Algorithms and Architectures for Quantum Computers

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Overview

This research group seeks to understand and develop the experimental and theoretical potential for information processing and communications using the laws of quantum physics. Two fundamental questions motivate our work: (1) How can a large-scale, reliable quantum computer be realized? (2) What new metrology applications, mathematical algorithms, and cryptographic primitives are enabled by quantum information?

The first question is primarily experimental. We intend to build a large-scale, reliable quantum computer over the next few decades. Based on our successes with realizing small quantum computers, and after years of testing, modeling, and planning, we have come to understand how this can be achieved by combining fault tolerance techniques developed by von Neumann, with methods from atomic physics. Our main approach is to develop highly integrated trapped ion systems, in which states of single atoms and ions are quantum bits, and logic gates are realized using Coulomb interactions controlled by surface electrode potentials and pulsed laser excitation. This approach of chip-based ion traps also allows cryogenic operation, and integration with solid state quantum devices, such as superconductor based qubits and photon detectors. Trapped ions may also be coupled to high finesse optical resonators, to couple ion qubits with photon qubits.

The second question concerns the future of quantum information, which needs algorithms for more than just factoring, search, and key distribution. Protocols and quantum codes we have discovered in the last decade, for tasks such as distributed one-time computation and digital signatures, and universal quantum data compression, suggest new areas for useful quantum algorithms, and new models of quantum computation, which may eventually lead to large-scale quantum processors and quantum simulators which are fault-tolerant.

We are also leading a novel educational effort at MIT to develop a graduate study program in quantum information science and engineering, funded by an Integrative Graduate Education, Research, and Training grant from the National Science Foundation.

1. Research and Development of Integrated Ion Trap Quantum Computer Systems

Sponsors

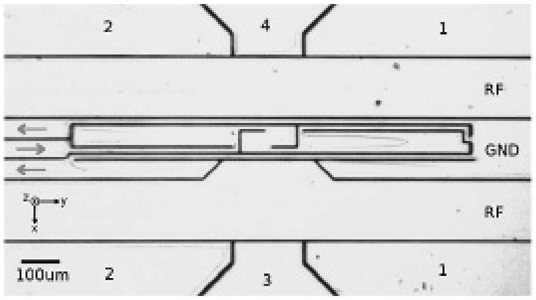
Japan Science and Technology Agency

Project Staff

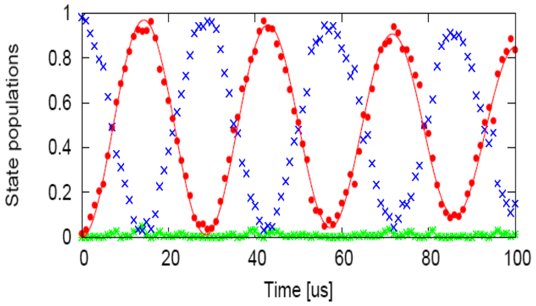
Paul Antohi, Xie Chen, David Leibrandt, Yufei Ge, Shannon Wang

1a. Realization of high selectivity ion qubit addressing scheme

Selectively addressing individual qubits in an array of ions is a vital task for scalable quantum computation with trapped ions. Traditionally, this is accomplished using complex optics for laser beam steering, but such schemes are not easily scalable. We have realized a scalable alternative which employs the advantages of microfabrication and cryogenic operation, and applies a magnetic field gradient to a chain of ions. The field is generated by a coil embedded within the trap structure, and self-aligned through simultaneous fabrication with trap electrodes. Measurements show that crosstalk between ions is below 3%:



Microphotograph of trap



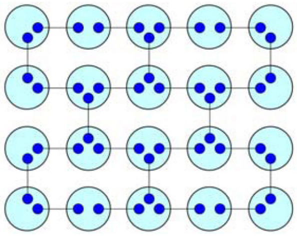
Selective Rabi Oscillations: Two qubits

This demonstration opens the door for use of superconductors to generate magnetic field gradients using persistent currents, for ion qubit addressing. This result [1] is described in Applied Physics Letters, volume 94, page 094103 (2009).

