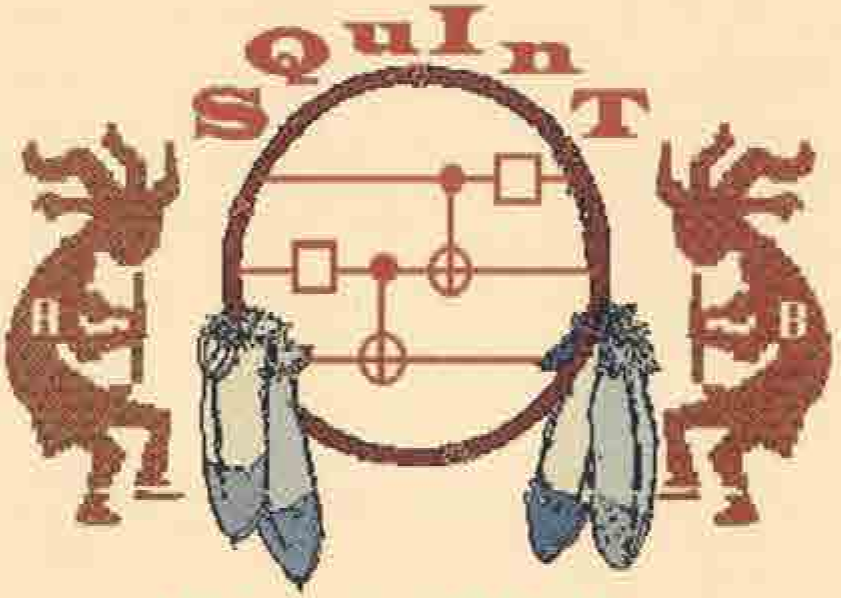
# Southwest Quantum Information and Technology




## Eighth Annual Workshop

**Hotel Albuquerque at Old Town**
**Albuquerque, New Mexico**
**February 16, 2006 – February 19, 2006**

CENTER for Advanced Studies

NIST

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## 8th Annual SQuInT Workshop Sponsored by

**University of New Mexico: Center for Advanced Studies.**

**Los Alamos National Laboratory: Quantum Institute.**

**National Institute of Standards and Technology, Boulder.**

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## Program

**DAY 1 – Friday, February 17, 2006**

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|---|---|
| 07:30 – 08:30 | **Breakfast (provided)** |
| 08:30 – 08:45 | **Welcome to SQuInT 2006** |
| **SESSION 1** | **Optical Quantum Computing and Networking** |
| 08:45 – 09:30 | Terry Rudolph (Imperial College – Invited Talk)<br>Toward Optical Quantum Computation with Realistic Devices |
| 09:30 – 10:00 | James Chin-wen Chou (Caltech)<br>Measurement Induced Entanglement for Excitation Stored in Remote Atomic Ensembles |
| 10:00 – 10:30 | **Morning Break** |
| 10:30 – 11:00 | Thaddeus Ladd (Stanford)<br>Practical Quantum Repeater Using Intense Coherent Light |
| 11:00 – 11:30 | Danna Rosenberg (Los Alamos National Laboratory)<br>Quantum Key Distribution with Noise-Free Detectors |
| 11:30 – 13:00 | **Lunch (provided)** |
| **SESSION 2** | **Quantum Measurement and Metrology** |
| 13:00 – 14:00 | Hans Briegel (Innsbruck – Invited Tutorial)<br>Graph States and the One-Way Quantum Computer |
| 14:00 – 14:30 | Michael Di Rosa (Los Alamos National Laboratory)<br>Quantum Nondemolition Detection of Photons |
| 14:30 – 15:00 | Afternoon Break |
| 15:00 – 15:30 | Ognyan Oreshkov (University of Southern California)<br>Weak Measurements and Differential Conditions on Entanglement Monotones |
| 15:30 – 16:00 | Diego Dalvit (Los Alamos National Laboratory)<br>Sub-Planck Structures and Heisenberg-Limited Measurements |
| 16:00 – 16:15 | **Afternoon Break** |
| **SESSION 3** | **Qubits in Condensed Matter** |
| 16:15 – 17:00 | Eva Weig (University of California, Santa Barbara – Invited Talk)<br>The Role of Dielectrics in Superconducting Quantum Circuits |
| 17:00 – 17:30 | Wang Yao (University of California, San Diego)<br>Electronic Spin Decoherence by Interacting Nuclear Spins in Quantum Dots |
| 17:30 – 18:00 | Frank Verstraete (Caltech)<br>Strongly Correlated Quantum Many Body Systems: A Quantum Information Perspective |
| 18:00 – 19:30 | **Poster Session** |

## Program

**DAY 2 – Saturday, February 18, 2006**

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|---|---|
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| **SESSION 4** | **Quantum Algorithms** |
| 08:30 – 09:00 | Christopher Moore (University of New Mexico)<br>Hidden Subgroups and Fourier Sampling: A Tutorial |
| 09:00 – 09:30 | Dave Bacon (University of Washington)<br>New Algorithms for the Nonabelian Hidden Subgroup Problem |
| 09:30 – 10:00 | **Morning Break** |
| 10:00 – 10:30 | Andrew Landahl (University of New Mexico<br>An Improved Quantum Algorithm for the Ordered Search Problem |
| 10:30 – 11:00 | Jonathan Walgate (Calgary)<br>Quantum Buried Treasure |
| 11:00 – 11:30 | Tony Dutoi (University of California – Berkeley<br>Simulated Quantum Computation of Molecular Energies |
| 11:30 – 13:15 | **Lunch (provided)** |
| **SESSION 5** | **Quantum Information Science with Atoms and Ions** |
| 13:15 – 14:00 | Thad Walker (University of Washington – Madison – Invited Talk)<br>Quantum Manipulation of Atoms Using Rydberg States |
| 14:00 – 14:30 | Poul Jessen (University of Arizona)<br>Progress Towards Quantum Logic and Real-Time Quantum State Estimation |
| 14:30 – 15:00 | Matt Blain (Sandia National Laboratory)<br>Microfabrication and Packaging of Ion Trap Chips for Quantum Simulation |
| 15:00 – 15:30 | **Afternoon Break** |
| **SESSION 6** | **Fault-Tolerant Quantum Computing** |
| 15:30 – 16:30 | John Preskill (California Institute of Technology – Invited Tutorial)<br>Topological Quantum Computation |
| 16:30 – 17:00 | Break |
| 17:00 – 17:30 | Bryan Eastin (University of New Mexico)<br>Thresholds for Arbitrary Error Channels Using Perfect Ancillae |
| 17:30 – 18:00 | Robert Raussendorf (California Institute of Technology<br>A Fault-Tolerant One-Way Quantum Computer |
| 18:00 – 19:00 | **Additional Poster Viewing** |
| 19:00 - | **Conference Banquet** |

# Program

**DAY 3 – Sunday, February 19, 2006**

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|---|---|
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| **SESSION 7** | **Trapped Ion Quantum Information** |
| 08:30 – 09:00 | Roee Ozeri (National Institute of Standards and Technology)<br>Steps Toward Scalable Trapped-Ion QIP at NIST |
| 09:00 – 09:30 | Peter Maunz (University of Michigan)<br>Quantum Information Processing with Ultrashort Pulses |
| **SESSION 8** | **Fundamental Quantum Information Science** |
| 09:30 – 10:00 | A.R.P. Rau (Louisiana State University)<br>Geometric Phase and General Solution for N-level Systems |
| 10:00 – 10:30 | **Morning Break** |
| 10:30 – 11:00 | Brian Smith (University of Oregon)<br>Photon Wave Mechanics |
| 11:00 – 11:30 | Shohini Ghose (Wilfrid Laurier University)<br>Non-Gaussian Ancilla States for Continuous Variable Quantum Information Process |
| 11:30 – 12:00 | Masoud Mohensi (University of Southern California<br>Direct Characterization for Open Quantum Systems Dynamics |
| 12:00 – 12:30 | Lunch |
| 12:30 – 13:00 | Kurt Jacobs (Louisiana State University)<br>Complementarity Between Work, Entanglement, and Reference Frame Ability |
| 13:00 – 13:30 | Peter Love (DWave, Inc.)<br>Entanglement in Four Superconducting Qubits |

# Oral Presentations

# Session #1 Optical Quantum Computing and Networking

### Towards Optical Quantum Computation with Realistic Devices (Invited)

**Terry Rudolf,** ***Imperial College, London***

**Abstract:** The primary technological hurdle facing linear optical quantum computation is commonly thought to be the construction of efficient sources and detectors. I will argue that the primary hurdle is in fact theoreticians who haven't devoted enough time to thinking about whether we can get by with the devices we have. In defense of this thesis I will discuss how, by making use of some neat features of cluster state computation, we can get by with much more noisy devices than one might have hoped, and why I am optimistic that smarter theoreticians then me should be able to relax these fault tolerant thresholds even further.

### Measurement Induced Entanglement for Excitation Stored in Remote Atomic Ensembles

**James Chin-Wen Chou,** ***California Institute of Technology***

**Abstract:** A critical requirement for diverse applications in Quantum Information Science is the capability to disseminate quantum resources over complex quantum networks. This requires the realization of a quantum memory that would allow the storage and retrieval of quantum states. Recently, atomic ensembles rise to be a promising candidate for this task. In this contribution we report observation of entanglement between two atomic ensembles located on different tables in distinct apparatuses separated by 2.8 meters. Quantum interference in the detection of a photon emitted by the samples projects the otherwise independent ensembles into an entangled state with one joint excitation stored remotely in ~10^5 atoms at each site. After a delay of 1 microsecond to demonstrate quantum memory, we confirm entanglement by mapping the state of the atoms to optical fields and then measuring mutual coherence and photon statistics for these fields. We thereby determine a quantitative lower bound for the entanglement of the joint state of the ensembles.

