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 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 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 algorithms, based on symmetries such as the Schur duality and non-additive quantum codes. 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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An essential elementary step in all exponentially fast quantum algorithms is extraction of data about global properties of a function. This process is very similar to how quantum error correction codes are constructed, because a primary function of such codes is to store information in a distributed fashion so as to prevent degradation by local noise[1]. Viewed as an encoding circuit for some code, however, the quantum Fourier transform constructs codewords which are not members of the standard "stabilizer" family of quantum codes. This motivates the need to understand the broader nature of what makes good quantum codes, outside of the stabilizer formalism, so that the presence of code structures within quantum algorithms can be readily identified and taken advantage of.

We have recently identified, and applied methods for constructing a new class of non-stabilizer quantum codes [2]. This *codeword stabilized quantum codes* ("CWS" quantum codes) formalism constructs the desired quantum code based on a binary code C, chosen to correct a certain error pattern induced by a self-dual additive quantum code, which is without loss of generality, taken to be a stabilizer state. This method thus reduces the problem of finding a quantum code into a problem of finding a certain classical code. All previously known non-stabilizer quantum codes can be constructed within the CWS construction, and many new codes have been found as well, although there remain further quantum codes outside of the CWS formalism:

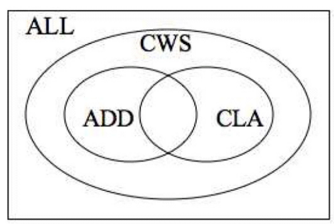


Fig. 1. The relationship of CWS codes with additive quantum codes and classical codes: ALL: all quantum codes; CWS: CWS codes; ADD: additive codes; CLA: classical codes.

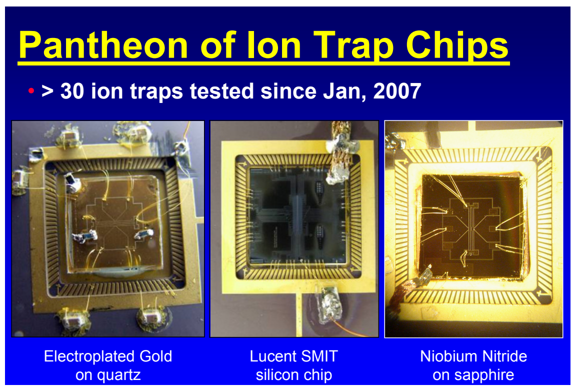
Our method for constructing CWS codes is an algorithm which reduces the search for CWS codes to a problem of identifying maximum cliques in a graph. While solving this problem in general is very hard, we provide three structure theorems which reduce the search space, specifying certain admissible and optimal ((n,K, d)) additive codes. In particular, we find there does not exist any ((7, 3, 3)) CWS code though the linear programming bound does not rule it out.

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

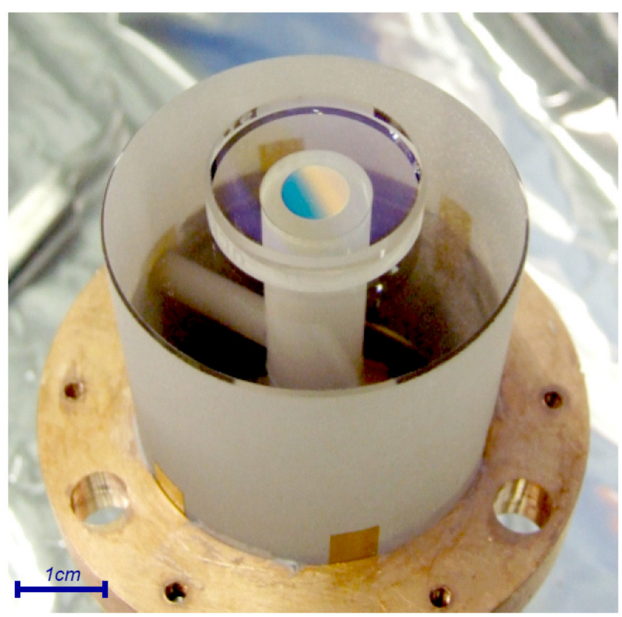
Sponsors
Japan Science and Technology Agency

Project Staff
Paul Antohi, Yufei Ge, Jaroslaw Labaziewicz, Ruth Shewmon, Shannon Wang

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. These traps enable systematic analysis of the behavior of the quantum state of trapped ions, near the surface of traps, for realization of large-scale quantum computers. We have operated and tested many of these new surface electrode ion traps in the past year, including traps made of silver on quartz and sapphire, gold on quartz[3], aluminum on silicon, and niobium nitride on sapphire (the last being a superconducting trap, fabricated in collaboration with Karl Berggren's group):



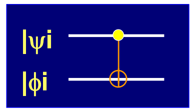
In order to utilize these microfabricated ion traps for quantum computation, frequency stable laser sources must be provided. The ion we trap is Sr^{+}, which has an S-D transition at 674nm with a lifetime better than 1 Hz, which can thus serve as an excellent quantum bit. We have implemented a laser capable of addressing this qubit transition using an optical feedback monolithic external cavity diode laser setup, stabilized to a newly completed Fabry-Perot cavity, made of ULE glass[4]. The cavity (figure below) is temperature stabilized to better than 1 millikelvin, and is held in high vacuum, giving a finesse of better than 700,000. Using Pound-Drever-Hall locking, we currently have a short-term locked laser linewidth better than 0.4 Hz, limited by the bandwidth of the AOM presently used, and acoustical noise through the isolation chamber.