1b. Universal resource state for One-Way Quantum Computation

A fascinating model for quantum computing, other than the traditional quantum circuit model, is the "one-way" model that is based on simply doing single qubit measurements to a fixed, initial entangled quantum state of many qubits. By feeding back measurement results to control the axis of subsequent measurements, any quantum circuit can be simulated and any quantum computation can be efficiently and universally implemented. The main challenge is thus realization of the necessary initial, entangled state, which has previously required many-body, non-nearest neighbor interactions to realize, such as for the standard cluster state.

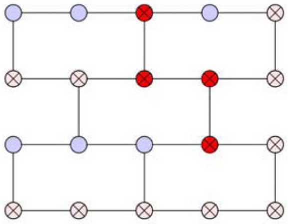
We have discovered a new construction for one-way quantum computation which is universal, which utilizes the unique ground state of a physical system with a Hamiltonian which is two-body and gapped. Thus, in principle, the required initial state could be realized in Nature, simply by cooling down some solid state system which is governed by this Hamiltonian.



- Singlet pairs on a hexagonal lattice
- Projection at each site:

$$|\tilde{0}\rangle\langle 000| + |\tilde{1}\rangle\langle 111| \;\; + \\ |\tilde{2}\rangle\langle 001| + |\tilde{3}\rangle\langle 110| \;\; + \\ |\tilde{4}\rangle\langle 010| + |\tilde{5}\rangle\langle 101|$$

- 6 dimensional Particle



- Two-qubit Control-Not gate
- Cluster State: Measure in basis $\{|0\rangle \pm |1\rangle\}$
- Tri-Cluster: Measure in basis $\{|0\rangle \pm |1\rangle,$ $|2\rangle \pm |3\rangle,$ $|4\rangle \pm |5\rangle\}$
- **Universal!**

The ground state, known as a "tri-cluster" state, is a two-dimensional hexagonal lattice of six-dimensional "qudits" (rather than qubits), as depicted above. Quantum gates, such as the controlled-NOT and single qubit rotations, are implemented by measurements in specific bases, followed by change in the Pauli frame of the measurement apparatus, much like with the standard cluster state.

In addition to novel implications for condensed matter systems, this result suggests that lattices of ions or neutral atoms may be constructed using nearest neighbor interactions, which could then be used for universal measurement-based quantum computation. Measurement based quantum computation requires no active quantum gates, and thus also represents a novel approach towards fault tolerant, large-scale quantum computation. The result [2] is described in Physical Review Letters volume 102, page 220501 (2009), and was selected to be featured in a Spotlight on Physics by the American Physical Society.

2. Center for Ultracold Atoms

Sponsors

National Science Foundation

Project Staff

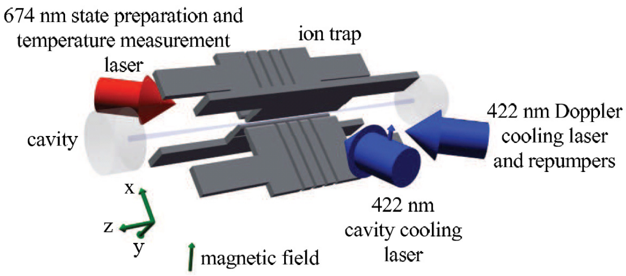
Paul Antohi, Robert Clark, Elizabeth George, David Leibrandt, Carter Lin, David Schuster

<u>Demonstration of resolved sideband cavity cooling of a single ion</u>

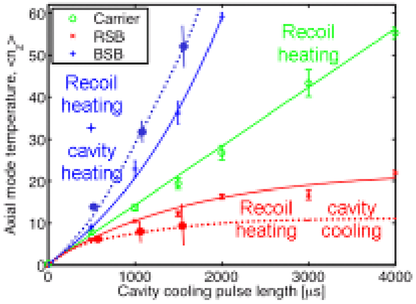
This is joint work with Vladan Vuletic.

