a wiring method that allows to address qubits densely and accurately. A quantum socket that serves this purpose has been designed and tested at millikelvin temperatures. In this talk, we show results where the socket is used at millikelvin temperatures to measure an on-chip superconducting resonator. The control electronics is another fundamental element for scalability. We will present a proposal based on the quantum socket to interconnect a classical control hardware to a superconducting qubit hardware, where both are operated at millikelvin temperatures.

9:24 AM X48.00008 Development of superconducting bonding for multilayer microwave integrated quantum circuits. TERESE BRETCHT, CHRISTOPHER AXLINE, YIWEN CHU, WOLFGANG PFAFF, LUIGI FRUNZIO, MICHEL DEVORET, ROBERT SCHOELKOPF, Yale University — Future quantum computers are likely to take the shape of multilayer microwave integrated quantum circuits. The proposed physical architecture retains the superb coherence of 3D structures while achieving superior scalability and compatibility with planar circuitry and integrated readout electronics. This hardware platform utilizes known techniques of bulk etching in silicon wafers and requires metallic bonding of superconducting materials. Superconducting wafer bonding is a crucial tool in need of development. Whether micromachined in wafers or traditionally machined in bulk metal, 3D cavities typically possess a seam where two parts meet. Ideally, this seam consists of a perfect superconducting bond. Pursuing this goal, we have developed a new understanding of seams as a loss mechanism that is applicable to 3D cavities in general. We present quality factor measurements of both 3D cavities and 2D stripline resonators to study the losses of superconducting bonds. [1] Brehc, T., et al., arXiv:1509.01119 (2015) [2] Brehc, T., et al., arXiv:1509.01119 (2015)

9:36 AM X48.00009 High speed on-chip current measurement using a low-Q tunable LC resonator. BROOKS CAMPBELL, Z. CHEN, B. CHIAO, A. DUNSWORTH, C. NIEU, P.J.J. O’MALLEY, C. QUIRTANA, A. VAISENSCHER, J. WENNER, UC Santa Barbara, R. BAREND, Y. CHEN, A. FOWLER, E. JEFFREY, J. KELLY, E. LUCERO, A. MEGRANT, J. MUTUS, M. NEELY, P. ROUSHAN, D. SANK, Google, Santa Barbara, T.C. WHITE, JOHN M. MARTINIS, UC Santa Barbara and Google, Santa Barbara — Superconducting quantum computing technology requires precise high frequency analog waveforms to perform single and multi-qubit gates. Due to signal path irregularities, gates are tuned-up by perturbing the drive signal until qubit state populations indicate the desired gate function. A more direct approach is to measure the effect of circuit imperfections by sampling control waveforms directly, as seen by the qubits. We proceed by measuring the resonant frequency shift of a capacitively shunted SQUID and converting the control waveform to DC flux applied to the SQUID. By measuring the reflected phase of a CW tone applied to this resonant circuit while applying the resonance-shifting flux pulse, we are able to reconstruct the current waveform of the input pulse at the SQUID loop. This device’s geometry is the same as the z-control lines used in qubit experiments to control the qubit frequency. We will present this method of on-chip waveform sampling for superconducting circuits in addition to proof of concept data. This technique opens the door for improved gate bring up and a deeper understanding of qubit control as well as the circuit parasitics that deform these waveforms.
Area laws for entanglement provide crucial insight into the low-energy behavior of many-body systems and are intimately connected to the efficiency of classical computational methods. For 1D systems, an area law was rigorously proven for ground states of gapped Hamiltonians with local interactions and for states with exponentially decaying correlations. In the presence of long-range interactions, the proof of an area law for gapped ground states becomes much more challenging because long-range interactions can change the effective dimensionality of the system and introduce correlations decaying slower than an exponential. Based on recent theoretical advances that reveal strong remnants of locality in quenched systems with power-law decaying interactions, we prove an area law for a large class of gapped Hamiltonians with long-range interactions. As an intermediate step, we prove tight bounds on the decay of ground-state correlations.