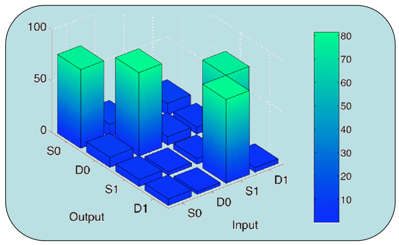
This narrow qubit laser has made possible the recent implementation of a high fidelity controlled-NOT gate in our microfabricated gold on sapphire ion trap. This gate utilizes a single trapped Sr+ ion located about 100mm above the surface of the trap, with one qubit being the 674nm S-D transition, and the second qubit being the n=0 and n=1 motional states of the center-of-mass motion of the ion in the trap. The gate fidelity was evaluated using verification of the classical truth table quantified with classical fidelity:

Control: Two Qubit CNOT Gate

- Basic primitive for quantum computation:



- Data: (very recent!)



Ideal Truth Table

Input	Output
00	00
01	01
10	11
11	10

>90% Classical Fidelity CNOT realized (one ion, 2 qubits)

Work is in progress to evaluate the quantum fidelity of the gate using full quantum process tomography. The successful implementation of this two-qubit logic gate opens the door to realization of simple quantum algorithms with trapped ions at MIT, and confirms that microfabricated surface-electrode traps are a viable system for densely packed trapped ion quantum computation.

3. Center for Ultracold Atoms: Towards Quantum Simulations & Trapped Molecular ions

Sponsors

National Science Foundation

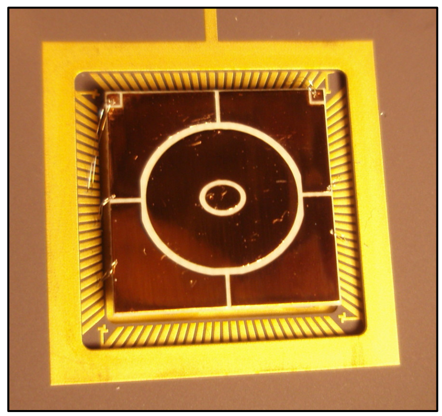
Project Staff

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

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 two goals: (1) quantum simulations of a variety of fundamental problems in condensed matter physics and quantum optics, and (2) cooling and control of molecular systems using single polar molecular ions, for quantum simulations and quantum computation.

1. Ion Lattices for Quantum Simulations

During the past year, this project has demonstrated trapping of hot strontium ions in a mesh trap [5], had designed a method for optical coupling to ions for readout [6], has developed a detailed theoretical model of expected simulation performance [7], and has demonstrated coherent control capabilities which will be needed in realizing simulations.

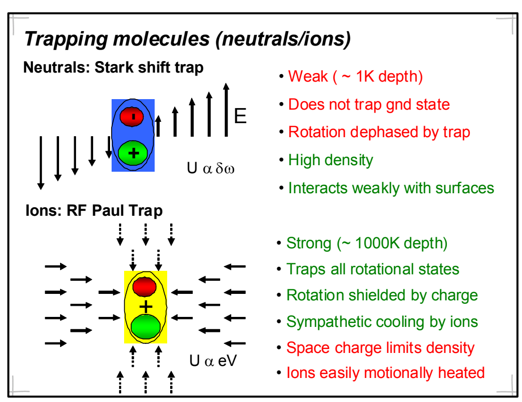


Our long-term goal is demonstrating a simple quantum simulation with three or more ions, coupled by their Coulomb interaction, modeling a Bose-Hubbard Hamiltonian, based on theory by Porras and Cirac, and taking advantage of the new surface-electrode trap geometry we have been developing. This will require sideband cooling to the motional ground state with high fidelity, traps with very long motional coherence times, and a high degree of coherent control.