Efficient quantum information processing requires qubits to be initialized to a known logical state. Moreover, such state preparation must often be performed during the course of a quantum computation, for example, to prepare ancilla states necessary for quantum error correction, or for multi-qubit gates. Trapped ion quantum computation needs such state preparation, in order for two-qubit gates to operate with high fidelity. Initially, the ion qubits may be laser sideband-cooled into their motional quantum ground states $|n=0\rangle$, but during the course of a quantum computation the motional state typically heats up, and becomes a thermal mixture instead of the necessary quantum ground state. Standard laser cooling is inappropriate for re-cooling during quantum computation, because it will typically strongly perturb or destroy ion qubits while cooling, because laser cooling employ closed cycle transitions which include the same narrow transitions used for representing qubits. One solution to this need for quantum non-demolition cooling is to employ another species of ion, for sympathetic cooling, but this requires the secondary ion to be moved immediately adjacent to the computational ions, as well as new sets of lasers for cooling the secondary ion.

Quantum non-demolition cooling may also be accomplished with trapped ions, using a new technique, known as *resolved sideband cavity cooling*, in which laser cooling is done non-resonantly, by virtue of coupling through strong cooperativity to a high finesse cavity. We have experimentally demonstrated the basic principles of this cooling mechanism, for the first time, using a single Sr+ ion trapped within a knife-edge trap, enclosed within a high finesse optical cavity:



Experimental Setup



Measurement results

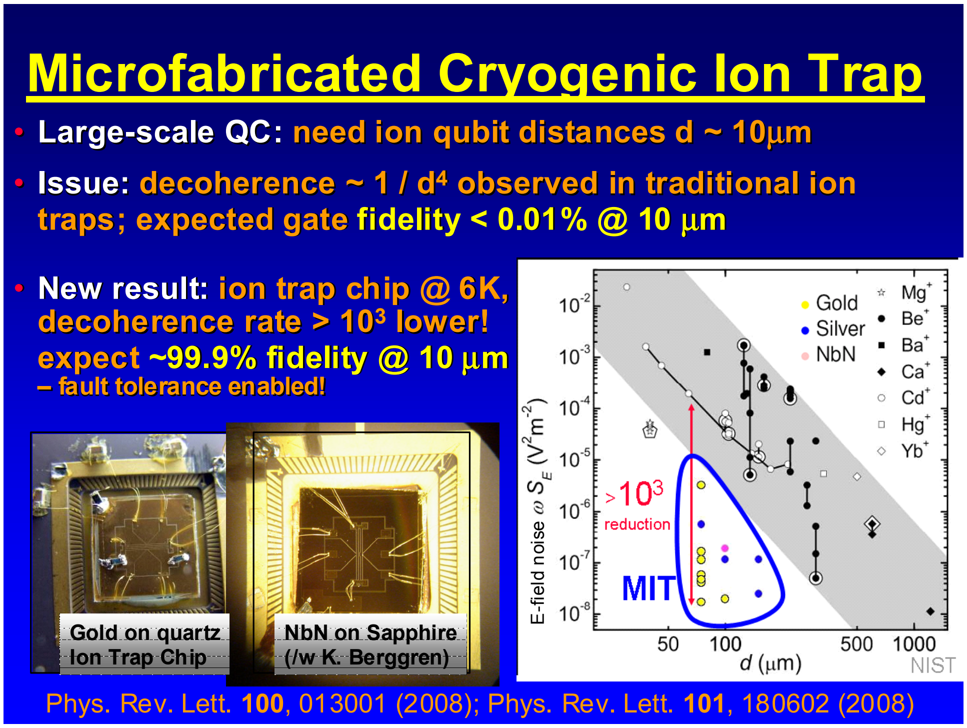
The cooling laser in the experiment was tuned to be resonant with the cavity, in which no cooling was obtained, and the ion would heat up through normal processes (green line); the laser was tuned to the blue side of the cavity, in which case cavity interactions would cause additional heating, by scattering photons even bluer than the incident light (blue line); or the laser was tuned to the red side of the cavity, in which case cavity induced cooling was observerd (red line). This cooling resulted in a equilibrium temperature just below the Doppler limit, and definitively shows agreement with published theories for resolved sideband cavity cooling. This work was partially supported in addition by JST The results [3,4] are described in Physical Review Letters, volume 103, page 103001 (2009).