Because long-range interactions can change the effective dimensionality of the system and introduce correlations decaying slower than an exponential, the proof of an area law for gapped ground states becomes much more challenging. Based on recent theoretical advances that reveal strong remnants of locality in quenched systems with power-law decaying interactions, we prove an area law for a large class of gapped Hamiltonians with long-range interactions. As an intermediate step, we prove tight bounds on the decay of ground-state correlations.
the alignment of the molecules by aligning the host matrix with the substrate. To analyse the polarization of this light to determine the alignment of the molecules. I will report on our efforts to control this bag in order to exclude oxygen, which improves the photostability of the DBT molecules by orders of magnitude. We image the fluorescence of single DBT molecules demonstrating the realization of this proposal. A new method has been developed for evaporating AC and DBT to produce crystals that are wide and thin. The crystals are believed to provide a high roughness of surface electrodes by deriving a Greens function describing this roughness, and evaluating its effects on adsorbate-surface binding energies. At cryogenic temperature, surface roughness is found to exponentially enhance or suppress heating rate, depending on the density distribution of surface adsorbates. Our result suggests that heating rates can be tuned over orders of magnitude by careful engineering of electrode surface profiles.

Waveguide.

The effect of electrode surface roughness on the motional heating rate of electromagnetic trapped ions, KUAN-YU LIN, GUANG HAO LOW, ISAAC CHUANG, Massachusetts Inst of Tech-MIT — Electric field noise is a major source of motional heating in trapped ion quantum computation. While it is well known that this noise is influenced by trap electrode geometry in patch potential and surface adsorbate models, this has only been analyzed for smooth surfaces. We investigate the dependence of electric field noise on the roughness of surface electrodes by deriving a Greens function describing this roughness, and evaluating its effects on adsorbate-surface binding energies. At cryogenic temperature, surface roughness is found to exponentially enhance or suppress heating rate, depending on the density distribution of surface adsorbates. Our result suggests that heating rates can be tuned over orders of magnitude by careful engineering of electrode surface profiles.

Reference


Universal critical phenomena of the cloud → crystal phase transition in the Paul trap: Powerlaws, DANIEL WEISS, YUNSEONG NAM, REINHOLD BLMEL, Wesleyan University — N charged particles, simultaneously stored in a radio-frequency (rf) Paul trap, exhibit deterministic heating. Depending on the damping (γ) imparted to the system, these particles can exist in multiple phases, the most commonly found being the cloud and crystal phases. With a small γ, the particles exhibit gas-like behavior, where the heating and cooling equilibrate and a stable cloud results. For larger γ, the damping overcomes the heating and the particles are forced into the crystalline state. We explore the cloud → crystal transition as a critical phenomenon. We find that the transition occurs at a critical value γc of the damping constant γ. We find that as a function of N, γc scales approximately like an iterated log law. We also present a universal power law, γc ∼ (1 − γc)−β, γc > γc, β > 0, independent of both N and the Paul trap parameter a, depending only on the Paul trap parameter q, that describes the number of cycles necessary for the system to crystallize as a function of γ − γc.

Ion-crystal metamorphoses in the Paul trap, VARUN URSEKAR, YUN SEONG NAM, REINHOLD BLMEL, Wesleyan Univ — We construct a generalized time-independent pseudo potential to describe the crystal morphologies and transitions between them for a three-ion Coulomb-interacting system in a Paul trap. The derivation of this pseudo potential extends a similar method that was already successfully constructed for the two-ion case to the case of three ions. Our method is based on keeping second-order micro-motion terms in the derivation of the pseudo potential. The resulting improved pseudo potential predicts ion-crystal morphologies that are corroborated by numerical simulations but are not captured by the standard pseudo potential. We provide a general method for extending this improved pseudo potential to a system of N Coulomb-interacting ions in a Paul trap.

Storage of multiple single-photon pulses emitted from a quantum dot in a solid-state quantum memory, JIAN-SHUN TANG, ZONG-QUAN ZHOU, YI-TAO WANG, CHUAN-FENG LI, GUANG-CAN GUO, University of Science and Technology of China — Quantum repeaters are critical components for distributing entanglement over long distances in presence of unavoidable optical losses during transmission. Stimulated by Duan-Lukin-Cirac-Zoller protocol, many improved quantum-repeater protocols based on quantum memories have been proposed, which commonly focus on the entanglement-distribution rate. Among these protocols, the elimination of multi-photons (multi-photon-pairs) and the use of multimode quantum memory are demonstrated to have the ability to greatly improve the entanglement-distribution rate. Here, we demonstrate the storage of deterministic single photons emitted from a quantum dot in a polarization-maintaining solid-state quantum memory; in addition, multi-temporal-mode memory with 1, 20 and 100 narrow single-photon pulses is also demonstrated. Multi-photons are eliminated, and only one photon at most is contained in each pulse. Moreover, the solid-state properties of both sub-systems make this configuration more stable and easier to scalable. Our work will be helpful in the construction of efficient quantum repeaters based on all-solid-state devices.

