Advances in Quantum Computation

R. J. Hughes, D. J. Berkeland, D. Enzer, M. H. Holzscheiter, P. G. Kwiat, S. K. Lamoreaux, C. G. Peterson, M. M. Schauer, and A. G. White (P-23); J. Gomez, M. S. Gulley, V. Sandberg, and D. Tupa (P-25); A. G. Petschek (P-DO); D. F. V. James (T-4); J. M. Ettinger (NIS-8); and M. S. Neergaard (NIS-9)

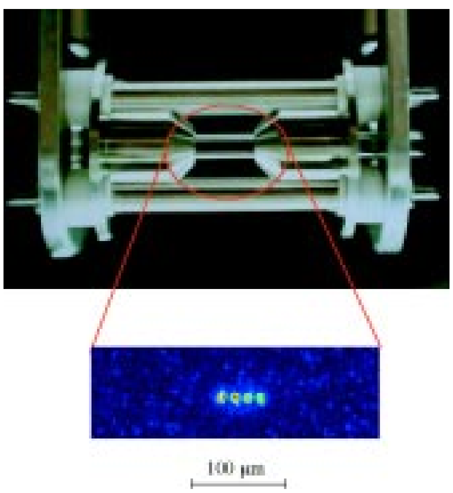

***Fig. 1** A string of four calcium ions localized by laser cooling in the ion trap. The trapping region is about 1-cm long by 1.8-mm high. The image is formed by the ion fluorescence in the 397-nm cooling laser beam.*

The representation of information by classical physical quantities such as the voltage levels in a microprocessor is familiar to everyone. But over the past decade, quantum information science has been developed to describe binary information in the form of two-state quantum systems, such as photon polarization states. (A single bit of information in this form has come to be known as a “qubit.”)

With two or more qubits it becomes possible to consider quantum logical-“gate” operations in which a controlled interaction between qubits produces a (coherent) change in the state of one qubit that is contingent upon the state of another. These gate operations are the building blocks of a quantum computer. In principle, a quantum computer is a much more powerful device than any existing or future classical computer because the superposition principle allows an extraordinarily large number of computations to be performed simultaneously. In 1994 it was shown that this “quantum parallelism,” which has no counterpart in conventional computation, could be used to efficiently find the prime factors of composite integers.[1] Integer factorization and related problems that are computationally intractable with conventional computers are the basis for the security of modern public-key cryptosystems. However, a quantum computer running at desktop personal computer speeds could break the keys of these cryptosystems in only seconds (as opposed to the months or years required with conventional computers).[2] This single result has turned quantum computation from a strictly academic exercise into a subject whose practical feasibility must be urgently determined.

The architecture of a quantum computer is conceptually very similar to a conventional computer: multiqubit, or “multibit,” registers are used to input data; the contents of the registers undergo logical-gate operations to effect the desired computation under the control of an algorithm; and, finally, a result must be read out as the contents of a register. The principal obstacles to constructing a practical quantum computer are (1) the difficulty of engineering the quantum states required; (2) the phenomenon of “decoherence,” which is the propensity for these quantum states to lose their coherence properties through interactions with the environment; and (3) the quantum measurements required to read out the result of a quantum computation. The first proposals for practical quantum-computation hardware, based on various exotic technologies, suffered from one or more of these problems. However, in 1994 it was proposed[3] that the basic logical-gate operations of quantum computation could be experimentally implemented with laser manipulations of cold, trapped ions: a qubit would comprise the ground (S) state (representing binary 0) and a suitably chosen metastable excited state (to represent binary 1) of an ion isolated from the environment by the electromagnetic fields of a linear radio-frequency quadrupole (RFQ) ion trap. Figure 1 shows schematically how the constituent parts of an ion trap quantum computer come together.

The principal components of this technology are already well developed for frequency-standard and high-precision spectroscopy work. Existing experimental data suggest that adequate coherence times are achievable, and a read-out method based on so-called “quantum jumps” has already been demonstrated with single trapped ions. We are developing an ion-trap quantum computer experiment using calcium ions, with the ultimate objective of performing multiple gate operations on a register of several qubits (and possibly small computations) to determine the potential and physical limitations of this technology.[4]

The heart of our experiment is a linear RFQ ion trap with cylindrical geometry in which strong radial confinement is provided by radio-frequency potentials applied to four “rod” electrodes, and axial confinement is produced by a harmonic electrostatic potential applied by two “end caps” (Fig. 1). After laser cooling on the 397-nm transition from the ground state (S) to the excited state (P), several calcium ions will become localized along the ion trap’s axis because their recoil energy (from photon emission) is less than the spacing of the ions’ quantum vibrational energy levels in the axial confining potential. Although localized to distances much smaller than the wavelength of the cooling radiation, the ions nevertheless undergo small amplitude oscillations, and the lowest frequency mode is the axial center of mass (CM) motion in which all the ions oscillate in phase along the trap axis. The frequency of this mode, whose quantum states will provide a computational “bus,” is set by the axial potential. The inter-ion spacing is determined by the equilibrium between this axial potential, which tends to push the ions together, and the ions’ mutual Coulomb repulsion. For example, with a 200-kHz axial CM frequency, the inter-ion spacing is on the order of 20 μm.