## Practical Quantum Repeater Using Intense Coherent Light

**Thaddeus Ladd,** ***Stanford University***

**Abstract**: Long-distance (~1000 km) quantum communication will require a quantum repeater system. For most existing repeater proposals, reasonable qubit-communication rates require technologies which are currently impractical, such as balanced, stabilized interferometry over very long distances or large numbers of efficient single-photon sources and detectors. We present detailed theoretical calculations demonstrating the feasibility of a more practical quantum repeater employing intense coherent light interacting dispersively with single emitters (atoms, quantum dots, semiconductor impurities, etc.). For a sufficient interaction strength, each emitter must be located in a high-Q optical cavity, but the weak-coupling regime is sufficient. Distribution of the intense coherent light among the intermediate qubits of the quantum channel followed by homodyne detection of the optical phase generates noisy, post-selected entangled pairs with high success probability. Local operations used for entanglement purification and entanglement swapping are based upon the same coherent-light resources and weak interactions as for the initial entanglement distribution. Assuming small local optical loss and high-fidelity single-qubit rotations, these local operations may be completely deterministic. Simulations of this system show qubit-communication rates approaching 100 Hz and final fidelities above 99% for reasonable system parameters.

## Quantum Key Distribution with Noise-Free Detectors

**Danna Rosenberg,** ***Los Alamos National Laboratory***

Abstract. Under ideal conditions, quantum key distribution (QKD) provides a method for two users to communicate with security guaranteed by the laws of physics. In the real world, the security of such a system is closely tied to the properties of the source and the detectors. In particular, the detection efficiency and the dark-count rate of the detectors used at the receiver play a critical role in determining the maximum length of a secure link. Unlike standard avalanche photo-diodes, which typically have low efficiency and high dark-count rates at the telecommunication wavelengths, transition-edge sensors (TESs) have virtually no dark counts and can be engineered to have high efficiency at telecommunications wavelengths. By incorporating TESs into a QKD system, we were able to 1) transmit key across 202 km of dark optical fiber and 2) demonstrate key transmission secure against photon-number-splitting attacks over 100 km of dark fiber, setting two new records for fiber quantum key distribution.

# Session #2: Quantum Measurement and Metrology

## Graph States and the One-Way Quantum Computer (Invited Tutorial)

**Hans Briegel,** *University of Innsbruck*

**Abstract:** This talk will give an introduction to the theory of graph states. Graph states arise naturally in the context of the one-way quantum computer, but they play a significant role in other fields of quantum information, too. We will discuss various properties of graph states, including their generalizations and applications.

## Quantum Nondemolition Detection of Photons

**Michale Di Rosa,** *Los Alamos National Laboratory*

Abstract. We propose to build a quantum nondemolition (QND) detector of single photons from the giant Kerr nonlinearity theoretically identified by Schmidt and Imamoglu [1]. To our knowledge, the experimental work would represent the first single-photon QND measurement by a cross-Kerr interaction, and we believe it would mark an important transition for the use of QND measurements in optics-based quantum computing. While single-photon QND measurements have been demonstrated through cavity QED, our use of a material nonlinearity will provide a QND measurement that can count photon numbers greater than one and allow photons to pass unimpeded for re-use in computations. We will review the theoretical template for the enhanced cross-Kerr interaction and show its match to an atomic system we have chosen for the experiments.

[1] H. Schmidt and A. Imamoglu, Opt. Lett. **21**, 1936 (1996).

## Weak Measurements and Differential Conditions for Entanglement Monotones

**Ognyan Oreshkov,** *University of Southern California*

Abstract. We have shown that every generalized quantum measurement can be implemented as a sequence of weak measurements, and presented an explicit construction of these weak measurements. The measurement procedure has the structure of a random walk in state space, with the measurement ending when one of the end points is reached. This allows us to think of measurements in quantum mechanics as resulting from continuous stochastic evolutions, and to make use of the powerful tools of differential calculus in the study of the transformations that a system undergoes upon measurement. We have used this result to derive necessary and sufficient differential conditions for a function of the state to be an entanglement monotone, by looking at the behavior of a prospective monotone under infinitesimal local operations. As an application, we have used the differential conditions to construct a new entanglement monotone for three-qubit pure states, which depends on the sixth-order polynomial invariant identified by Kempe. Future projects include application of the measurement decomposition to quantum control, and searching for new classes of entanglement monotones.

## Sub-Planck Structures and Heisenberg-Limited Measurements

**Diego Dalvit (Los Alamos National Laboratory)**

**Abstract:** We show how sub-Planck phase-space structures can be used to achieve Heisenberg-limited sensitivity in weak force measurements. Nonclassical states of harmonic oscillators, consisting of superpositions of coherent states, are show to be useful for the measurement of weak forces that cause translations or rotations in phase space, which is done by entangling the quantum oscillator with a two-level system. Implementations of this strategy in cavity QED and ion traps are described.

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# Session #3: Qubits In Condensed Matter

## The Role of Dielectrics in Superconducting Quantum Circuits (Invited Talk)

**Eva Weig, University of California Santa Barbara**

**Abstract:** Superconducting quantum bits are considered promising candidates for constructing a solid-state quantum computer. They are based on the Josephson junction, formed by sandwiching a thin dielectric between two superconducting leads, through which Cooper pairs can tunnel. The Josephson junction provides a nearly dissipationless, highly nonlinear circuit element that allows the construction of a quantum bit. A particular implementation, the phase qubit, is realized by current-biasing a Josephson junction near the critical current of the junction. Besides demonstrating long coherence times, phase qubits can be tuned over a large frequency range. Furthermore, they provide all the advantages of solid-state electrical circuits, as they can be fabricated using fully scalable conventional integrated circuit technology. In addition, controlled coupling to other quantum circuits can be achieved, facilitating readout and gate implementation. In order to achieve the maximum coherence time, to allow for multiple, complex quantum operations, the dissipation induced by the environment has to be minimized. Our research has therefore focused in part on minimizing environment-induced decoherence, and we have recently achieved a significant and important breakthrough, due to the realization that losses in the dielectrics, both in the Josephson junction itself and in associated circuitry, dominate the overall loss and limit the coherence time. Our demonstration of high visibility, long decoherence time qubits has been achieved by carefully redesigning and engineering our qubit circuit and the materials employed. Recent experiments have demonstrated qubit state preparation, manipulation and probing with a measurement fidelity of 95%. Rabi oscillations with a relaxation time T1 of 500 ns have been observed. Ramsey fringe as well as spin echo measurements yield decoherence times of T2 = 2 T1 and T2*= 150 ns. We have also be! gun to develop full quantum tomography of the qubit state. This experimental technique allows the reconstruction of the density matrix from a complete set of observables measured on an ensemble of identically prepared copies of the system. The detailed understanding of a single qubit will enable us to start focusing on coupled qubit systems. Experiments to violate Bells inequality as well as the implementation of a CNOT gate in a coupled qubit are in progress.

**Electron Spin Decoherence by Interacting Nuclear Spins in Quantum Dots**

**Wang Yao, Ren-Bao Liu and L. J. Sham (University of California San Diego)**

Abstract. Department of Physics, University of California, San Diego Abstract: Electron spins in semiconductor quantum dots are natural carriers of qubit for quantum information processing. A major issue that has to be addressed is the spin decoherence. Consensus holds that at low temperature, the lattice nuclear spin is the dominant agent for decoherence. In this talk, I will present a quantum theory to the electron spin decoherence by a nuclear pair-correlation method for the electron- nuclear spin dynamics under a strong magnetic field and low temperature. The theory incorporates the electron nuclear hyperfine interaction, the intrinsic nuclear interactions, and the nuclear coupling mediated by the hyperfine interaction with the electron in question. Results for both single electron spin free-induction decay (FID) and ensemble electron spin echo will be discussed. Single spin FID is affected by both the intrinsic and the hyperfine-mediated nuclear interactions, with the dominance determined by the dot size and external field. The spin echo eliminates the hyperfine-mediated decoherence but only reduces the decoherence by the intrinsic nuclear interactions. Thus, the decoherence times for FID and spin echo are significantly different. Electron spin decoherence is explained in terms of the quantum entanglement: due to the hyperfine interaction, the nuclear spins in a quantum dot, driven by nuclear spin pair-wise flip-flops, evolve in different pathways in the Hilbert space for different electron spin states, resulting in the electron-nuclei entanglement and hence the electron spin decoherence. When the electron spin is flipped by a pulse, the nuclear spin states for different electron spin states swap their pathways, and could intersect in the Hilbert space, which disentangles the electron and the nuclei and hence restores the electron spin coherence. The coherence restoration by disentanglement and the conventional spin echo in ensemble dynamics are fundamentally different and generally occur at different time. Pulse sequences can be applied to force the disentanglement to coincide with the spin echo, making the coherence recovery observable in ensemble dynamics.