Towards the coupling of single photons from dye molecules to a photonic waveguide, CLAUDIO POLISSEN, KIANG WEI KHO, KYLE MAJOR, SAMUELE GRANDI, SEBASTIEN BOISSER, JAEUK HWANG, ALEX CLARK, EDWARD HINDS, Imperial College London — Single photons are very attractive for quantum information processing given their long coherence time and their ability to carry information in many degrees of freedom. A current challenge is the efficient generation of single photons in a photonic chip in order to scale up the complexity of quantum operations. We have proposed that a dibenzoterylene (DBT) molecule inside an anthracene (AC) crystal could couple lifetime-limited indistinguishable single photons into a photonic waveguide if deposited in its vicinity. In this talk I describe the recent progress towards the realization of this proposal. A new method has been developed for evaporating AC and DBT to produce crystals that are wide and thin. The crystals are typically several microns across and have remarkably uniform thickness, which we control between 20 and 150 nm. The crystal growth is carried out in a glove bag in order to exclude oxygen, which improves the photostability of the DBT molecules by orders of magnitude. We image the fluorescence of single DBT molecules using confocal microscopy and analyse the polarization of this light to determine the alignment of the molecules. I will report on our efforts to control the alignment of the molecules by aligning the host matrix with the substrate.
9:36AM X50.00009 Ultra-Low Power Cross-Phase Shifts using Metastable Xenon in a High-Finesse Cavity†, GARRETT HICKMAN, TODD PITTMAN, JAMES FRANSON, University of Maryland, Baltimore County — Many important applications in quantum information and quantum communications make use of weak single-photon nonlinearities. These nonlinearities have been produced using a number of methods, but they generally require a complicated experimental setup. We demonstrate a relatively simple system for producing ultra-low power cross-phase modulation, by using metastable xenon as the nonlinear medium within an optical cavity. Using metastable xenon prevents the degradation of optical surfaces which typically occurs with the use of alkali vapors such as rubidium. We produce phase shifts of up to 10 mrad using 4.5-fJ control pulses. We discuss the performance of this system and outline the planned improvements that will allow the cavity to produce single-photon phase shifts on the order of 1 mrad.

†This work was supported in part by DARPA DSO Grant No. W31P4Q-12-1-0015 and by NSF Grant No. PHY-1402708.

9:48AM X50.00010 Electric-Field Noise above a Thin Dielectric Layer on Metal Electrodes, MUIR KUMP, IBM, CARSTEN HENKEL, Universitats Potsdam, PETER RABL, TU Wien, MICHAEL BROWNNUITT, The University of Hong Kong, RAINER BLATT, University of Innsbruck — The electric-field noise above a layered structure composed of a planar metal electrode covered by a thin dielectric is evaluated and it is found that the dielectric film considerably increases the noise level, in proportion to its thickness. Importantly, even a thin (mono) layer of a low-loss dielectric can enhance the noise level by several orders of magnitude compared to the noise above a bare metal. Close to this layered surface, the power spectral density of the electric field varies with the inverse fourth power of the distance to the surface, rather than with the inverse square, as it would above a bare metal surface. Furthermore, compared to a clean metal, where the noise spectrum does not vary with frequency (in the radio-wave and microwave bands), the dielectric layer can generate electric-field noise which scales inversely proportion to the frequency. For various realistic scenarios, the noise levels predicted from this model are comparable to those observed in trapped-ion experiments. Thus, these findings are of particular importance for the understanding and mitigation of unwanted heating and decoherence in miniaturized ion traps.

10:00AM X50.00011 Carving complex many-atom entangled states by single-photon detection, JIAZHONG HU, WENLAN CHEN, YIHENG DUAN, BORIS BRAVERMAN, HAO ZHANG, VLADAN VULETIC, Massachusetts Inst of Tech-MIT — We propose a versatile and efficient method to generate a broad class of complex entangled states of many atoms via the detection of a single photon. For an atomic ensemble contained in a strongly coupled optical cavity illuminated by weak single- or multi-frequency light, the atom-light interaction entangles the atomic ensemble with the collective spin of the atomic ensemble. Simple time-resolved detection of the transmitted photon then projects the atomic ensemble into a desired pure entangled state. This method can be implemented with existing technology, yields high success probability per trial, and can generate complex entangled states such as multicomponent Schrödinger cat states with high fidelity.

