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 algorithms, cryptographic primitives, and metrology techniques are senabled 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 will also allow cryogenic operation, and integration with solid state quantum devices, such as superconductor based qubits and photon detectors.

The second question concerns the future of quantum information, which needs algorithms for more than just factoring, search, and key distribution. Protocols we have discovered in the last five years, for tasks such as distributed one-time computation and digital signatures, and universal quantum data compression, suggest new areas for useful algorithms, based on symmetries such as the Schur duality. These theoretical studies will provide new approaches to realizing useful, large-scale quantum processors and quantum simulators which are fault-tolerant.

1. Applications of the Schur Basis to Quantum Algorithms

Sponsors
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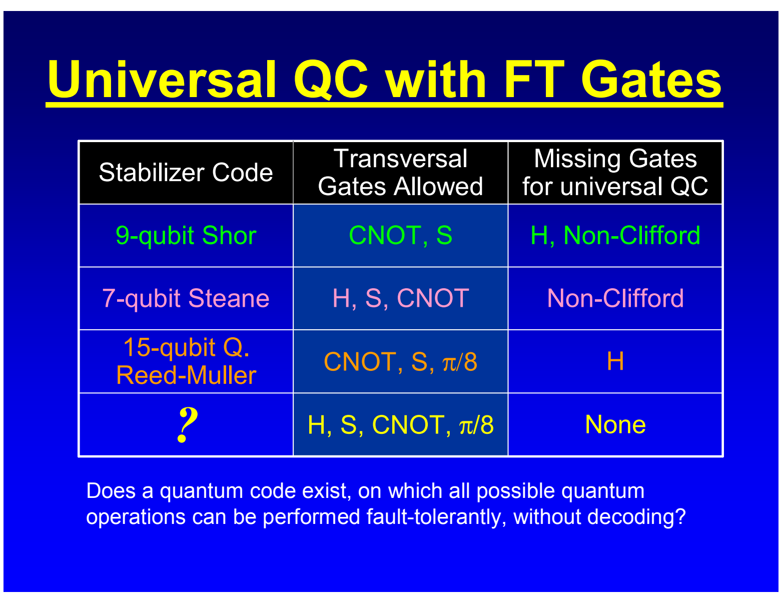
Many of the most successful quantum algorithms are designed around symmetries, for which group representation theory provides the mathematical foundation. These algorithms traditionally have achieved their speedups with the quantum Fourier transform (QFT), but this is not the only method known to exploit group symmetries. One concept which has been productive in mathematics, chemistry, physics, and recently quantum information theory, is known as Schur (or Schur-Weyl) duality. Early in this project we gave an efficient quantum circuit, which we call the Schur transform by analogy to the QFT, for transforming quantum data between two different forms: the standard computational basis and the Schur basis [1]. This allows quantum computers to efficiently compute using the Schur symmetries of quantum information. While this already has applications to quantum communication, one of our main goals is to find algorithmic uses of the transform. We are also looking at ways of using Schur symmetry in a purely mathematical sense to construct quantum algorithms, so that Schur duality would be used in the analysis of the algorithm but its implementation would not explicitly use the Schur transform [2].

During our search for possible new quantum algorithms based on the Schur transform, we studied properties of particular entangled states corresponding to graphs, and how they were transformed under symmetries such as those employed in quantum algorithms. Such entangled states can be used as resources to speed up quantum computations, in a manner which is vital to implementing quantum algorithms such that they can be robust against local gate failures.

We have recently discovered that such use of entanglement, to “teleport gates,” is not just a nice way to provide fault tolerance, but indeed, a necessary ingredient for fault tolerance, using any presently known quantum code [3]. This result answers a long-standing question: does a standard (“stabilizer”) quantum code exist, on which universal quantum computation can be accomplished without decoding the quantum data? The answer is “no,” and the reason has to do with fundamental properties of quantum codes, and allowable automorphisms on the groups involved.