3. Comprehensive Materials and Morphologies Study of Ion traps (COMMIT) for Scalable Quantum Computation

Sponsors
Army Research Office

Project Staff
Paul Antohi, David Leibrandt, Shannon Wang, Yufei Ge

A significant problem facing trapped ion quantum computation is the excess noise which grows in power as $1/d^4$, for trap size d, due probably to fluctuations of surface charges. This noise significantly degrades the performance of two-qubit quantum logic gates such as the controlled-NOT gate, making fault-tolerant operation impossible with the noise, at the desired distance scale of 10 micrometers. We have realized an experiment to reduce this noise by freezing out surface charge fluctuations using a cryogenic environment at liquid nitrogen and liquid helium temperatures. The traps are microfabricated ion trap chips, made of gold on quartz, NbN on sapphire, and other materials. A single strontium ion trapped above these chips at a distance of 75 micrometers shows heating rates of ~1 quanta/second, which is better than three orders of magnitude lower than the best comparable room temperature traps.



Microfabricated Cryogenic Ion Trap

- Large-scale QC: need ion qubit distances d ~ 10µm
- Issue: decoherence ~ 1 / d^4 observed in traditional ion traps; expected gate fidelity < 0.01% @ 10 µm
- New result: ion trap chip @ 6K, decoherence rate > 10^3 lower! expect ~99.9% fidelity @ 10 µm
  – fault tolerance enabled!

Phys. Rev. Lett. **100**, 013001 (2008); Phys. Rev. Lett. **101**, 180602 (2008)

This is a very surprising and remarkable result. Temperature dependence measurements indicate that the charge noise does not have a Boltzmann activation potential, but could be related to sources of noise seen in gravitational observatory measurements and magnetic force resonance microscopy experiments. These results were made possible in part by novel high stability, low noise, optical feedback stabilized, monolithic lasers, which were designed and implemented for high fidelity pulsed control of our trapped ion qubit. The lasers are described in Optics Letters, volume 32, page 572 (2007), and the new experimental measurements [5,6] are described in Physical Review Letters volume 100, page 013001 (2008), and Physical Review Letters, volume 101, page 180602 (2008). Initial results from this research were partially supported by JST.