10:12AM X50.00012 Exponentially small dependence of the Q-function on quantum coherence, R. A. BREWSTER, J. D. FRANSON, University of Maryland Baltimore County — We show that the Huvisi-Q-function has an exponentially small dependence on the relative phase of a Schrödinger cat state, as might be expected from its definition. This raises the question as to whether or not the Q-function provides a complete description of the coherence of quantum states. We calculate the Q-function for a cat state and then invert it by first calculating the Glauber-Sudarshan P-function using a Fourier transform, which can then be used to calculate the state itself. This process is shown to multiply the small phase-dependent terms in the Q-function by an exponentially large factor as needed in order to obtain the original state once again. This exponential factor is strongly degraded by decoherence, such as by amplification of the original state.

†Funded by the Office of Naval Research.

10:24AM X50.00013 Generation and multi-pass propagation of a squeezed vacuum field in hot Rb vapor, MI ZHANG, College of William and Mary, R. NICHOLAS LANNING, ZHIHAO XIAO, JONATHAN P. DOWLING, Louisiana State University, IRINA NOVIKOVA, EUGENIY E. MIKHAILOV, College of William and Mary — We study a squeezed vacuum field (with reduced quantum noise level) generated in hot Rb vapor via the polarization self-rotation effect. By propagating the strong laser beam through a vapor cell once, we were able to achieve a noise suppression of 1.5-2 dB below shot noise. Our previous experiments showed that the amount of observed squeezing may be limited by the contamination of the squeezed vacuum output with higher-order spatial modes, also generated inside the cell. Here, we investigate whether or not the squeezing can be improved by making the light interact several times with a less dense atomic ensemble. We carry out a comparison of various conditions, e.g. injection power, atomic density, passing numbers etc., and studied their effect on squeezing level and the spatial structure of the output squeezed vacuum field. We believe(or show) optimization of the conditions can lead to higher achievable squeezing which would be very useful for precision metrology and quantum memory applications.

†This project is supported by AFOSR grant FA9550-13-1-0098.

10:36AM X50.00014 Bright Single Photon Emitter in Silicon Carbide, BENJAMIN LIENHARD, TIM SCHROEDER, SARA MOURADIAN, FLORIAN DOLDE, Massachusetts Inst of Tech-MIT, TOAN TRONG TRAN, IGOR AHARONOVICH, University of Technology Sydney, Australia, DIRK ENGLUND, Massachusetts Inst of Tech-MIT — Efficient, on-demand, and robust single photon emitters are of central importance to many areas of quantum information processing. Over the past 10 years, color centers in solids have emerged as excellent single photon emitters. Color centers in diamond are among the most intensively studied single photon emitters, but recently silicon carbide (SiC) has also been demonstrated to be an excellent host material. In contrast to diamond, SiC is a technologically important material that is widely used in optoelectronics, high power electronics, and microelectromechanical systems. It is commercially available in sizes up to 6 inches and processes for device engineering are well developed. We report on a visible-spectrum single photon emitter in 4H-SiC. The emitter is photostable at both room and low temperatures, and it enables 2 million photons/second from unpatterned bulk SiC. We observe two classes of orthogonally polarized emitters, each of which has parallel absorption and emission dipole orientations. Low temperature measurements reveal a narrow zero phonon line with linewidth < 0.1 nm that accounts for more than 30% of the total photoluminescence spectrum. To our knowledge, this SiC color emitter is the brightest stable room-temperature single photon emitter ever observed.

10:48AM X50.00015 Ring-shaped Wigner crystals of trapped ions at the micromscale, HAOKUN LI, ERIK URBAN, CRISTAL NOEL, ALEXANDER CHUANG, YANG XIA, BORGE HEMMERLING, YUAN WANG, XIANG ZHANG, HARTMUT HAEFNER, University of California, Berkeley — Trapped ion crystals are ideal platforms to study many-body physics and quantum information processing, with both the internal electronic states and external motional degree-of-freedoms controllable at the single quantum level. In contrast to conventional, finite, linear chains of ions, a ring topology exhibiting periodic boundary conditions and rotational symmetry opens up a new directions to diverse topics. However, previous implementations of ion rings result in small aspect ratios (< 0.07) of ion-electrode distance to ring diameter, making the rotational symmetry of the ion crystals prone to stray electric fields from imperfections of the trap electrodes, particularly evident at low temperatures. Here, using a new trap design with a 60-fold improvement of this aspect ratio, we demonstrate crystallization of 40Ca+ ions in a ring with rotational energy barriers comparable to the thermal energy of Doppler laser cooled ion crystals. When further reducing the rotational energy barriers, we observe delocalization of the ion rings. With this result, we enter a regime where quantum topological effects can be studied and novel quantum computation and simulation experiments can be implemented.
11:15AM Y48.00001 Design and Simulation of Microwave Attenuators for Superconducting Quantum Devices. JAY LEFEBVRE, Department of Physics, University of Maryland, College Park. JEN-HAO YEH, Laboratory for Physical Sciences, College Park, MD and Department of Physics, University of Maryland, College Park, MD, FREDERICK WELLSTOOD, Department of Physics, University of Maryland, College Park, MD — We have found that dephasing times for quantum superconducting transmons operating nominally at T = 20 mK can be limited by thermal photons in the read-out cavity due to non-equilibrium noise on our input microwave line. In an effort to reduce this noise, we have used finite-element simulations to design attenuators that provide better thermalization of the input microwave signals being delivered to our devices. Our thermal simulations incorporate both electron-phonon decoupling effects due to dissipated power in each element of the attenuator as well as phonon thermal conduction and Kapitza boundary effects. We combine the resulting thermal map with a thermal noise model of each dissipative element of the filter to estimate the effective noise temperature of our filter design.