* *This work was supported by NSF DMR- 0403465, NSA/ARO, and DARPA/AFOSR.*

**Strongly Correlated Quantum Many Body Systems: A Quantum Information Perspective**

**Frank Verstraete, *California Institute of Technology***

Abstract. Entanglement theory provides a unique perspective on the properties of strongly correlated quantum systems. We will discuss numerical renormalization group methods on the one hand, and properties like topological quantum order in toric code states on the other hand.

# Session #4: Quantum Algorithms

## Hidden Subgroups and Fourier Sampling: A Tutorial

**Cristopher Moore,** *University of New Mexico / Santa Fe Institute*

**Abstract:** Ever since Shor's celebrated factoring algorithm, we have been looking for additional quantum algorithms that solve computer science problems exponentially faster than their classical counterparts. Most such algorithms fall under the general heading of the Hidden Subgroup Problem, in which we try to find the symmetries (e.g. periodicities) of some function defined on a group by measuring in the Fourier basis. When the function is defined on a non-Abelian group such as the permutation group, however (which is the group relevant to the Graph Isomorphism problem) the "frequencies" of a function become matrix valued representations. I will give an accessible introduction to the representation theory of finite groups, and explain why the non-Abelian Hidden Subgroup Problem remains a challenging and exciting frontier for quantum algorithms.

## New Algorithms for the Nonabelian Hidden Subgroup Problem

**Dave Bacon,** *University of Washington*

**Abstract:** Quantum computers can efficiently solve the hidden subgroup problem over abelian groups. This fact lies at the heart of Peter Shor's efficient quantum algorithm for factoring whole numbers. Whether quantum computers can efficiently solve the hidden subgroup problem over nonabelian groups is one of the grand outstanding challenges in the theory of quantum algorithms. Such efficiently algorithms would lead to efficient quantum algorithms for the graph isomorphism problem and for certain shortest vector in a lattice problems. Recently a tremendous amount of progress has been made on understanding the nonabelian hidden subgroup problem. In this talk I will discuss how some of this work has lead to efficient new quantum algorithms and in particular to such algorithms which move beyond the quantum fourier transform barrier. This is joint work with Andrew Childs (Caltech) and Wim van Dam (UCSB).

## An Improved Quantum Algorithm for the Ordered Search Problem

**Andrew Landahl,** *University of New Mexico*

**Abstract:** I will show that a class of "symmetry invariant" quantum query algorithms for searching an ordered list of N items can be expressed as a set of feasible solutions to a certain semidefinite program (SDP). By numerically solving this SDP, we have found quantum query algorithms for this problem that are more than twice as fast as the best-possible classical algorithm. I will further demonstrate that symmetry invariance can be used to derive Grover's algorithm as an essentially unique solution for the unordered search problem. I will conclude with a discussion of the role of automated computer searches in the quest for finding new quantum algorithms.

## Quantum Buried Treasure

**Jonathan Walgate,** *University of Calgary*

**Abstract:** A swashbuckling tale of greed, deception, and quantum data hiding on the high seas. When we hide or encrypt information, it's probably because that information is valuable. I present a novel approach to quantum data hiding based on this assumption. An entangled treasure map marks the spot where a hoard of doubloons is buried, but the sailors sharing this map want all the treasure for themselves! How should they study their map using local operations and classical communication? This simple scenario yields a surprisingly rich and counterintuitive game theoretic structure. A maximally entangled map performs no better than a separable one, leaving the treasure completely exposed. But non-maximally entangled maps can hide the information almost perfectly! Quantum data hiding was developed with two motivations. It is worth investigating purely as cryptographic scheme, allowing data to be concealed from cryptanalysts sharing a perfect copy. However it also provides an operational framework for studying entanglement and nonlocality, as it hinges on the difference between local and global physical information. `Quantum buried treasure' schemes have four key advantages. Firstly, the local perspectives of those sharing the quantum system are clearly revealed, and this allows a more detailed comparison between the local and global information. (Previous schemes have treated local observers as a single collective eavesdropper, albeit operating under local constraints.) Secondly, interesting competitive situations emerge among the local parties. These suggest a useful role for game theory in quantum mechanics that emerges naturally from its nonlocal structure, unlike artificial attempts to unify the two. Thirdly, buried treasure provides a more realistic model both of encrypted information, which tends to be actually valuable, and of the motivations of those attempting the decryption. Last but not least, Alice and Bob get to be pirates!

## Simulated Quantum Computation of Molecular Energies

**Anthony Dutoi,** *University of California Berkeley*

**Abstract:** The calculation time for the energy of atoms and molecules scales exponentially with system size on a classical computer, but polynomially using quantum algorithms. We will discuss how such algorithms can be applied to problems of chemical interest using modest numbers of quantum bits. Calculations of the H2O and LiH molecular ground-state energies have been carried out on a quantum computer simulator using a recursive phase estimation algorithm. The recursive algorithm reduces the number of quantum bits required for the read-out register from approximately twenty to four. Different mappings of the molecular wave function to the quantum bits are discussed. An adiabatic method for the preparation of a good approximate ground-state wave function is described and demonstrated for stretched H2. The prospects of an experimental implementation of the algorithm, as well as precision considerations will be discussed. Our future and present research directions will be presented! . We will describe the main capabilities of our quantum simulation computer program (Tequila).

*Reference: A. Aspuru-Guzik, A. D. Dutoi, P. J. Love, M. Head-Gordon, Science 309 1704 (2005)*

## Session #5: Quantum Information Science with Atoms and Ions

### Quantum Manipulation of Atoms Using Rydberg States (Invited Talk)

**Thad Walker,** *University of Wisconsin, Madison*

**Abstract:** I will describe an apparatus designed to trap 1-50 Rb atoms in multiple dipole traps at spacings of 8 microns for a variety of quantum manipulation experiments. We have demonstrated site-addressable Rabi flopping at MHz rates with cross-talk of less than 0.001 to the neighboring site. The measured dephasing time of 870 microseconds gives a very good figure of merit for precision manipulation of the atoms confined in the traps. We have demonstrated high fidelity single-atom detection using a modulated readout scheme that avoids excited-state hyperfine mixing and heating due to the intense trap light. We have also observed sub-Poissonian atomic number distributions in the traps. The next step in these experiments involves excitation of the atoms to n~50 Rydberg states. In order to produce entanglement between atoms in neigboring sites, it will be advantageous to produce the Rydberg atoms under conditions where the Rydberg-Rydberg interactions are strong (1/R^3) and isotropic. I will describe how dressing the atoms with microwave fields allows such interactions.

### Progress Towards Quantum Logic and Real-Time Quantum State Estimation

**Poul Jessen,** *University of Arizona*

**Abstract:** Neutral atoms trapped in optical lattices provide an excellent platform for quantum information science, in part due to the very long lifetime of ground state populations and coherences, and in part due to the large experimental toolbox available to prepare, manipulate and measure their quantum state. I will describe experimental progress towards the demonstration of two-qubit quantum logic via controlled ground state collisions. These collisions, along with their ability to entangle atom pairs, can be probed in ensemble experiments where the collisional interaction is inserted between the pulses of a standard Ramsey interrogation sequence. An essential part of such an experiment is the ability to perform very high fidelity single qubit rotations. We have implemented high fidelity single qubit control in a 3D optical lattice by driving the atoms with resonant microwave radiation. The qubit dynamics are probed using an optical probe polarization measurement, which has allowed us to observe and optimize gate performance in nearly real-time. Gate performance across the ensemble is compromised by spatial variations in the microwave intensity and an inhomogeneous AC Stark shift of the qubit transition frequency imposed by the optical lattice. Nevertheless we are able to achieve single-qubit gates with a fidelity of 0.990(5). We have further investigated the use of composite pulses of the type used in NMR experiments, with demonstrable gain in the robustness against errors. In our system, however, the extra decoherence accrued during the longer composite pulses largely outweigh gains from added robustness, and we see no significant increase in gate performance. In a second experiment we use an optical probe polarization measurement to acquire complete information about the single atom density matrix for an ensemble of Cs atoms in the F = 3 hyperfine ground manifold. This is accomplished by continually measuring a single atomic observable (e. g. a component of the spin), while driving the system in such a way that it gradually explores

the entire spin state space. The quantum state can then be estimated from the measurement record in the presence of the known system dynamics. We have shown that high fidelity estimates can be achieved for a wide variety of test states, including squeezed- and similar non-classical states generated by the action of the tensor light shift. Our estimation procedure is non-destructive, in the sense that the ensemble remains available in a known quantum state that has not decohered at the end of the estimation process. It can also in principle be performed in real time, though our current implementation remains far from that limit. This suggests that the procedure may serve as the starting point for a new type of feedback that involves partial or complete estimation of the quantum state of the ensemble.

### Microfabrication and Packaging of Ion Trap Chips for Quantum Simulation

**Matthew G. Blain,** ***Sandia National Laboratory***

**Abstract:** We present our progress on the microfabrication and packaging of chip-scale Paul traps for applications in quantum simulation experiments. The trap electrode fabrication process, based on a MEMS fabrication technology utilizing molded tungsten, is summarized. Additionally, we discuss the implications of using high resistivity silicon as the RF trap substrate upon which the trap electrodes are formed, as well as the formation of optical access holes in the Si to allow for laser access to the traps. We also show results of the development of a custom RF chip packaging technology that maximizes optical access to the traps and provides an experimentally compatible set of materials for both chip and package.
*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.*

## Session #6: Fault-Tolerant Quantum Computing

### Topological Quantum Computation (Invited Tutorial)

**John Preskill,** ***California Institute of Technology***

**Abstract:** The standard theory of fault-tolerant quantum computing shows that clever software design can overcome the deficiencies of noisy quantum hardware, as long as the noise is not too strong. In this lecture I will describe a different approach, in which the hardware itself is intrinsically resistant to noise. In a topological quantum computer, quantum information is encoded in the fusion spaces of nonabelian anyons in a two-dimensional medium, and can be manipulated robustly by guiding the anyons along specified trajectories. If the anyons have suitable properties, the topological computer can simulate efficiently an arbitrary quantum computation.