4. Entanglement Transfer & Processing with Photons Interconnecting Atomic and Trapped Ion Ensembles

Sponsors

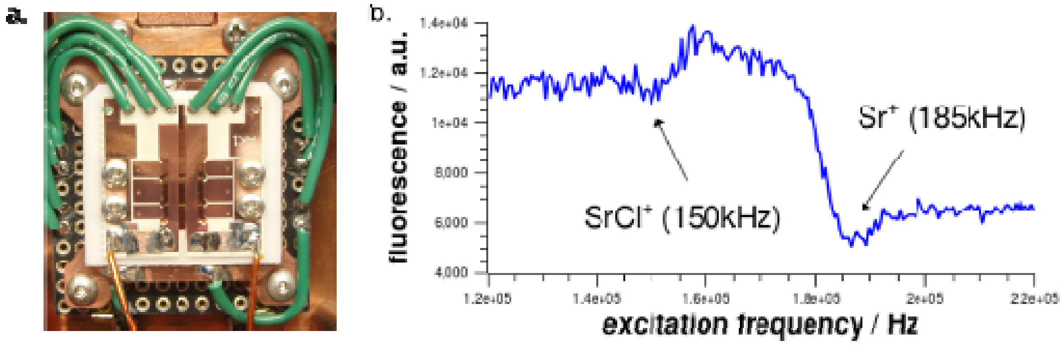
DARPA

Project Staff

Peter Herskind, David Leibrandt, Stephan Schulz, Paul Antohi

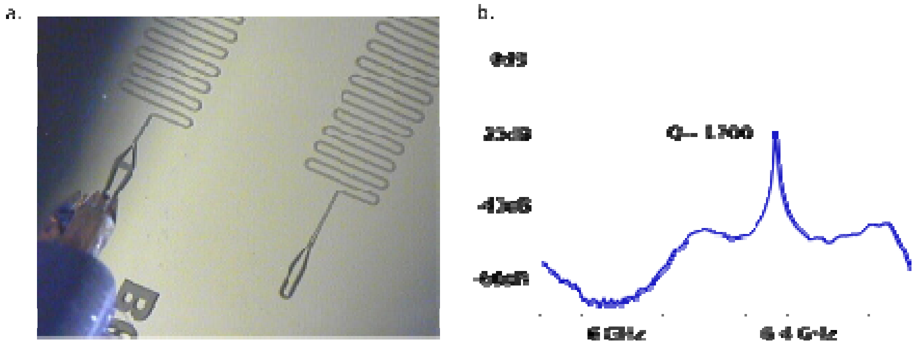
This is a joint project with Karl Berggren, Jeffrey Shapiro, and Vladan Vuletic.

We have designed and fabricated a cryogenic ion trap suitable for coupling molecular ions with a superconducting microwave stripline resonator. Simultaneous mixed-species loading of Sr^+ and $SrCl^+$ have been demonstrated in this trap, which uses copper electrodes on a microwave compatible substrate. The fluorescence signal of the Sr^+ ions shows the different species in a vibrational excitation mass spectroscopy measurement.



(a) Surface-electrode ion trap for investigation of the molecular ion-microwave coupling operated at 684Vrf at 10.5MHz. The radial frequencies for the trapped Sr^+ ions are 1.3MHz and 0.8MHz, the axial frequency 130 kHz. The trap depth for Sr^+ ions is about 0.32eV. (b) Total Sr^+ fluorescence of a mixed-species ion cloud of Sr^+ and $SrCl^+$ ions for different vibrational excitation frequencies.

An advanced microfabricated stripline resonator has also been fabricated, from niobium on quartz, and characterized at different temperatures in a cryogenic probe station setup. Measurements show a quality factor of ~1700 at 4K, with a resonance frequency at ~6 GHz, in excellent agreement with numerical simulations. These resonators may be integrated with ion traps for direct detection of molecular ions.



(a) Meander-type microwave coplanar waveguide resonators in a cryogenic probe station setup. The 3-finger microprobes for the transmission measurements are mounted on translation stages and are moved in-situ. (b) Transmission measurement of the meander-type resonators.

This work was supported in part by the NSF CUA.