11:27AM Y48.00002 Cavity Dephasing in Transmon Qubits from Non-equilibrium Noise. JEN-HAO YEH, Laboratory for Physical Sciences, College Park, MD and Department of Physics, University of Maryland, College Park, MD, JAY LEFEBVRE, Department of Physics, University of Maryland, College Park, MD, FREDERICK WELLSTOOD, Department of Physics, University of Maryland, College Park, MD, and Joint Quantum Institute, University of Maryland, College Park, MD, BENJAMIN PALMER, Laboratory for Physical Sciences, College Park, MD and Department of Physics, University of Maryland, College Park, MD — The dephasing times for transmon qubits in a 3D cavity can be limited by coupling of the cavity input and output lines to non-equilibrium noise from higher temperature stages. In our system, the dominant source of thermal photons in the cavity is the last microwave attenuator in the microwave input line which is mounted on the 20 mK stage. Guided by thermal and microwave simulations, we have fabricated microwave attenuators and tested them in a 3D transmon measurement system. The performance of the attenuators was quantified by measuring the Ramsey decay time of a transmon qubit as a function of the temperature of the mixing chamber and power dissipated in the attenuator. Based on the Ramsey decay times and properties of the transmon-cavity system, we estimate the effective output noise temperature of the attenuator and compare our results to simulations.

11:39AM Y48.00003 Qubit dephasing due to photon shot noise from coherent and thermal sources. S. GUSTAVSSON, F. YAN, A. KAMAL, T. P. ORLANDO, W. D. OLIVER, MIT, J. BIRENBAUM, A. SEARS, D. HOVER, T. GUDMUNSEN, J. YODER, MIT Lincoln Laboratory — We investigate qubit dephasing due to photon shot noise in a superconducting flux qubit transversely coupled to a coplanar microwave resonator. Due to the AC Stark effect, photon fluctuations in the resonator cause frequency shifts of the qubit, which in turn lead to dephasing. While this is universally understood, we have made the first quantitative spectroscopy of this noise for both thermal (i.e., residual photons from higher temperature stages) and coherent photons (residual photons from the readout and control pulses). We find that the bandwidth of the shot noise from thermal and coherent photons differ by approximately a factor of two, which we attribute to differences in the correlation time for the two noise sources. By comparing the results with noise spectra measured without any externally applied photons, we conclude that the qubit coherence times in our setup were limited by photon shot noise from thermal radiation, with an average resonator photon population of 0.006. Equipped with this knowledge, we improved the filtering for thermal noise and thereby improved the qubit coherence times by more than a factor of two, with T2 echo times approaching 100 us. From the measured T2 decay, we determine an upper bound on the residual photon population of 0.0004.

11:51AM Y48.00004 Suppression of photon shot noise dephasing in a tunable coupling superconducting qubit. GENGYAN ZHANG, YANBING LIU, JAMES RAFTERY, ANDREW HOUCK, Princeton University — We report on the suppression of photon shot noise dephasing in a tunable coupling qubit (TCQ). This is achieved by eliminating the dispersive coupling rate, χ, between the TCQ and the readout cavity. We observe that the coherence time approaches twice the relaxation time and becomes less sensitive to thermal photon noise when χ is tuned close to zero. Experimental results of tunable χ and its impact on qubit coherence will be presented.

