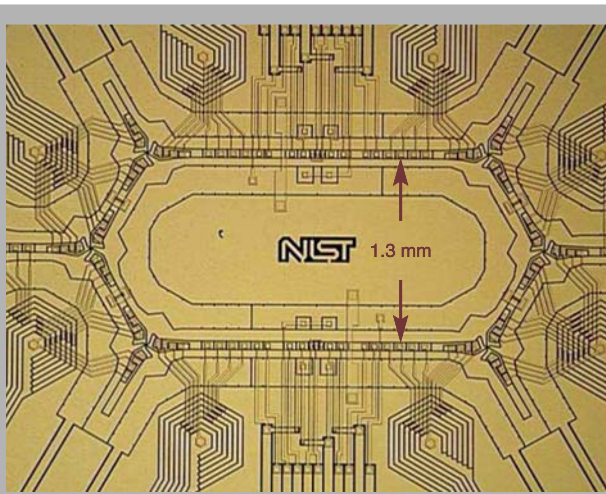
Abstract: The use of trapped atomic ions in the field of quantum information processing is briefly reviewed. We summarize the basic mechanisms required for logic gates and the use of the gates in demonstrating simple algorithms. We discuss the potential of trapped ions to reach fault-tolerant error levels in a large-scale system, and highlight some of the problems that will be faced in achieving this goal. Possible near-term applications in applied and basic science, such as in metrology and quantum simulation, are briefly discussed.



Photograph of a "surface-electrode" trap composed of 150 zones and six "Y"-type junctions, where the ion qubits are suspended approximately 40 μm above the surface. By applying time varying potentials to the electrodes, ions in different locations can be brought together to implement logic gates with laser beams that are focused onto the ions. (Trap fabrication and photograph by Jason Amini, NIST)

Quantum information processing and metrology with trapped ions

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Received: 19 August 2010, Accepted: 18 September 2010
Published online: 25 January 2011

Key words: coherent quantum control; quantum information processing; quantum state control; trapped ions

1. Introduction

Following Shor's introduction of a quantum-mechanics-based algorithm for efficient number factoring [1] and its recognized potential practical applications, there was a dramatic increase of activity in the field of quantum information science. The possible realization of general-purpose quantum information processing (QIP) is now explored in many settings, including condensed-matter, atomic, and optical systems. Trapped atomic ions have proven to be a useful system, in which to study the required elements [2] for such a device. Ions are attractive, in part, because quantum bits or "qubits" based on their internal states have very long coherence times, in some cases exceeding ten minutes [3,4].

In addition, due to their mutual Coulomb repulsion, trapped ions naturally form into arrays of spatially separated qubits. With the use of focused laser beams, this enables selective qubit addressing, coherent manipulations, and high-fidelity qubit-state readout with state-dependent

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laser scattering [5,6]. With these tools, simple algorithms have been demonstrated [6]. However, current operation fidelities are significantly below those required for fault tolerance (error probability per gate $< 10^{-4}$), and efforts towards scaling to a large system are only beginning. Solving these problems will involve significant technical challenges, but straightforward solutions are being explored. In the meantime, some of the basic ideas of QIP are starting to be applied to metrology and quantum simulation. Also, quantum communication systems that utilize trapped ions will likely soon be implemented, but for this topic we refer to other reviews [7–9].

This article briefly summarizes the ideas behind QIP with trapped ions, and will attempt to give an idea of the state of the art. We summarize current capabilities, limitations, and topics for future consideration. Comprehensive treatments including technical details are given elsewhere [6–17] (see also the Special Issue on Modern Applications of Trapped Ions in J. Phys. B **42**, 2009). Many experimental research groups throughout the world are now working on various aspects of trapped-ion QIP; currently, the list includes groups at Duke University, ETH Zürich, Garching (MPQ), Georgia Tech, Griffiths University, Imperial College, Innsbruck University, Lincoln Laboratories, Mainz University, MIT, National University of Singapore, NIST (USA), NPL (UK), Osaka University, Oxford University, PTB and University of Hannover (Germany), Saarbrücken, Sandia National Laboratory (USA), Siegen University, Simon Fraser University, Sussex University, University of Aarhus, University of California Berkeley, University of Maryland, Université de Paris, University of Sydney, University of Ulm, University of Washington, Wabash College, and the Weizmann Institute.