5. IGERT: Interdisciplinary quantum information science and engineering

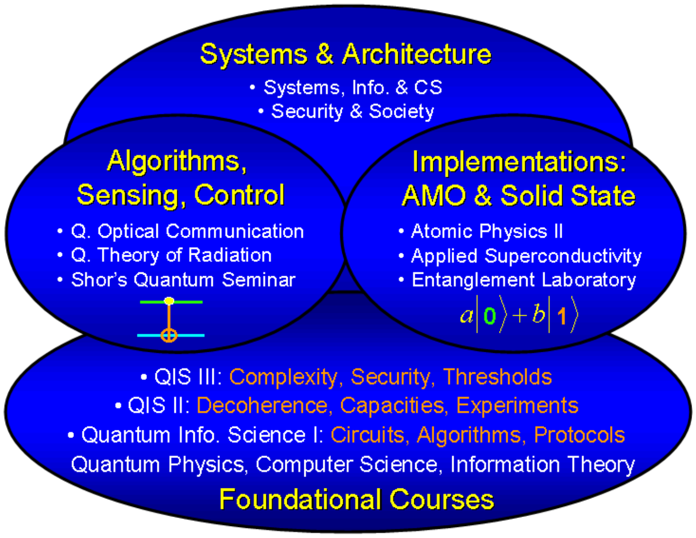
Sponsors
NSF

Project Staff
Rita Tavilla, Franco Wong

This program is a new approach to educating and training students in quantum information science & engineering, based on a unified, interdisciplinary curriculum, crossing traditional barriers between science and engineering, with the goal of nurturing a new generation of students, from education through employment, and of providing a case for a future permanent doctoral program at MIT. The program involves 14 faculty members at MIT, across five departments, and offers Course Q, a comprehensive doctoral program in quantum information; the Fellowship of Quantum Information, a community of graduate students researchers in the field; QIS@MIT, a teaching and seminar program; and InQuIRE, an outreach program connecting government and industrial partners and quantum information research, for students and the public.

iQuISE
INTERDISCIPLINARY QUANTUM INFORMATION SCIENCE AND ENGINEERING
Supported by the National Science Foundation (NSF)

Support is provided by the Integrative Graduate Education, Research, and Training (IGERT) program of the NSF. This IGERT has enrolled 18 graduate students as associates, and as of the Fall of 2009, it will fully support six or more students (three women; more applications are still in progress). The academic curriculum has also developed, with a new graduate course in Quantum Complexity Theory offered, and a consistent three-semester sequence in quantum information science being offered starting the Fall of 2009:



A new Quantum information Science Teaching Laboratory is also being established, which will offer hands-on experience with quantum optics experiments, including testing fundamental predictions separating quantum from classical mechanics, using entangled photons. And a summer course on Quantum Information Science for Undergraduates, QuISU, was offered for the first time, in June, 2009, and was attended by 21 students, including 4 women and 2 underrepresented minorities.

See http://iquise.mit.edu for more information.

EECS physics@mit MIT MATHEMATICS MITMECHE DEPARTMENT OF NUCLEAR SCIENCE & ENGINEERING

Publications

Journal Articles

[1] Shannon X. Wang, Jaroslaw Labaziewicz, Yufei Ge, Ruth Shewmon, Isaac L. Chuang "Individual Addressing of Ions Using Magnetic Field Gradients in a Surface-Electrode Ion Trap," Appl. Phys. Lett., vol. 94, 094103 (2009).

[2] Xie Chen, Bei Zeng, Zheng-Cheng Gu, Beni Yoshida, and Isaac L. Chuang "Gapped Two-Body Hamiltonian Whose Unique Ground State Is Universal for One-Way Quantum Computation ," Phys. Rev. Lett, vol. 102, page 220501 (2009).

[3] David R. Leibrandt, Jaroslaw Labaziewicz, Vladan Vuletic, Isaac L. Chuang, "Cavity Sideband Cooling of a Single Trapped Ion," Phys. Rev. Lett., vol. 103, 103001 (2009).

[4] David Leibrandt, MIT Physics Ph.D. Thesis, "Integrated chips and optical cavities for trapped ion quantum information processing," (2009).

[5] P. B. Antohi, D. Schuster, G. M. Akselrod, J. Labaziewicz, Y. Ge, Z. Lin, W. S. Bakr, I. L. Chuang, "Cryogenic Ion Trapping Systems with Surface-Electrode Traps ," Rev. Sci. Inst., vol. 80, 013103 (2009).

[6] Jaroslaw Labaziewicz, Yufei Ge, David R. Leibrandt, Shannon X. Wang, Ruth Shewmon, and Isaac L. Chuang, "Temperature Dependence of Electric Field Noise above Gold Surfaces," Phys. Rev. Lett., vol. 101, 180602 (2008).