12:03PM Y48.00005 Dephasing of superconducting asymmetric transmon qubits. M. HUTCHINGS, MATTHEW WARE, YEBIN LIU, SYRACUSE UNIVERSITY. JARED B. HERTZBERG, JERRY M. CHOW, IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA. B. L. T. PLOURDE, SYRACUSE UNIVERSITY — As quantum computing implementations based on superconducting qubits increase in scale and complexity, fabrication tolerances and frequency crowding make it desirable to have layouts with at least some of the qubit frequencies being tunable. Split-junction transmon qubits allow for the tuning of qubit energy levels with a magnetic flux. However, this tunability can lead to excess dephasing due to flux noise. By making the two junctions asymmetric, the modulation range of the qubit energy bands can be reduced along with the sensitivity to flux noise. Such asymmetric transmons have been used previously for demonstrations of flux-modulated first-order sideband transitions between a qubit and cavity. We will report on the sensitivity of qubit dephasing to magnetic flux noise for different junction asymmetry. For large asymmetries, of the order of 10:1, the dephasing due to flux noise is greatly reduced compared to a symmetric junction device, whilst still maintaining a useful level of frequency tunability.

12:15PM Y48.00006 Paramagnetic spins on Al2O3 with varied surface termination. KEITH RAY, LAWRENCE Livermore National Laboratory. DONGHWA LEE, CHONNAM National University. NICOLE ADELSTEIN, San Francisco State University. JONATHAN DUBOIS, VINCENZO LORDI, LAWRENCE Livermore National Laboratory — Superconducting qubits (SQs) are promising building blocks for a quantum computer, however, coherence in SQs is reduced by unintended coupling to magnetic noise sources. The microscopic origins of the magnetic noise have not been satisfactorily characterized. Building on previous computational studies [PRL 112, 017001 (2014)] of magnetic spins induced by molecules adsorbed on bare Al terminated Al2O3, we present a density functional theory investigation of magnetic noise associated with other Al2O3 surfaces likely to be encountered in experiment. We calculate the exchange interaction between native defects and adsorbed molecules, as well as the magnetic states energy splitting and anisotropy, on fully hydroylated Al2O3, with and without a water over-layer. We also present simulated x-ray adsorption and x-ray magnetic circular dichroism spectra of these systems with the aim of aiding experimental surface characterization.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.
12:27PM Y48.00007 Suppression of 1/f Flux Noise in Superconducting Quantum Circuits
dr Kevin Osborn, Laboratory for Physical Sciences and Joint Quantum Institute, ARUNA RAMANAYAKA, BAHMAN SARABI, Laboratory for Physical Sciences and University of Maryland Physics Dept., U. OF MARYLAND TEAM — Noise from atomic tunneling two-level systems (TSs) limit the performance of various superconducting devices, ranging in application from astronomy to quantum computing. We study superconducting resonators with films containing TS and measure the resulting 1/f frequency noise caused by resonant TS. The resonators are designed such that they apply a uniform ac electric field to the films which allows a direct measurement of permittivity noise in the film as a function the electric field. An intrinsic value of noise is found as well as the power law for ac-field saturation. The temperature dependence of 1/f noise below 200 mK fits to a relationship found previously in high-Q resonators. However, our data yield a model different than a previous experimental study; in our work TS phenomena are modeled with frequency diffusion. Our measured noise times the temperature is found to be the same to within error in the different films when normalized to the loss tangent at low temperature, despite dramatically different loss tangents. Following from the general nature of the TS models, we expect the same permittivity noise in many other devices.

12:39PM Y48.00008 Measurement of the Magnetic Flux Noise Spectrum in Superconducting Xmon Transmon Quantum Bits, BEN CHIARO, UC - Santa Barbara, D. SANK, J. KELLY, Google - Santa Barbara, Z. CHEN, B. CAMPBELL, A. DUNSWORTH, P. O'MALLEY, C. NEILL, C. QUINTANA, A. VAINESCHER, J. WENNER, UC - Santa Barbara, R. BARENDTS, Y. CHEN, A. FOWLER, E. JEFFREY, A. MIGRANT, J. MUTUS, P. ROUSHAN, T. WHITE, Google - Santa Barbara, J. M. MARTINIS, UC - Santa Barbara and Google - Santa Barbara — Dephasing induced by magnetic flux noise limits the performance of modern superconducting quantum processors. We measure the flux noise power spectrum in planar, frequency-tunable, Xmon transmon quantum bits (qubits), with several SQUID loop geometries. We extend the Ramsey Tomography Oscilloscope (RTO) technique by rapid sampling up to 1 MHz, without state reset, to measure the flux noise power spectrum between 10−2 and 105 Hz. The RTO measurements are combined with idle gate randomized benchmarking and Ramsey decay to give a more complete picture of dephasing in SQUID-based devices.