The first excited state of a calcium ion has a long radiative lifetime (~1 second), so the transition from this level (D) to the ground state has such a narrow width that it develops upper and lower sidebands separated from the central frequency by the CM frequency. With a laser that has a suitably narrow linewidth and is tuned to the lower sideband, an additional stage of laser cooling is used to prepare the "bus" qubit (CM vibrational mode) in its lowest quantum state ("sideband cooling"). On completion of this stage, the quantum computer is prepared with all qubits in the "zero" state, ready for quantum computation (see Fig. 2).

The narrow-linewidth laser tuned to the S-D transition is the essential tool for changing the contents of the quantum register of ions and performing quantum logical-gate operations. By directing this laser at an individual ion for a prescribed time, we will be able to coherently drive the ion's quantum state between the two qubit levels that the ion represents. An arbitrary logical operation can be constructed from a small set of elementary quantum gates, such as the so-called "controlled-NOT" operation, in which the state of one qubit is flipped if a second qubit is in the "1" state but left unchanged if the second qubit is in the "0" state. This gate operation can be effected with five laser operations using quantum states of the ion's CM motion as a computational bus to convey quantum information from one ion to the other. The result of the quantum computation can be read out by turning on the S-P laser. An ion in the "0" state will fluoresce, whereas an ion in the "1" state will remain dark. So, by observing which ions fluoresce and which are dark, a value can be obtained.

To date, we have succeeded in laser-cooling calcium ions into crystalline strings in our ion trap, which will be used as a quantum register. We used a charge-coupled device (CCD) camera to image ion strings of various lengths (see Fig. 1).

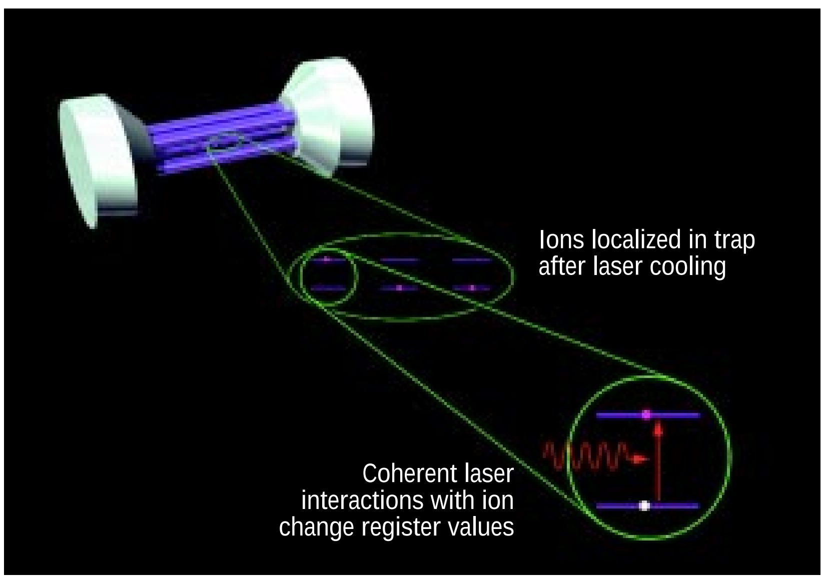

Fig. 2 A schematic representation of an ion trap quantum computer. Within the cylindrical RFQ ion trap, ions are radially confined by radio-frequency potentials applied to the four rod electrodes and axially confined by a harmonic electrostatic potential applied to the end caps. After a first stage of laser cooling, ions become localized along trap's axis. A second stage of laser cooling cools the ions to their lowest quantum states. The quantum computer is then ready for computation.

In addition, we have developed an optical system that can direct the computational laser beam with low-crosstalk to individual ions and rapidly switch the beam from ion to ion as required for quantum computational operations. We have also studied the intrinsic computational potential of ion-trap quantum computers. By taking into account the relevant decoherence mechanisms, we have found that on the order of one million gate operations could be performed on registers of 50 or so ions.[5] This is a tremendous amount of quantum computation relative to the current state of the art: one logic operation on two qubits. We have also performed a theoretical study of the mechanisms causing ion heating, which limit the amount of computation possible in an ion trap system, and we have determined how the heating rate depends on critical parameters such as the trap dimensions and frequencies. Because a quantum computer can create an arbitrary quantum state using quantum logic operations, this computational capacity opens up a wide variety of quantum-mechanics experiments in domains that are today inaccessible. We expect therefore that ion-trap quantum computers will allow us to explore quantum computation and the foundations of quantum mechanics.

References

[1] P. W. Shor, "Algorithms for Quantum Computation: Discrete Logarithms and Factoring," 35th Annual Symposium on the Foundations of Computer Science (Santa Fe, New Mexico, 1994), *Proceedings of the 35th Annual Symposium on the Foundations of Computer Science*, S. Goldwasser, Ed. (IEEE Computer Society Press, Los Alamitos, California, 1994) p. 124–134.

[2] R. J. Hughes, "Crytography, Quantum Computation, and Trapped Ions," *Philosophical Transactions of the Royal Society of London A* 356, 1853 (1998).

[3] J. I. Cirac and P. Zoller, "Quantum Computation with Cold, Trapped Ions," *Physics Review Letters* 74, 4094 (1995).

[4] R. J. Hughes, *et al.*, "The Los Alamos Trapped Ion Quantum Computer Experiment," *Fortschritte der Physik* 46, 329 (1998).

[5] R. J. Hughes, *et al.*, "Decoherence Bounds on Quantum Computation with Trapped Ions," *Physical Review Letters* 77, 3240 (1996).