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

Sponsors
Japan Science and Technology Agency

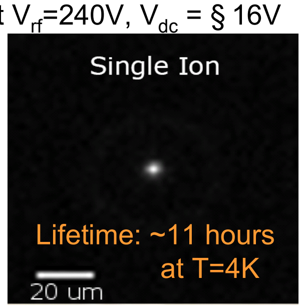
Project Staff
Kenneth Brown, Paul Antohi, Yufei Ge, Jaroslaw Labaziewicz, Ruth Shewmon

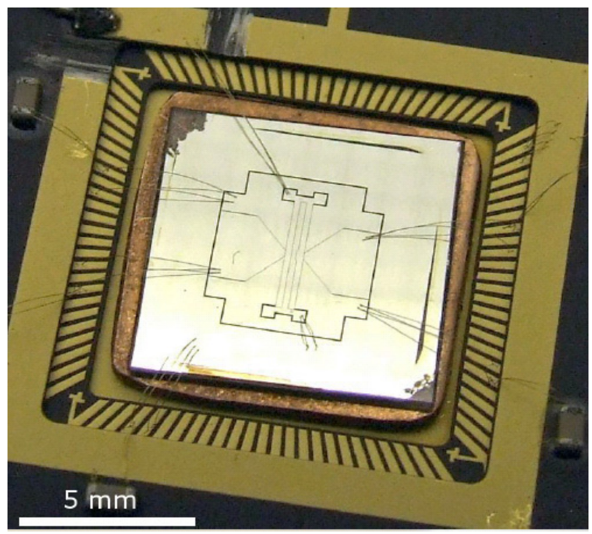
Traditional ion trap traps are three dimensional systems operated at room temperature. We have experimentally implemented a new kind of ion trap, based on semiconductor lithography, fabricated at MIT, and operated at liquid helium temperature. This ion trap chip, pictured below, has enabled us to trap single ions of strontium for extremely long times, held ~100 micrometers above an electrode surface, and laser-cooled to its quantum ground state with better than 90% fidelity.

MIT Cryogenic Ion Trap Chip

- Ion Chip: 5 electrodes, silver on quartz
- Ion height: 150 µm
- Trap frequencies: 1.92, 1.94, 0.76 MHz

  At V_{rf}=240V, V_{dc} = § 16V





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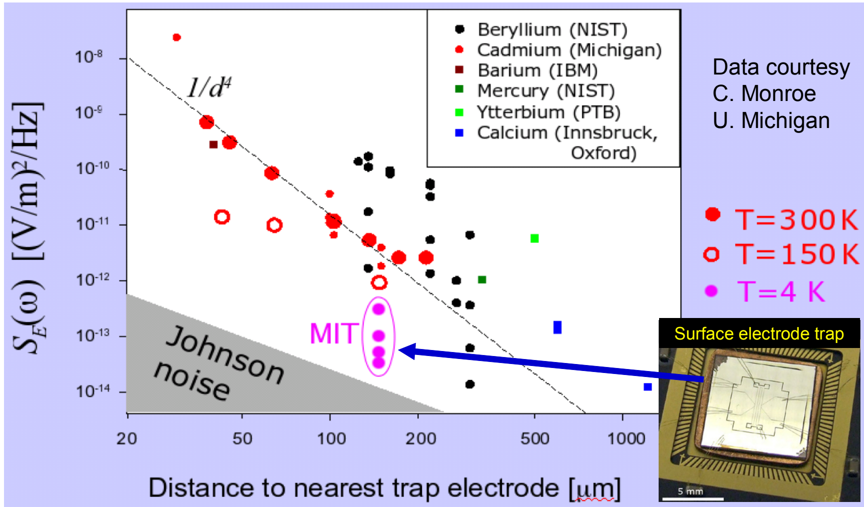
A significant problem facing ion traps is the excess noise which grows in power as $1/d^4$, for trap size d, due probably to fluctuations of surface charges. This noise significantly degrades the performance of two-qubit quantum logic gates such as the controlled-NOT gate.

Our silver-on-sapphire ion trap chip reduces the heating rate to less than one quantum of increase in harmonic motion per second, which is two orders of magnitude better than previous results in comparably sized traps, and seven orders of magnitude less than the heating rate observed in a trap of the same design at room temperature [4].