2. Background

At the 1994 International Conference on Atomic Physics in Boulder, Colorado, Artur Ekert presented a lecture outlining the ideas of quantum computation [18], a subject new to most of the audience. This inspired Ignacio Cirac and Peter Zoller, who attended that conference, to propose a basic layout for a quantum computer utilizing trapped ions in their seminal paper of the following year [5]. In this scheme (Fig. 1), ions are strongly coupled through their mutual Coulomb interaction, and their combined motion is best described by normal modes [11,19]. In this sense, they act like an artificially constructed molecule. In general, the motion of each mode is shared amongst all the ions and can act as a data bus for transferring information between ions. A qubit rotation on an individual ion is implemented by applying a focused laser beam or beams onto that ion. A logic gate between two selected ions is implemented by first freezing out the motion of the ions (putting all modes in the ground state) with laser cooling. Referring to Fig. 1, laser beam 1 then transfers the internal qubit state of one ion onto the qubit formed from the ground and first

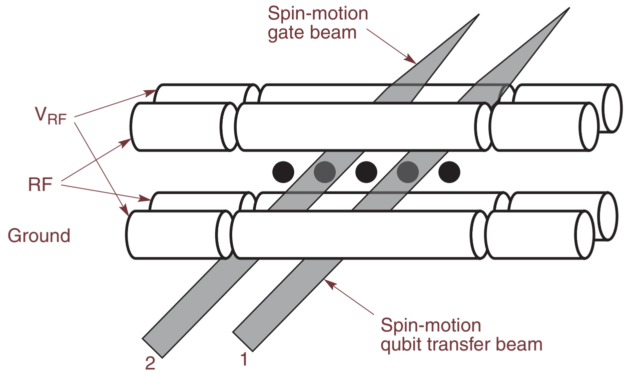

Figure 1 (online color at www.lphys.org) Scheme for trapped-ion quantum computation proposed by Cirac and Zoller [5]. Quadrupolar electrodes are configured to produce a linear array of trapped ion qubits (filled black circles). Two diagonally opposite rods support an RF potential to produce a ponderomotive pseudopotential transverse to the trap's (horizontal) axis. Static potentials applied to the end electrode segments confine ions along the axis. Ideally, all motional modes are laser-cooled to the ground state before logic operations are implemented. The quantized modes of motion can be used as a data bus to share information between ion qubits that are selected by focused laser beams (see text)

excited state of a particular mode of motion. Laser beam 2 then performs a logic gate between the (shared) motion qubit and a second selected ion. Finally, the initial transfer step on the first ion is reversed, restoring the motion to the ground state. Overall, these operations implement a logic gate between the internal qubit states of the two selected ions. The logic gate between the motion qubit and internal-state qubit was demonstrated in [20] and the complete Cirac/Zoller gate between two selected qubits was first demonstrated in [21]. More streamlined versions of such deterministic multi-qubit logic gates have now been realized (see below), but they all employ the basic idea that the ions' collective motion provides the data bus for sharing quantum information between qubits.

3. Requirements for trapped-ion QIP

3.1. Traps

The most common type of trap for QIP as been the linear radio frequency (RF) quadrupole Paul trap, shown schematically in Fig. 1 [22–25]. This trap is basically an RF quadrupole mass analyzer with the addition of axial confinement provided by appropriate static potentials. To a first approximation, it can be viewed as providing a 3-D harmonic well with the strength of the well along the trap axis made relatively weak compared to the transverse directions. In this case, at low temperatures the ions arrange