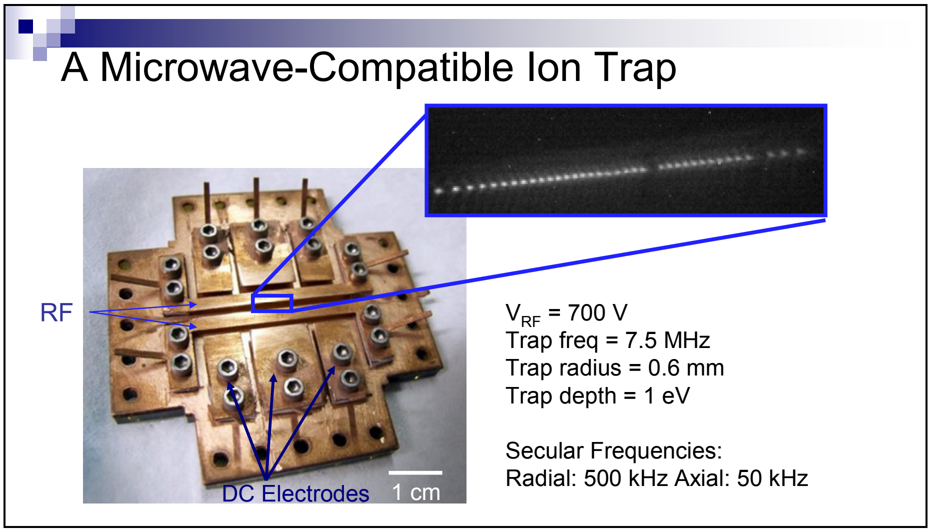
We have now demonstrated that these requirements can be satisfied in ion traps operated in a 4K cryostat, and our focus for this project has been bringing the suitable multi-ion, two-dimensional traps to cryogenic temperatures, and demonstrating the necessary coherent control. A new elliptical geometry microfabricated ion trap made of electroplated copper on glass-composite substrate has been designed and operated (see figure above: the chip trap is ~1cm square). This trap is designed to tightly confine a triangular configuration of ions, in which the principles of quantum simulations of frustrated spin lattices can be demonstrated. Ions have been trapped in this chip, and the behavior of the trapped ions is being studied for the quantum simulation application.

2. Polar Molecular Ion Trap

The polar molecular ion project seeks to trap, cool, and control a diatomic molecular ion such as SrO^+ or $CaCl^+$, using sympathetic cooling via Sr^+ ions in the same trap, and employing a microwave stripline resonator to couple the rotational mode to an integrated superconducting qubit. We have recently completed a significant goal, to develop a theoretical model for the expected coupling between the molecular ion and the superconducting qubit (work done in collaboration with Schoelkopf and DeMille at



Yale) [8]. Comparing polar molecules with polar molecular ions, there are interesting gains to be made, and some costs to be paid. In particular, the ions can be trapped much more deeply, and using a degree of freedom different from the rotational mode, which might be employed as a qubit in the molecule. The limitation is that space charge limts density, and charge noise may lead to motional heating.



We have devised three model experiments, using conservative estimates of the initial polarization, showing that a realistic experiment can expect to have ~100 Hz scale couplings between a molecular ion and a microwave stripline resonator embedded in the ion trap, even at relative large ~mm size scales.

Initial experiments confirm our ability to trap molecular ions, in a novel geometry which simultaneously allows RF and microwaves to couple to the trapped ions (figure above). We have successfully trapped a variety of polar molecular ions in our microwave compatible trap, as determined using tickling spectroscopy. This trap is currently macroscopic, but a microfabricated version of the trap has been designed and is being fabricated.

Publications

Journal Articles

[1] H. Chung, "The Study of Entangled States in Quantum Computation and Quantum Information Science," MIT Department of Electrical Engineering and Computer Science, M.Eng. Thesis, 2008.

[2] I. L. Chuang, A. W. Cross, G. Smith, J. A. Smolin, and B. Zeng. "Codeword stabilized quantum codes: algorithm and structure," submitted to Phys. Rev. A (preprint quant-ph/0803.3232), 2008.

[3] J. Labaziewicz, Y. Ge, P. Antohi, D. Leibrandt, K. Brown, and I. Chuang, "Suppression of heating rates in cryogenic surface-electrode ion traps," Phys. Rev. Lett. v.100, p. 13001 (2008).

[4] R. Shewmon, "Coherent manipulations of Trapped 88Sr+ using the 4D_5/2 to 5S_1/2 Transition," MIT Department of Physics S.B. Thesis, 2008.

[5] R. J. Clark, T. Lin, K. R. Brown, and I. L. Chuang, "A Two-dimensional Lattice Ion Trap for Quantum Simulation," submitted to J. Appl. Phys. (preprint quant-ph/0809.2824), 2008.

[6] E. George, "Fiber optic integration in Planar Ion Traps," MIT Department of Physics S.B. Thesis, 2008.

[7] Z. Lin, "Quantum Simulations with $88Sr^+$ Ions on Planar Lattice Traps," MIT Department of Physics S.B. Thesis, 2008.

[8] D. I. Schuster, I. L. Chuang, D. P. DeMille, and R. J. Schoelkopf, "Cavity QED in a molecular ion trap," submitted to Phys. Rev. Lett., 2008.