Ion Heating Rate Measured at 4K



MIT Cryogenic Ion Trap: one ^{88}Sr ion, sideband cooled to $\bar{n}$=0.1

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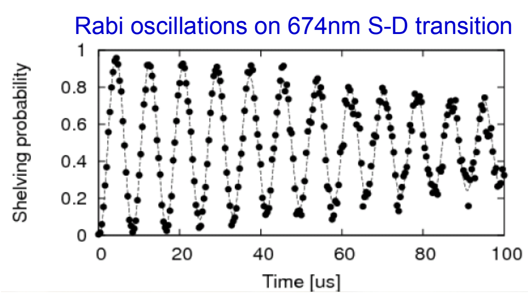
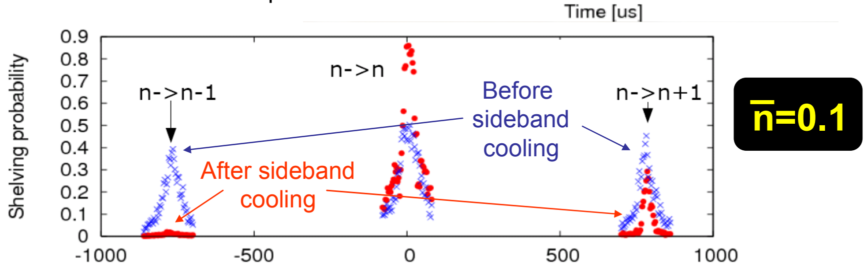
This remarkable result suggests that surface charge noise strongly depends on temperature, and indicates the importance of studying surface electrode materials and fabrication methods for trapped ion chips.

These measurements were made possible by pulsed sideband cooling of a strontium ion to its motional quantum ground state, as evidenced by observations of Rabi oscillations, and asymmetry in the red and blue motional sidebands around the 674nm S to D transition of the ion. This transition has a natural linewidth less than 1 Hz wide, and the experiment employed a laser stabilized by a ULE cavity operated in vacuum, with finesse of 300,000.

Sideband Cooling of Sr^+ at 4K

- Result 1: Rabi oscillations observed (on carrier transition)
- Result 2: 90% motional ground state reached after 250 sideband cooling pulses, in surface-electrode ion trap





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3. Coherent molecule traps for quantum information technology

Sponsors
Hewlett-Packard

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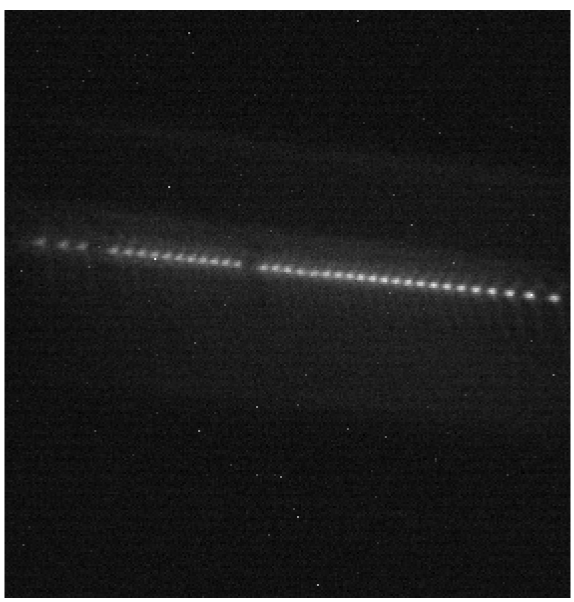
Quantum information science seeks to harness the coherent dynamics of nanoscale systems for information technology. These quantum dynamics offer new computational and cryptographic capabilities which are impossible using conventional classical m echanics and electrodynamics alone. One promising platform for experimentally realizing such quantum machines is based on spins in molecules, as has been demonstrated by the realization of Shor's factoring algorithm in a fluorinated molecule usin g magnetic resonance.

A natural interface between quantum computers and classical machines could thus be provided by molecules confined on patterned semiconductor substrates. However, such trapped molecules typically interact strongly with their confining electrodes, and thereby loose the quantum coherence necessary for quantum computation. The quantum gates then rapidly become unreliable, making it difficult to realize a working quantum system. This project seeks to develop a novel mechanism for trapping molecules, addressing how coherent dynamics in trapped molecules can be harnessed for quantum computation.

We have implemented an electrodynamical Paul trap operated at around 4 Kelvin, in a continuous flow cryostat. Using laser ablation[5], we have loaded a mixture of strontium ions and other molecules in the trap, and laser cooled the assembly of ions to crystalization. Individual strontium ions can be optically resolved in chains, such as the one pictured below, in which are interspersed dark ions that are molecules, and isotopes of strontium other than the one addressed by the main laser.