**Thresholds for Arbitrary Error Channels Using Perfect Ancillae**

**Bryan Eastin,** *University of New Mexico*

*Abstract:* I will present a procedure for calculating thresholds for quantum computation as a function of error model given the availability of ancillae with independent, identically distributed errors prepared in logical states. The thresholds are determined via a simple counting argument performed on a single qubit of an infinitely large CSS code. I give concrete examples of thresholds thus achievable for both Steane and Knill style fault tolerant implementations.

**A Fault-Tolerant One-Way Quantum Computer**

**Robert Raussendorf,** *California Institute of Technology*

**Abstract:** We describe a fault-tolerant one-way quantum computer on cluster states in three dimensions [quant-ph/0510135]. The presented scheme uses methods of topological error correction resulting from a link between cluster states and surface codes. The error threshold is 1.4% for local depolarizing error and 0.11\% for each source in an error model with preparation-, gate-, storage- and measurement errors. This is joint work with Jim Harrington (LANL) and Kovid Goyal (Caltech).

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## Session #7: Trapped Ion Quantum Information

**Steps Towards Scalable Trapped-Ion QIP at NIST***

**Roee Ozeri,** *NIST Boulder*

**Abstract:** Recent progress towards realizing a scalable trapped-ion quantum information processor at NIST will be reviewed. Quantum algorithms have been performed on registers of up to six ion-qubits in a multi-zone linear RF Paul trap. For example, many-particle entanglement was studied by generating Schroedinger cat states of up to six ions. Steps towards achieving fault-tolerant quantum computation were implemented: memory coherence times were extended using a qubit transition which, to first order, is independent of the magnetic field. The fundamental limits to stimulated-Raman induced quantum gates were investigated by studying the effect of spontaneous scattering of photons on hyperfine coherence. More complex trap architectures and fabrication methods that will enable the scaling of ion-traps to a large multiplexed trap array are also being developed.

* *Supported by DOT, ONR & NIST .*

### *Quantum Information Processing with Ultrashort Pulses*

**Peter Maunz,** ***University of Michigan***

**Abstract:** The application of ultrashort laser pulses on ions stored in a Paul trap opens up new possibilities for quantum information processing. Ultrashort pulses can be used for remote entanglement of ions via emitted photons [1], and to realize fast quantum gates [2]. In this talk we present experiments demonstrating important steps toward the realization of these ideas. We show the generation of ion-photon entanglement and we demonstrate second order interference of single photons emitted from different Cadmium ions. In a second experiment we use two consecutive picosecond pi-pulses to transfer a qubit stored in the hyperfine levels of a Cadmium ion from the ground state to the excited state and back while preserving the spin coherence.

[1] C. Simon, and W.T.M. Irvine, PRL 91, 110405, (2003)
[2] J.J. Garcia-Ripoll, P. Zoller and J.I. Cirac, PRL 91, 157901, (2003)

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## Session #8: Fundamental Quantum Information Science

### Geometric Phase and General Solution for N-level Systems

**A.R.P. Rau,** ***Louisiana State University***

Abstract. Berry's geometric phase is important in quantum physics and now is central to the field of quantum computation. For spin-1/2 and its associated SU(2) group, the Bloch sphere and a U(1) phase provide a complete description. We generalize this construction to any N-level system and SU(N), setting up an iterative scheme to reduce the problem to SU(N-n). A general time-dependent Hamiltonian is thus solved, closely paralleling the SU(2) case. For n=1, each step, which involves the solution of a vector Riccati equation, provides a U(1) phase, along with its decomposition into dynamical and geometrical parts. the technique also extends to non-Hermitian Hamiltonians and non-unitary evolution described by master equations when dissipation and decoherence are present.

### Photon Wave Mechanics

**Brian Smith,** ***University of Oregon***

Abstract: Coordinate-space photon wave functions and their quantum-mechanical equations of motion are presented. It is shown that the two-photon wave function is equivalent to the two-photon detection amplitude under the quantum measurement collapse hypothesis.

## Non-Gaussian Ancilla States for Continuous Variable Quantum Information Processing

**Shohini Ghose,** ***Wilfrid Laurier University***

**Abstract:** Quantum computation can be performed with continuous rather than discrete variables in an optical setting using the electromagnetic field amplitudes. Universal quantum computation requires the application of nonlinear transformations corresponding to Hamiltonians that are not linear or quadratic functions of the continuous variables. We investigate the use of non-Gaussian states as ancillary inputs in Gaussian preserving circuits for generating the required nonlinear transformations for quantum computation with continuous variables. We present a detailed analysis of a recent proposal for off-line preparation of a non-Gaussian cubic phase state [1]. We extend our previous studies of this scheme and discuss the fidelity of preparing an ideal cubic phase state, taking into account currently achievable levels of squeezing and photodetection efficiency. Our studies indicate that although a good approximation to the ideal cubic phase states is not currently feasible! , the prepared state can nevertheless generate nonlinear gates that may be sufficient for universal quantum computation. In addition to the cubic phase state, we also analyze the use of ancilla Fock states in optical circuits. We generalize our previous results and compute the set of gates that can be implemented using such ancilla states in any circuit with Gaussian inputs, linear optics and squeezing elements, homodyne detection and feed forward. Our results show that such circuits can approximately implement a broad class of unitary gates. We also discuss the efficiency of classical simulation of such circuits. These results extend the existing no-go theorems for continuous variable quantum information processing [2].

[1] D. Gottesman, A. Kitaev and J. Preskill, Phys. Rev. A 64, 012310 (2001).
[2] S. D. Bartlett, B. C. Sanders, S. L. Braunstein and K. Nemoto, Phys. Rev. Lett. 88, 097904 (2002).

## Direct Characterization for Open Quantum Systems Dynamic

**Masoud Mohseni,** ***University of Toronto***

**Abstract:** Experiments are always conducted on open systems, i.e., systems that interact with an external environment. The characterization of the dynamics of open quantum systems is a fundamental and central problem in quantum mechanics. Algorithms for performing this task are known as quantum process tomography, and typically rely on subjecting a complete set of quantum input states to the same open system dynamics. The corresponding output states are measured via a process known as quantum state tomography. Here we present an optimal algorithm for complete and direct characterization of quantum dynamics, which does not require quantum state tomography. We demonstrate a quadratic advantage in the number of ensemble measurements over all previously known quantum process tomography algorithms, and prove that this is optimal. As an application of our algorithm, we demonstrate that for a two-level quantum system that undergoes a sequence of amplitude damping and phase! damping processes, the relaxation time T1 and the dephasing time T2 can be simultaneously determined via a single measurement. Moreover, we show that generalized quantum superdense coding can be implemented optimally using our algorithm. We argue that our algorithm is experimentally implementable in a variety of prominent quantum information processing systems, and show explicitly how the algorithm can be physically realized in photonic systems with present day technology.

### Complementarity Between Work, Entanglement and Reference Frame Ability

**Kurt Jacobs**, ***Lousiana State University***

**Abstract:** Superselection rules (SSRs) limit the mechanical and information processing resources represented by quantum states. However SSRs can be violated using reference systems to break the underlying symmetry. We show that there is a duality between the ability of a system to do mechanical work and to act as a reference system. Further, for a bipartite system in a globally symmetric pure state, we find a triality between the system's ability to do local mechanical work, its ability to do "logical work" due to its accessible entanglement, and its ability to act as a shared reference system.

### Entanglement in Four Superconducting Qubits

**Peter Love**, ***DWave Inc.***

**Abstract:** Entanglement lies behind the greater information-theoretic power of quantum systems. Shared entangled states are required for the implementation of quantum cryptographic schemes, and quantum computers require entanglement to exceed the capabilities of classical computers. We define a set of elementary entanglement monotones and give a single measure of entanglement in terms of these monotones which is zero except on globally entangled (fully inseparable) states. We describe some properties of this measure and its use to characterize the entanglement present in the ground state of four coupled flux qubits.

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# Poster Presentations

# Posters

### 1. The Non-Relativistic Inverted Harmonic Oscillator and Unruh/Hawking Effect

**Paul M. Alsing,** ***Air Force Research Laboratory***

**Abstract:** We demonstrate the analogy between scattering solutions of the non-relativistic inverted harmonic oscillator and the thermal radiation produced from the Unruh and Hawking effect. We related this analogy to the quantum phase catastrophe in slow-light which has recently been discussed [U. Leonhardt, Phys. Rev. A 65, 043818 (2002); Nature 415, 406 (2002)] as an optical analogy for Unruh and Hawking radiation.