12:51PM Y48.00009 1/f noise driven qubit dynamics in presence of a bosonic thermostat
KOSTYANTYN KECHEDZHI, FEDIR VASKO, ANDRE PETUKHOV, NASA Ames Research Center, Mail Stop 269-3, Moffet Field, CA 94035, VADIM SMELYANSKIY, Google, Venice, CA 90291, US — Motivated by observations of distinct sources of noise in superconducting flux qubits over a wide frequency range, we analyze a qubit, a two level system, coupled to two microscopic sources of noise: 1/f low frequency noise and the Ohmic high frequency noise. The noise sources are treated as independent and characterized by different temperatures. We analyze the steady state regime of the resulting out-of-equilibrium dynamics focusing in particular on the effects of the interplay of the two types of noise on spectroscopic characteristics of the qubit. We calculate both analytically and numerically the steady state population of the qubit energy levels, relaxation and dephasing times and effective renormalization of the qubit’s energy level splitting.

1:03PM Y48.00010 1/f permittivity noise probed uniformly in a film with two level systems: The power law of field saturation and the relationship to loss, KEVIN OSBORN, Laboratory for Physical Sciences and Joint Quantum Institute, ARUNA RAMANAYAKA, BAHMAN SARABI, Laboratory for Physical Sciences and University of Maryland Physics Dept., U. OF MARYLAND TEAM — Noise from atomic tunneling two-level systems (TSs) limit the performance of various superconducting devices, ranging in application from astronomy to quantum computing. We study superconducting resonators with films containing TS and measure the resulting 1/f frequency noise caused by resonant TS. The resonators are designed such that they apply a uniform ac electric field to the films which allows a direct measurement of permittivity noise in the film as a function the electric field. An intrinsic value of noise is found as well as the power law for ac-field saturation. The temperature dependence of 1/f noise below 200 mK fits to a relationship found previously in high-Q resonators. However, our data yield a model different than a previous experimental study; in our work TS phenomena are modeled with frequency diffusion. Our measured noise times the temperature is found to be the same to within error in the different films when normalized to the loss tangent at low temperature, despite dramatically different loss tangents. Following from the general nature of the TS models, we expect the same permittivity noise in many other devices.

1:15PM Y48.00011 Flux noise due to magnetic impurities in superconducting circuits: Optimal spin texture and role of phase transition, ROGÉRIO DE SOUSA, Department of Physics and Astronomy, University of Victoria, British Columbia, Canada — Superconducting quantum interference devices (SQUIDs) and other superconducting circuits are limited by intrinsic flux noise with spectral density 1/αf with α < 1 whose origin is believed to be due to spin impurities. We present a theory of flux noise in the presence of phase transitions and arbitrary spin textures in the impurity spin system [1]. At higher temperatures we find that the spin-spin correlation length scale (describing, e.g., the average size of ferromagnetic spin clusters) greatly impacts the scaling of flux noise with wire geometry. At lower temperatures we find that flux noise is quite sensitive to the particular spin texture realized by the spin system ground state. Remarkably, we show that flux noise is exactly equal to zero when the spins form a poloidal texture. Flux noise is nonzero for other spin textures, but gets reduced in the presence of correlated ferromagnetic fluctuations between the top and bottom wire surfaces, where the flux vectors are antiparallel. This demonstrates the idea of engineering spin textures and/or intersurface correlation as a method to reduce flux noise in superconducting circuits.

1:27PM Y48.00012 Spin noise and magnetic screening of impurities in a BCS superconductor, MATTHIAS LE DALL, Department of Physics and Astronomy, University of Victoria, British Columbia, Canada, LUIS G. G. V. DIAS DA SILVA, Instituto de Física, Universidade de São Paulo, Brazil, ROGÉRIO DE SOUSA, Department of Physics and Astronomy, University of Victoria, British Columbia, Canada — The coupling of a localized impurity to a BCS superconductor (SC) leads to the formation of impurity Cooper-pairs via the proximity effect, generating two bound states within the SC energy gap, the so-called Yu-Rusinov-Shiba (YSR) states. They are similar to the Andrew Bound States that originate from Andreev reflection, e.g. when the impurity is hosted in a Josephson junction, and are known to produce sharp sub-gap resonances in charge noise [de Sousa et al., PRB 2009], providing a natural explanation for the observation of microresonators in superconducting devices [Simmonds et al., PRL 2004]. Here we present a theory for the spin noise generated by magnetic impurities in a SC, and discuss the impact of the Shiba states on models of flux noise in superconducting qubits. We use a combination of analytical methods and the numerical renormalization group technique to calculate the spin noise of an Anderson impurity in a SC, unveiling the competition between the proximity effect and Kondo correlations. Both mechanisms produce magnetic screening and a corresponding reduction in spin noise, giving rise to new insights on the kinds of impurities that are responsible for the observed 1/fα flux noise in superconducting circuits.