CCD image of strontium ion chain: the spacing between ions is about 15 micrometers.

4. Center for Ultracold Atoms: Towards Quantum Simulations

Sponsors
National Science Foundation

Project Staff
Robert Clark, Elizabeth George, David Leibrandt, Carter Lin

This project is an initiative in the NSF sponsored Center for Ultracold Atoms that combines techniques of ultracold atoms, trapped ions, and quantum computation to explore quantum simulations of a variety of fundamental problems in condensed matter physics and quantum optics. Feynman, in 1982, pointed out that quantum systems cannot be efficiently simulated by computers operating according to the laws of classical physics alone, but can be using a machine based on quantum physics. However, progress has been limited by the difficulty of creating controllable quantum systems with coherence times that are long enough for meaningful studies. Our quantum simulation project addresses this challenge.

A quantum simulator is inherently a quantum computer, but there are some important distinctions. The level of complexity is much less than required for a useful quantum computer. Specifically, the physical system used for the simulator need only have a number of degrees of freedom (e.g. controllable internal quantum states) comparable to the system being simulated. For example, to simulate an N-spin Ising model it suffices to have a lattice of ~N atoms. Furthermore, the control scheme is intrinsically simpler and under the right circumstances, can be more robust (i.e. less susceptible to errors) than that required for quantum computation.

These simplicities allow for the possibility of realizing a quantum simulator with technology at hand along the following lines. The working medium is a two-dimensional array of ultracold ions whose internal hyperfine states model degrees of freedom of the system being simulated. The vibrational states of the ions are entangled via the Coulomb interaction, and mapped onto internal states of the ions with laser-driven Raman transitions. This general approach has already been applied to linear chains of four to six ions for metrology, clocks, and simple quantum algorithms, at a variety of institutions around the world.

Extending trapped-ion techniques to systems of tens to hundreds of ions presents a formidable challenge, but we believe that it is possible using a two-dimensional radio-frequency ion trap that we have implemented based on ideas advanced at NIST. The special feature of our implementation is that it is entirely planar; it is fabricated from a single layer of metal, deposited on a glass composite substrate, and lithographically patterned to produce segmented electrodes. The advantages of this geometry are that it is readily fabricated and can be extended in size because it is fully compatible with semiconductor fabrication techniques. Also, it has the intrinsic geometry of two-dimensional neutral atom traps already used at CUA, which is important in loading the cold ions. This approach opens the door to achieving the electrostatic control required to manipulate tens to hundreds of ions.

We have carried out preliminary studies of this system and implemented several key components: construction and demonstration of ion crystallization in a linear trap, lithographic fabrication of a planar ion trap, and development of methods to load shallow traps. Our current experiment realizes a two-dimensional lattice of ions, with a spacing larger than several hundred micrometers. This trap size is being significantly reduced in a second generation realization, to about 100 micrometers, a size at which ion-ion interactions should become measurable. Methods for coupling ions through optical cavities are also being investigated.

Publications

Journal Articles

[1] D. Bacon, I. Chuang and A. Harrow. "Efficient Circuits for Schur and Clebsch-Gordon transforms." *Phys. Rev. Lett.*, 97, 170502 (2006).

[2] D.A.Bacon, I.L. Chuang, A.W. Harrow. "The Quantum Schur Transform: I. Efficient Qudit Circuits." *Proc. 18th ACM-SIAM Symposium on Discrete Algorithms*, 1235-1244 (2007).

[3] B. Zeng, A. Cross, and I. Chuang "Transversality versus Universality for Additive Quantum Codes," submitted to IEEE Transactions on Information Theory (2007).

[4] J. Labaziewicz, Y. Ge, P. Antohi, D. Leibrandt, K. Brown, and I. Chuang, "Suppression of heating rates in cryogenic surface-electrode ion traps," submitted to Phys. Rev. Lett. (2007).

[5] D. Leibrandt, R. Clark, J. Labaziewicz, P. Antohi, W. Bakr, K. Brown, and I. Chuang, "Laser ablation loading of a surface-electrode ion trap," to appear in Phys. Rev. A (2007).