### 2. Solvability of Hamiltonians and Limits on Lie-Algebraic Computation

**Howard Barnum,** ***Los Alamos National Laboratory***

**Abstract:** We consider quantum computational models defined via a Lie-algebraic theory, where Lie-group-coherent initial states are acted on by unitary or non-unitary Lie-algebraically generated quantum gates, and the final-state expectation value of a Lie algebra element is measured at the end. We show that these models can be efficiently simulated on a classical computer in time polynomial in the dimension of the algebra, even if the dimension of the Hilbert space where the algebra acts grows exponentially. Similar results hold for the computation of the expectation value of the gate-sequence. We also introduce a Lie-algebraic notion of generalized mean-field Hamiltonians, that is to say, ones belonging to family of faithful finite-dimensional matrix representations of polynomial-dimensional semisimple Lie algebras, and show that they are efficiently solvable by means of a Jacobi-like diagonalization method even though the representation Hilbert space may grow exponentially. Certain lattice spin systems are examples. Our results generalize earlier ones on fermionic linear optics computation, while providing close analogues to simulatability results about bosonic quantum computation with linear optics and homodyne detection (or even squeezing) and provide insight into the source of the power of the conventional model of quantum computation. If time permits, some conjectures about a possible close mathematical relationship between our results and the Gottesman-Knill theorem will be outlined.

### 3. Study of Decoherence in Photon-Substracted Entangled Non-Gaussian States

**Asoka Biswas,** ***University of Southern California***

**Abstract:** Entanglement in Gaussian states has been well discussed in literature, while that in non-Gaussian states is not much explored till date, though these states are often encountered in quantum information processing. In this work we study the dynamics of entanglement in a specific family of non-Gaussian states under different decoherence model. We consider non-Gaussian entangled states, which are photon subtracted two-mode squeezed vacuum states. We study the dynamics of entanglement in these states in presence of the following environmental decays: (i) Independent amplitude decays of two modes, (ii) Correlated amplitude decays of two modes, (iii) Collective dephasing. We show existence of a whole class of decoherence-free subspace under collective dephasing.

**4. Generalized Coherent States via Markovian Decoherence**

**Sergio Boixo,** ***University of New Mexico***

**Abstract:** Coherent states were introduced in the early days of quantum physics as 'quasiclassical' quantum states of an isolated quantum system. The decoherence program defines 'quasiclassical' (or 'pointer') states as states which are most stable in the presence of a coupling with the environment. Operationally, pointer states may be identified through the extremization of an appropriate 'predictability' functional on the Hilbert space. It has been known for some time that for the harmonic oscillator algebra both concepts coincide under very generic conditions. Coherent states have been extended in the 70s to generalized coherent states. Recently, this approach has served as the basis to define generalized entanglement as well as conditions for quantum complexity. Here, we investigate the stability of generalized coherent states under Markovian open-system dynamics. In particular, we identify conditions under which generalized coherent states emerge as pointer states for systems described by algebras more general that the standard oscillator algebra. In the process, we present a streamlined method to find pointer states in the relevant weak-coupling approximation, and discuss conditions for this approximation to be valid. We find that generalized coherent states and pointer states coincide under more restrictive conditions than the canonical, harmonic-oscillator coherent states. Finally, we address the connection of generalized coherent states to decoherence free subspaces and noiseless subsystems.

**5. Quantum Shapelets**

**Mark Coffey,** ***Colorado School of Mines***

**Abstract.** Quantum shapelets arise as the solution of a d-dimensional harmonic oscillator or D-dimensional Coulomb problem and may be obtained by requiring scale-space invariance. These functions have application to image processing in conventional or quantum contexts. Novel analytic properties of these functions are presented [1]. Many of these relations also have application to the combinatorics of zero-dimensional quantum field theory.

[1] M. W. Coffey, J. Phys. A (to appear)

**6. Implementation of Two-Qubit Deutsch-Jozsa Algorithm in Atomic Ensemble**

**Shubhrangshu Dasgupta,** ***University of Southern California***

**Abstract:** We show how one can implement two-qubit Deutsch-Jozsa algorithm in an effectively decoherence-free system. In this model, two freely propagating photons dispersively interact with an atomic ensemble. The resulting Stark shifts of the atomic levels lead to a NMR-like Hamiltonian, which would be useful to implement the algorithm. Wave-plates and microwave pulses are used to provide the required single-qubit operations. We provide supporting numerical results with available experimental parameters. We further discuss in detail the experimental set-up required to implement the algorithm.

### 7. Linear Optical Quantum Computing, Imaging, and Metrology

**Jonathan P. Dowling,** *Louisiana State University*

**Abstract.** Recently it was shown that scalable quantum computing is possible with only linear optical elements and single-photon sources and detectors. I will discuss experimental and theoretical progress on these ideas and show how to adapt them to quantum communications devices as well as to sub-shotnoise quantum metrology and quantum imaging.

### 8. Communication-Assisted Local-Hidden-Variable Models for Stabilizer States

**Matt Elliott,** *University of New Mexico*

**Abstract:** In this talk I present communication-assisted local-hidden-variable models for measurements of products of Pauli matrices on stabilizer states. Models are analyzed with respect to restrictions imposed and their efficacy in predicting overall measurement outcomes as well as outcomes of correlated subsets of measurements. In particular, I present a model in which the quantum mechanical results of Pauli product measurements can be predicted by a local-hidden-variable table supplemented by an efficient amount of classical communication and computation.

### 9. An Efficient Source of Single Indistinguishable Photons

**Dirk Englund,** *Stanford University*

**Abstract:** We demonstrate an efficient source of nearly indistinguishable single photons from an InAs quantum dot coupled to a photonic crystal microcavity. This QD-cavity coupled system has applications in quantum information science.

### 10. Quantum Complexity of Partition Functions from Statistical Physics

**Joseph Geraci,** *University of Southern California*

**Abstract.** It has been demonstrated that the exact evaluation of the partition function for the Ising Spin Glass or Potts Model is a #P problem. This means that there is very little hope of a classical algorithm that provides an exact evaluation. Further, even approximation schemes will not do well. However, just because the general problem is hard, it does not mean that all instances of the problem are intractable. Our research involves studying instances of Ising Spin Glasses and Potts Models that appear to be difficult for classical computers but that may give way to quantum algorithms. We are not interested in the algorithm per se, but in demonstrating the quantum computer's superiority at the evaluation in question, whether exact or approximate. We are using several approaches to achieve our goal including topology and certain algebraic identities. This is work in progress. References: 1. D.A. Lidar, "On the Quantum Computational Complexity of the Ising Spin Glass Partition Function and of Knot Invariants", New J. Phys. 6, 167 (2004). 2. J. Geraci and D.A. Lidar, "A Note on the Efficient Approximation of the Potts Partition Function by Quantum Computers", to be published.

**11. Production of Optical Coherent State Superpositions Using the Kerr Effect**
**Scott Glancy,** ***NIST Boulder***
**Abstract:** One can produce superpositions of optical coherent states (also known as "cat states") by sending a single coherent state through a medium that exhibits the Kerr effect having a Hamiltonian proportional to the square of the number of photons. We examine the effect of photon absorption on this process. We calculate the fidelity with which one may hope to make cat states and find that this fidelity is a function of the ratio of the loss to the Hamiltonian's coupling strength. This ratio is much too large to allow cat production with standard optical fibers.

**12. Quantum logic in Group-II Neutral Atoms via Nuclear-Exchange Interactions**
**David Hayes,** ***University of New Mexico***
**Abstract:** The spin exchange-interaction provides a means of producing an entangling quantum-logic gate, the square-root of SWAP, at the heart protocols employing single electron quantum dots. This is typically accompanied by strong Coulomb interactions and commensurate decoherence due to strong coupling of charge degrees of freedom to the noisy environment. We propose a protocol utilizing a nuclear-exchange interaction that occurs through ultra-cold collisions of identical spin-1/2 Group-II neutral atoms. A natural advantage is gained by storing the quantum information in nuclear spin states with long coherence times. Unlike NMR protocols based on weak magnetic dipole-dipole interaction, the nuclear exchange interaction stems from strong s-wave scattering of electrons. Nuclear exchange is ensured by the Fermi symmetry of the overall wave function. We have studied this protocol in the context of 171Yb atoms trapped in far-off resonance optical dipole traps. Using numerical analysis, we show that high-fidelity operation is possible through controlled collisions in varied double-well trapping potentials.

**13. Magnetoelectrostatic Ring Trap for Neutral Atoms**
**Asa S. Hopkins,** ***California Institute of Technology***
**Abstract:** We are in the process of building a novel trap for confining cold neutral atoms in a microscopic ring using a magneto-electrostatic potential. The trapping potential is derived from a combination of a repulsive magnetic field from a hard drive atom mirror and the attractive potential produced by a charged disk patterned on the hard drive surface. We calculate a trap frequency of 42.6 kHz and a depth of 1 mK for 87Rb. A loading scheme and fabrication process have been devised. For sufficiently cold atoms, this device will provide a one-dimensional potential in a ring geometry that may be of interest to the study of trapped quantum degenerate one-dimensional gases.

**14. Entanglement-Assisted Capacity of Quantum Multiple Access Channels**
**Min-Hsiu Hsieh,** ***University of Southern California***
**Abstract:** We find a regularized formula for the entanglement-assisted (EA) capacity region for quantum multiple access channels (QMAC). We illustrate the capacity region calculation with the example of the collective phase-flip channel which admits a single-letter characterization. On the way we provide a first principles proof of the EA coding theorem based on a packing argument. We observe that the Holevo-Schumacher-Westmoreland theorem may be obtained from a modification of our EA protocol. We remark on the existence of a family hierarchy of protocols for multiparty scenarios with a single receiver, in analogy to the two-party case. In this way we relate several previous results regarding QMACs.