This research was supported by the Natural Sciences and Engineering Research Council of Canada (RGPIN/342982- 2010, EGP/429649-2012) through its Discovery and Engage programs.

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1:39PM Y48.00013 Geometrical Effects in Noise Spectra of Superconducting Flux Qubits1, ANDRE PETUKHOV, NASA Ames Research Center, Moffett Field, California, VADIM SMELYANSKIY, Google Inc, Venice, California, JOHN MARTINIS, University of California, Santa Barbara and Google Inc, Santa Barbara, California — We present theoretical study of geometrical effects related to spin diffusion in superconducting flux qubits. We adopt a model of a long superconducting wire surrounded by a thin oxide layer with spins distributed uniformly over cross-sectional area of the oxide layer. Using a continuous transformation from a round cylinder to a flat wire strip, we demonstrate that the noise spectral density tends to a power law $S(\omega) \propto (\omega/\Gamma)^{-s}$ with $s \gtrsim 3/4$, approaching $s = 3/4$ for very thin wires. The $\omega^{-s}$ dependence is valid in a broad frequency range above $\omega \gtrsim \Gamma$ stretching up to four orders of magnitude in units of characteristic diffusion decay rate $\Gamma \sim 1 - 10^2$ Hz. The effect is highly sensitive to a cross-sectional aspect ratio of a thin wire thus revealing its geometrical origin. We substantiate our findings by detailed comparison with available experimental data and conclude that $3/4$ power law distinguishes spin diffusion flux noise from generic $1/f$ family.

1Supported by the AFRL Information Directorate under grant F4HBKC4162G001

1:51PM Y48.00014 Suppression of dephasing by qubit motion in superconducting circuits1, D.V. AVERIN, Dep-t of Physics and Astronomy, Stony Brook University, SUNY, K. HU, Y. P. ZHONG, C. SONG, H. WANG, Dep-t of Physics, Zhejiang University, China, S. HAN, Dep-t of Physics and Astronomy, University of Kansas — We suggest and demonstrate a protocol which suppresses dephasing due to the low-frequency noise by qubit motion, i.e., transfer of the logical qubit of information in a system of $n \geq 2$ physical qubits. The protocol requires only the nearest-neighbor coupling and is applicable to different qubit structures. Motion of a logical qubit limits the correlation time of the effective noise seen by this qubit and suppresses its decoherence rate. This effect is qualitatively similar to the dynamic decoupling, but relies on the different resource: additional physical qubits, not extra control pulses. In this respect, suggested protocol can serve as the basis for an alternative approach to scalable quantum circuits. We further analyze its effectiveness against noises with arbitrary correlations. Our analysis, together with experiments using up to three superconducting qubits, shows that for the realistic uncorrelated noises, qubit motion increases the dephasing time of the logical qubit as $\sqrt{n}$. In general, the protocol provides a diagnostic tool for measurements of the noise correlations.

1This work was supported by the National Basic Research Program of China (2014CB921200, 2012CB927404), US NSF grants PHY-1314758 and PHY-1314861, the National Natural Science Foundation of China, and Zhejiang Provincial Natural Science Foundation

2:03PM Y48.00015 Long range correlations by local dissipation in lattice waveguide QED, BAPTISTE ROYER, ARNE L. GRIMSMO, Univ of Sherbrooke, ALEXANDRE BLAIS, Univ of Sherbrooke, CIFAR — In waveguide QED, superconducting qubits acting as artificial atoms are coupled to 1D superconducting transmission lines playing the role of common bath for the qubits. By controlling their effective separation and coupling to the transmission line, it is possible to engineer various types of dissipation-induced interactions between the qubits. In this talk, we consider the situation where multiple superconducting qubits are coupled to a lattice of superconducting transmission lines. We show that this can lead to the creation of highly entangled dark states using local dissipation only. Using tensor networks techniques, we study such large-scale highly-correlated systems.