**15. Dynamical Error Correction without Measurement**

**Kaveh Khodjasteh,** ***University of Southern California***

**Abstract:** Dynamical methods for protection against errors and decoherence are useful in bounded environments and require straightforward (not cheap though) resources: precise and strong control of Hamiltonians. In their simplest manifestation, dynamical decoupling (bang-bang, spin echo) removes unwanted coupling terms form a qubit Hamiltonian to preserve its arbitrary initial state. Generally speaking, Dynamical error correction is feedback (measurement) free and in its simplest setting does not require extra qubits. In this work, we review the basics of dynamical decoupling in a simple setting. We present a theoretical estimate of the efficiency of dynamical decoupling in terms of the minimum pulse switching times and pulse imperfections. As an important side note, two heuristic arguments based on operator-norm inequalities are presented on (i) why ideal dynamical decoupling does not increase error rates and (ii) why single-bit quantum operations do not introduce errors stronger than those already present. Based on our estimates, we present and compare different dynamical decoupling strategies: periodic bang-bang, concatenated, and Trotter-Suzuki decoupling. Simple simulation results on spin qubits coupled to a spin bath and some preliminary experimental data are presented. In the second part of the talk, we present a scheme for combining stabilizer quantum error correction codes with dynamical decoupling for correcting operational errors (standard dynamical decoupling only corrects quantum memory errors). As a final deliberation we ask fundamental questions on the limits of applicability of dynamical methods posed by entropy considerations.

**16. Hitting time for quantum walks on the hypercube**

**Hari Krovi,** ***University of Southern California***

**Abstract:** Hitting time for a random walk on a graph is a measure of the average time it takes the walk to reach a given ending condition. In order to give an analogous definition for quantum walks, we consider measured walks: walks with repeated measurements as well as unitary evolution. In such a walk, one first performs the unitary operation (the product of a coin flip operator and shift operator) and then a coarse-grained measurement on the vertices of the graph. This measurement is a two outcome measurement to verify if the particle is at the final vertex or not. If it reaches the final vertex, the walk stops. We derive an expression for the hitting time of a measured quantum walk on a graph in terms of superoperators acting on the initial density matrix of the particle, and evaluate it numerically for the quantum walk on the hypercube with the Grover matrix as the coin flip. Comparing the result to the classical hitting time on the hypercube, we find that the quantum hitting time is exponentially smaller. This speed-up is not necessarily true for every walk, however. We numerically demonstrate that the hitting time of the quantum walk using the DFT coin can be infinite. We then construct a projector onto all initial states which give infinite hitting times for the DFT coin. Any state that has a non-zero overlap with this projector will have an infinite hitting time. In fact, for any evolution operator, if the degeneracy is sufficiently large---more precisely, greater than the degree of the graph---there exist states which have infinite hitting times. This is caused by destructive interference at the final vertex for certain starting states, an aspect of quantum walks that has no classical analogue. These dramatic speed-ups and slow-downs for the quantum walk can be traced to the symmetry of the hypercube, though symmetry need not be the only reason. Finally, we numerically studied the effect of distortions of the hypercube on the hitting time. In this case, the quantum hitting time was longer than that of the undistorted hypercube, presumably due to loss of symmetry. Thus, symmetry seems to play a very important role in both exponential speed-ups and infinite hitting times of quantum walks.

**17. Phase-Locked Scanning Interferometer for Frequency Stabilization of Multiple Lasers, A. Light and M.D. Di Rosa,** ***Los Alamos National Laboratory***

**Abstract:** A simple laser stabilization scheme for use in the laser cooling of calcium monohydride (CaH) molecules is demonstrated. Because there is no convenient table-top absorption reference for CaH, we lock the four lasers needed for the cooling scheme to a single stabilized cavity. Schematically, we transfer the stability of a frequency-locked HeNe to the other lasers by way of a scanning confocal etalon (a commercial spectrum analyzer). A piezo drives one of the cavity mirrors and the cavity length is scanned sinusoidally over a portion of its free spectral range (300 MHz) at the piezo resonance near 5 kHz. The average cavity length is then phase-locked to the periodic transmission of the stabilized HeNe. This setup allows > 10x faster feedback control of the cavity length than did previous arrangements [1]. Our use of phase-sensitive detection also reduces the susceptibility of our locking technique to noise from non-synchronous sources, such as laser jitter. In principle, any other laser can be frequency-stabilized by directing its output through the analyzer and locking its periodic transmission to a particular phase of the piezo motion. By scanning the spectrum analyzer over nearly one free spectral range, we stabilize four laser sources simultaneously to a single cavity. We have found an advantage in using high multiples of the drive frequency for phase sensitive detection. We can also use the stabilized cavity to measure precise absolute frequencies with reference to the stabilized HeNe frequency if a coarse measurement is available. A simulation of the system and measurements of cavity and laser frequency stability are presented.

[1] W.Z. Zhao, J.E. Simsarian, L.A. Orozco, and G.D. Sprouse, Rev. Sci. Instrum. 69, 3737 (1998)

**18. Reducing decoherence in an atomic-ion based quantum information processor C. Langer,** ***National Institute of Standards and Technology***

**Abstract:** Scalable quantum information processing (QIP) requires physical systems capable of reliably storing coherent superpositions for periods over which quantum error correction can be implemented. Moreover, suppressing memory error rates to very low levels allows for simpler error-correcting algorithms. In many current atomic-ion QIP experiments, a dominant source of memory error is decoherence induced by fluctuating ambient magnetic fields. We address this problem by creating long-lived qubit memories using a first-order magnetic-field-independent hyperfine transition. Our results with 9Be+ qubits show a coherence time of approximately 15 seconds, an improvement of over five orders of magnitude from previous experiments [1]. Errors during quantum gate operations must also be maintained to low levels to enable efficient error correction. In many atomic-ion based QIP architectures, off-resonant laser light is used to perform quantum gate operations. In such schemes, spontaneous photon scattering is a fundamental source of decoherence. We experimentally study the decoherence of coherent superpositions of hyperfine states of 9Be+ in the presence of off-resonant laser light. Our results indicate that the decoherence is dominated by inelastic Raman photon scattering which, for sufficient detunings from the excited states, occurs at a rate much smaller than the elastic Rayleigh scattering rate. For certain detunings, the measured decoherence rate is a factor of 19 below the calculated total scattering rate indicating that qubit coherence is maintained in the presence of photon scattering [2].

[1] C. Langer et al., Phys. Rev. Lett. 95, 060502 (2005).
[2] R. Ozeri et al., Phys. Rev. Lett. 95, 030403 (2005).

**19. On the Consistency of Local Density Matrices**
**Yi-Kai Liu,** ***University of California, San Diego***
**Abstract:** We prove the following result: Suppose we have an n-qubit system, and we are given a collection of reduced density matrices rho_1,...,rho_m, where each rho_i describes a subset C_i of the qubits. If rho_1,...,rho_m are consistent with some global state rho > 0, then they are also consistent with a state rho' of the form rho' = exp(M_1+...+M_m), where each M_i is a Hermitian matrix acting on the qubits in C_i. (This state is the quantum analogue of the Gibbs distribution.) Intuitively, our result says that a Gibbs state rho' can simulate an arbitrary state rho > 0, with respect to an observer who can only access subsets of the qubits. This is related to the study of the Local Hamiltonian problem. We also prove a more general result, for the case where the observer only knows the expectation values of an incomplete set of observables T_1,...,T_r (which need not commute). We show that any physically possible set of expectation values (assuming rho > 0) can be realized by a Gibbs state. This is related to the maximum entropy principle in statistical mechanics. While this is plausible in most physical systems, the general result is less obvious. The proof relies on the theory of quantum exponential families.

**20. Simulating Classical Channels with Quantum Side Information**
**Zhicheng Luo,** ***University of Southern California***
**Abstract.** We study and solve the problem of classical channel simulation with quantum side information. This is a generalization of both the classical reverse Shannon theorem (CRST), and the classical-quantum Slepian-Wolf (CQSW) problem. The optimal noiseless communication rate is found to be reduced from the mutual information between the sender (Alice) and receiver (Bob) by the Holevo information between Bob and the side information. Our main theorem has two important consequences: common randomness distillation and classical rate-distortion theory with quantum side information. Simple proof of the both direct coding theorems can be made based on our result. The formula for the trade-off between the one-way communication invested and the distilled common randomness also follows from our theorem.

**21. Interferometry and Quantum Phase Transitions with a Bose-Einstein Condensate,** **Calum MacCormick,** ***Los Alamos National Laboratory***
**Abstract:** We describe two experiments with a Bose-Einstein condensate confined with time-dependent optical dipole potentials. First, we are building an optical waveguide atom interferometer in which adiabatic transformation of a single optical trap into two spatially-separated traps forms the arms of the interferometer. Second, we plan to manipulate the flexible optical potential to investigate the non-equilibrium dynamics of quantum phase transitions.

**22. Entanglement of Rotationally Symmetric States**
**Kiran Manne,** ***University of New Mexico***
**Abstract:** We examine the entanglement present in states that are invariant under a global rotation. By using a technique pioneered by Terhal, Vollbrecht and Werner we are able to derive analytic expressions for the entanglement of formation for these states in a 2xd-dimensional system. We also obtain expressions for the I-concurrence, I-tangle, and the convex-roof-extended negativity. We have some partial results for the entanglement of 3xd-dimensional rotationally symmetric states.

**26. Photon Blockade in an Optical Cavity with One Trapped Atom**

**Tracy Northup,** ***California Institute of Technology***

**Abstract:** The phenomenon of photon blockade occurs when the absorption of a first input photon by an optical device blocks the transmission of a second one, thereby leading to nonclassical output photon statistics. In the context of cavity quantum electrodynamics (cQED), the blockade is due to the anharmonicity of the Jaynes-Cummings ladder of eigenstates. If an incoming photon resonantly excites the atom-cavity system from its ground state to |1,+(-)> (where |n,+(-)> denotes the n-excitation dressed state with higher (lower) energy), then a second photon at the same frequency will be detuned from either of the next steps up the ladder, i.e. from states |2,+(-)>. In the strong coupling regime, for which the coherent rate of evolution exceeds the atomic and cavity decay rates, this detuning is much larger than the excited-state linewidths, so that the two-excitation manifold will rarely be populated. This in turn leads to the ordered flow of photons in the transmitted field, which emerge from the cavity one at a time. We have recently observed photon blockade in the light transmitted by a high-finesse optical cavity containing one trapped Cesium atom strongly coupled to the cavity field [1]. The coherent excitation at the cavity input is near-resonant with one of the two sidebands in the previously-determined vacuum-Rabi spectrum for our system [2]. Measurements of the second-order intensity correlation function at the cavity output show that the emerging photon stream displays antibunching and sub-Poissonian statistics. The atom is localized within the cavity mode by the anharmonic potential of a red-detuned far-off-resonant trap. The axial and radial motion-induced modulation on the atom-cavity coupling can be observed on the cavity transmission and hence on its correlation function. A Fourier transform of the second order intensity correlation function reveals a narrow peak just below the calculated maximum oscillation frequency in the axial direction, corresponding to the lowest-lying vibrational level. We use the shape of this peak to estimate that the atoms are distributed among only the lowest ten levels, with maximum energy for axial motion E/kB ~ 250 microKelvin. In addition, we discuss schemes for generation of polarized single photons from a cQED system. Our previous work generated single photons "on demand" which were randomly polarized [3]; here, we propose to generate photons in a single polarization mode. A variation on this method produces photons whose polarization is entangled with the Zeeman state of the atom in the cavity.

[1] K. M. Birnbaum et al., Nature 436, 87 (2005).
[2] A. Boca et al., Phys. Rev. Lett. 93, 233603 (2004).
[3] J. McKeever et al., Science 303, 1992 (2004).

**27. Novel Micron-Scale Ion Traps**

**Steven Olmschenk,** ***University of Michigan***

**Abstract.** Two of the major hurdles in realization of an ion trap quantum computer are scalability of ion trap structures and anomalous heating of the trapped atoms. Novel ion trap designs have allowed us to investigate these obstacles. First, we report the successful operation of an integrated radiofrequency trap etched from a doped gallium-arsenide heterostructure. The use of semiconductor micro-electromechanical systems (MEMS) technology in the fabrication process eliminates the need for manual assembly and alignment, making such structures suitable for miniaturization and scaling. Second, the employment of a double needle quadrapole trap has allowed for a precise study of the anomalous heating that plagues ion traps. Here, the variable spacing of the needle electrodes and the ability to cool the electrodes via a liquid nitrogen reservior has lead to characterization and suppression of this heating.

**28. Steps towards scalable trapped-ion QIP at NIST***
**Roee Ozeri,** ***NIST Boulder***

**Abstract**: Recent progress towards realizing a scalable trapped-ion quantum information processor at NIST will be reviewed. Quantum algorithms have been performed on registers of up to six ion-qubits in a multi-zone linear RF Paul trap. For example, many-particle entanglement was studied by generating Schroedinger cat states of up to six ions. Steps towards achieving fault-tolerant quantum computation were implemented: memory coherence times were extended using a qubit transition which, to first order, is independent of the magnetic field. The fundamental limits to stimulated-Raman induced quantum gates were investigated by studying the effect of spontaneous scattering of photons on hyperfine coherence. More complex trap architectures and fabrication methods that will enable the scaling of ion-traps to a large multiplexed trap array are also being developed.

* Supported by DOT, ONR & NIST .

**29. Robust Single-Qubit Control and Real-Time Measurement of Neutral Atom Qubits, Worawarong Rakreungdet,** ***University of Arizona***

**Abstract:** We demonstrate high-precision robust control of an atomic qubit ensemble in a 3D optical lattice using a resonant microwave field. The microwave-driven spin dynamics can be continuously probed using a weak optical polarization measurement, which allows us to observe and optimize the quality of single-qubit gates in near real-time. These gates are performed in the presence of unavoidable inhomogeneities in the microwave amplitudes, light shifts and magnetic fields, as a result of which the gate fidelity is degraded. By minimizing these sources of errors, we are able to achieve single-qubit gate fidelities of 0.990(5) for atomic qubits trapped in a 3D optical lattice. We also investigate the use of composite pulses originally developed by the NMR community. We will present detailed results and discuss some limitations of using microwaves and composite pulses in our atom/lattice system.

**30. A Quasi-Hermitian Pseudopotential for Higher Partial Waves**
**Iris Reichenbach,** ***University of New Mexico***

**Abstract:** The interaction between atoms in separated traps leads to interesting effects, e.g. to trap induced shape resonances. Their very complicated interaction potential can be modeled by a pseudo potential, which is proportional to a delta shell at a small radius s and the scattering length. For higher partial waves this pseudo potential is not hermitian, but quasi hermitian, leading to a biorthonormal set of eigenfunctions. However, these eigenfunctions can still be used as a basis to expand and diagonalize the additional part of the Hamiltonian, which is due to the separation. This procedure will be explained.

**31. Networking surface-electrode ion traps for large-scale QIP***
**Rainer Reichle, *NIST* Boulder**

**Abstract:** We discuss how surface-electrode ion traps, i.e., planar miniaturized Paul traps where all electrodes reside in a single plane and ions reside above the plane, have many advantages over their multilayer variants for large scale trapped-ion quantum computing. In addition to their relatively simple manufacturing by standard microfabrication techniques, we consider some issues that make them preferable for their use in large scale structures. In the proposed multiplexing versions for large scale ion trap architectures, nodal points are required. These nodes serve as junctions for the ion qubits, to reliably and arbitrarily transfer quantum information from one location to another in the two planar dimensions. We propose optimized geometric layouts for these nodal points that allow for simple concatenation to a multiplexed architecture. High-fidelity simulations show that the proposed layouts are capable of reliably shuttling ion qubits between these elementary units. More explicitly, we identify problems that might arise in the realization of the nodal points and show how they can be eliminated. We provide accurate analytical models for surface-electrode ion traps for characterizing their global behavior, discuss design issues to avoid sites of anti-binding, introduce electrode shapes to smooth the transport characteristics near nodal points, and present ideas to compensate for micromotion in surface-electrode traps. Comparisons between simulations and preliminary experimental data are consistent to within a few percent. * supported by DTO and NIST. # present address: LANL.

**32. Microfabricated surface-electrode ion traps***
**Signe Seidelin, *NIST Boulder***

**Abstract:** We report trapping of laser-cooled 24Mg+ ions in a microfabricated linear Paul trap where all the electrodes reside in a single plane [1]. Such surface-electrode traps are amenable to complex, multi-zone ion trap structures of the sort needed by next generation quantum information processing experiments. Of note is the relative ease of fabrication of this design which arises from the use of standard techniques, including photolithography, electroplating and deep reactive ion etching (DRIE). We find evidence for heating rates comparable to typical two-layer miniature linear Paul trap, even though the trapping region lies about only 50 $\mu$m above the surface of the planar electrodes. The ion lifetime is not noticeably lower than conventional two-layer traps, despite a trap depth more than ten times smaller (approximately 0.17 eV).

*supported by DTO and NIST.

[1] J. Chiaverini, J. Britton, J. D. Jost, C. Langer, D. Leibfried, R. Ozeri, and D. J. Wineland, Quant. Inform. Comp. 5, 419-439 (2005).

**33. Quantum Codes Welcome Spatially Correlated Errors**
**Alireza Shabani, *University of Southern California***

**Abstract:** A formulation for evaluating the performance of quantum error correcting codes under a general error model is presented. In this formulation the concept of correlated errors is quantified based on a Hamiltonian description of the noise. In particular, we studied CSS codes and surprisingly we observed a better performance for some types of non-local bath models versus a local one. This finding weakens the belief that correlated errors are necessarily fatal for threshold results in fault-tolerant quantum computation. We also found that, to achieve maximum efficiency, the time at which the correction step is applied is an important parameter in the design of a coding system.

### 34. Measuring With Qubits

**Anil Shaji,** ***University of New Mexico***

**Abstract:** Using quantum properties of the probes in measurement schemes can lead to measurement accuracies that beat the standard quantum limit. When qubits are used to probe a quantum system, it is known that initializing N probes in a Schrodinger cat state, rather than in a separable state, can reduce the measurement uncertainty by a factor of $1/\sqrt{N}$. We study measurement schemes using quantum probes made of several qubits when the individual qubits are subject to decoherence. The total duration of the measurement is limited by decoherence if we want to preserve the enhancement in precision obtained by using an entangled state of the probe qubits. We estimate this limit for different models of decoherence. We also present the general theory of how entanglement and decoherence in the probe qubits affect the precision of the measurement.

### 35. Quantum state tomography via continuous measurement

**Andrew Silberfarb,** ***University of New Mexico***

**Abstract:** We present a protocol for quantum state reconstruction based on weak continuous measurement of an ensemble average. This procedure applies the techniques of quantum control theory and quantum measurement theory to achieve a more efficient reconstruction than those performed using standard projective measurement techniques. This efficiency allows reconstruction of a quantum state using an single ensemble with minimal quantum backaction, setting the stage for state-based feedback control. An experimental demonstration of the technique will be presented in the context of reconstruction of the spin state of the F=3 hyperfine ground-state manifold of Cs-133 using continuous polarization spectroscopy.

### 36. Non-destructive Quantum State Reconstruction of Cold Atomic Spins

**Greg Smith,** ***University of Arizona***

**Abstract.** We present results from an experiment to estimate the density matrix for individual spins in an ensemble of cold, neutral atoms. The estimation procedure utilizes a probe-induced quadratic light shift in conjunction with a carefully crafted magnetic field to drive the ensemble on a trajectory that fully explores state space. A real-time measurement record obtained by analysis of an optical probe polarization measurement during this evolution can then be used to estimate the most likely single-atom density matrix. Our experiments use laser-cooled Cs atoms with a large spin angular momentum of F=3, and show that high fidelity can be achieved for a wide variety of initial spin-states. Because the measurement is minimally perturbing and can be achieved in a single realization of the experiment, this technique provides a new tool for the study of quantum dynamics. Furthermore, the quantum control tools upon which the measurement is founded hold promise for arbitrary! state generation, which may be achieved by designing a trajectory that targets a specific state instead of exploring all of state space.

### 37. Quantum Simulations of Spin Systems Using Trapped Ions

**Rolando D. Somma,** *Los Alamos National Laboratory*

**Abstract:** Quantum spin systems can be efficiently studied and simulated using trapped ions interacting with laser beams of different intensities, frequencies, and polarizations. In general, this is a hard task for a conventional computer due to the exponential growth of the dimension of the associated Hilbert space with the volume of the system. Following the work of D. Porras and J. I. Cirac [1] we show that, in certain limits, an external magnetic field together with a state-dependent dipole force acting on the ions produces an effective Ising-type evolution of the system. In particular, a two-spin model is numerically simulated and the error of the simulation as a function of temperature (i.e., decoherence) is studied. This will be the basis for future experiments. Many-body simulations beyond the Ising model are also discussed.

[1] D. Porras and J. I. Cirac, Phys. Rev. Lett. 92, 207901-1 (2004).

### 38. Quantum Logic in Optical Lattices via Controlled Collisions of Cesium Atoms

**Rene Stock,** *University of Calgary*

**Abstract:** Controlled collisions of ultracold atoms in optical traps and optical lattices provide new avenues for quantum control and quantum information processing as well as for the controlled production of cold molecules. The ability to precisely vary optical lattice parameters and the rich internal structure of the trapped atoms allow for novel quantum state manipulation. Of particular interest is the investigation of controlled collisions of atoms in separated but close wells. In previous research, we showed that for certain well separations, resonances between molecular bound states and trap eigenstates appear when a weakly bound molecular state is shifted by the potential energy (ac-Stark shift) of the separated wells into resonance with a vibrational eigenstate of the trap. These trap-induced resonances provide a new handle for coherently controlling two-atom ground-state interactions and open up new possibilities for designing robust quantum logic gates. Here, we consider this new type of trap-induced resonance for the case of Cs-133 atoms, trapped in separated wells of a polarization-gradient optical lattice. The anomalously large scattering lengths and the presence of a very weakly bound molecular state in Cesium, lead to the possibility of creating trap-induced resonances under realistic experimental conditions. The short-range molecular interaction is accurately treated through a newly derived multichannel pseudopotential, parameterized by the K-matrix, which captures both the bound molecular spectrum as well as the energy-dependent scattering for all partial waves. Our theoretical studies establish realistic operating conditions under which the trap-induced resonance could be observed and show that this strong and coherent interaction could be used as a basis for high-fidelity two-qubit quantum logic operations in standard and addressable optical lattice systems.

### 39. A 2D Double-Well Optical Lattice for Manipulating Individual Atom Pairs

**Jennifer Strabley,** *NIST Gaithersburg*

**Abstract:** We describe the design of a 2D double well optical lattice suitable for isolating and manipulating an array of individual pairs of atoms in an optical lattice. The topology of the lattice is phase stable against phase noise imparted by vibrational noise on mirrors. The properties of the double well: the barrier height and the "tilt" (energy offset between sites within the double well), can be easily and dynamically controlled. Atoms in the lattice can be placed in a double well with any of their four nearest neighbors. This lattice can be used to test neutral atom motion control and perform two-qubit gates.

## 40. A Universal Model of a Quantum Robot

**Soraya Taghavi,** ***University of Southern California***

**Abstract**: Quantum Robot is described as a quantum system that moves in, and interacts with, an external environment of quantum systems. Such environments consist of arbitrary numbers and types of particles in two or three dimensional space lattices. The focus in this study is mainly on the universality of the quantum robot, which is shown in two steps. In the first step, using some concepts of Lie Algebra, the Robot can perform all single-body Hamiltonians on each particle. In the second step, the Single-body Hamiltonians together with a specific entangling Hamiltonian enable the robot to perform a general unitary operation on all particles. The argument in this step is based on a corollary to a theorem in majorization theory.

## 41. Quantum Chaos and Entanglement for Two Coupled Spins

**Collin M. Trail,** ***University of New Mexico***

**Abstract:** Quantum chaos is the study of the quantum mechanical features of systems for Hamilitonians whose classical description exhibits chaos. Recent work suggests that there is a connection between the rate of entanglement generation of a bipartite quantum mechanical system and the existence of chaos in the classical limit of that system. This work further explores this connection for the case of two spins in an atom, electron and nuclear, coupled by the hyperfine interaction and driven by an external magnetic field. We have studied numerical simulations of the classical limit of this system, and have results which show the appearance or lack of chaos for a variety of different fields and initial conditions.

## 42. Hidden Geometric Phases and Holonomies of the SU(4) Group of Two-Qubit Unitary Transformations, Dmitry Uskov , *Louisiana State University*

**Abstract:** Any unitary transformation of an arbitrary n-qubit system can be decomposed into a product of local operations and two-qubit binary operations. Therefore two-qubit operations are viewed as elementary building blocks of multiqubit quantum gates. From the mathematical point of view such operations are elements of the 15-dimensional SU(4) Lie group, and its (sub-)Riemannian geometry determines computational cost of various quantum operations. Intriguingly, geometric and algebraic properties of the SU(4) group are much richer than corresponding properties of an arbitrary SU(N) group because there exists an accidental isomorphism between the su(4) Lie algebra and the so(6) Lie algebra of orthogonal rotations of Euclidean 6-dimentional space. We exploit this properties to identify a set of new fiber bundles embedded in the SU(4) manifold and construct holonomies on these fiber bundles complementary to the well-known Berry and Wilczek-Zee geometric phases. We demonstrate some advantages of using these holonomies for constructing error-robust quantum gates.

**43. Simulating Quantum Systems with Trapped Ions**

**Kendra Vant,** ***Los Alamos National Laboratory***

**Abstract:** Many quantum systems cannot be simulated efficiently on a deterministic classical computer due to the large Hilbert space they inhabit. They may instead be investigated using a quantum simulator - a device which uses a number of more-easily controllable quantum bits to mimic the quantum spins in the system to be studied. The states of the simulator follow the same equations of motion as the real system, yet are directly accessible to the experimenter. Trapped ions may make this kind of simulation possible. Long-lived internal states of individual ions (qubits) can be coupled through both the Coulomb interaction and applied radiation fields. We will describe the experimental status of the proposed LANL trapped-ion quantum simulator. In particular, we will discuss our ideas for the generation of spin-dependent optical forces to produce ion-ion interactions that mimic interactions in Ising-like model Hamiltonians. Prospects for using this interaction as the basis of a few-ion simulator for this model and others will also be described. In addition, recent collaboration between Los Alamos and Sandia National Labs has led to the construction of microfabricated trapping structures; development of their use for quantum simulations will also be a major focus in the near future. These multizoned traps should be more suitable for quantum simulation than single well traps. We will discuss the trap development and testing.

**44. Reducing the sensitivity of the M-S gate to unbalanced laser intensities**

**Janus H. Wesenberg,** ***NIST Boulder***

**Abstract:** High-fidelity quantum gates have been experimentally demonstrated for ions confined in strongly binding RF-traps. One notable example is the geometric gate implemented at NIST in Boulder. This gate is closely related to a gate suggested by Moelmer and Soerensen, but implementation is simpler because only one pair of Raman beams is used, in contrast to the two pairs employed by the Moelmer-Soerensen (M-S) gate. Unfortunately, the simpler NIST gate does not work if the qubit is encoded in field-insensitive states, that is, states with vanishing differential Zeeman shift. Since such encodings have many advantages over field-sensitive encodings, there is a renewed interest in implementing the original M-S gate. In the originally proposed form, the M-S gate is highly sensitive to differences in effective strength between the two pairs of Raman beams. Since avoiding such strength differences would present significant experimental difficulties, it is preferable to modify the gate to make it intrinsically insensitive to strength differences. We show that such intrinsic insensitivity can be achieved by means of a simple modification of the gate operation, combined with traditional re-focusing techniques.