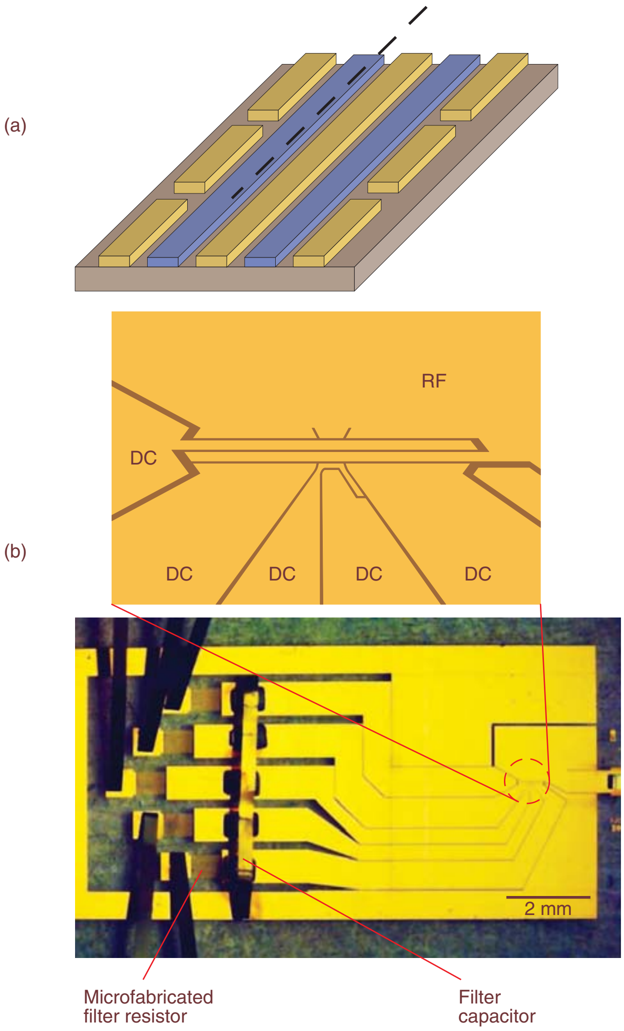

Figure 2 (online color at www.lphys.org) Example of a surface-electrode trap. (a) – the electrode geometry shown in Fig. 1 can be transformed so that all electrodes lie in a plane, as shown schematically. The axis of the trap lies above the plane, as indicated by the dashed line. (b) – photographs of a single-zone surface-electrode trap, in which gold electrodes are deposited on a quartz substrate with the use of lithographic techniques (from [26]). Advantages of such a geometry include the ability to fabricate many traps in the same number of steps required to fabricate a single trap, and the precise electrode alignment provided by lithography

into a linear array, where the ion spacings are determined by a balance between the external confining potential and the ions' mutual Coulomb repulsion. Typical ion spacings range from approximately 2 to 10 μm. A single trapped ion's transverse oscillation frequencies are given by

$$\omega_{x,y} \simeq \frac{qV_{RF}}{\sqrt{2}\Omega_{RF} m R^2}\,, \qquad (1)$$

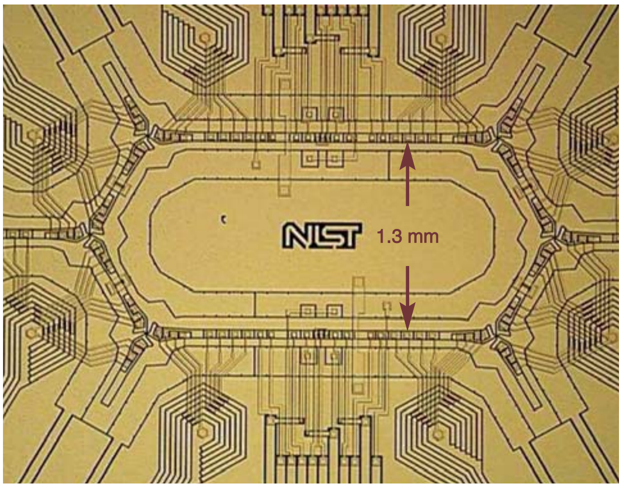

Figure 3 (online color at www.lphys.org) Surface-electrode trap composed of 150 zones and six "Y"-type junctions [33]. Such a geometry is in principle scalable to an arbitrarily large number of zones. The trap incorporates the use of a basic component design library that can be quickly assembled to form structures designed for a particular experiment or function

where q and m are the ion's charge and mass, V_{RF} and Ω_{RF} are the RF (peak) potential and (angular) frequency, and R is the distance from the trap axis to the nearest electrode surface. For $V_{RF} = 150$ V, $\Omega_{RF}/2\pi = 50$ MHz, and $R = 150$ μm, $^{25}Mg_{+}$ ions have a transverse oscillation frequency of $\omega_{x,y}/2\pi \simeq 12.3$ MHz. Since two-qubit gate speeds scale with the motional frequencies (limited by $\omega_{x,y}$ if we maintain a linear ion array), small traps are desired. For simplicity of construction, the three-dimensional trap electrode structure shown in Fig. 1 can be transformed into a planar electrode structure where the ions are trapped above the plane, as indicated in Fig. 2. Various types of "surface-electrode" traps are being implemented in several labs [26–34]. Fig. 3 shows another surface-electrode trap that has 150 zones.

Penning traps are also being considered for quantum information processing. Here the qubits might be electrons [35,36] or ions in a surface-electrode geometry [37,38]. Initial demonstrations of ion transport have now been made [39].

3.2. State-sensitive qubit detection

In trapped-ion (and neutral atom) QIP experiments, qubits are formed from two internal atomic states. For state detection, it is very useful to have one of these states form a "cycling" transition with a particular optically excited state. The cycling transition is chosen to scatter many photons before optical pumping relaxation occurs, while scattering from the other qubit state is minimal. Even if only a small fraction of the photons are detected, overall state-detection efficiency can be quite high [40–43] and near-unity detection efficiency is possible. With the use of this technique, detection fidelities in trapped-ion QIP experiments have now reached 0.9999 [44,45].

3.3. Qubit logic gates

For brevity, we consider only one of the simplest forms of coupling (and the one employed in the Cirac/Zoller scheme [5]). More comprehensive discussions of the various couplings and multi-qubit gates are given elsewhere [6,10–16]. Consider a single trapped ion that has an optical transition (frequency ω_0) corresponding to a single-electron electric-dipole interaction. The ion is illuminated by a laser beam of frequency ω_L propagating along the z axis. The resulting interaction is described by the Hamiltonian

$$H_I = -e\,\mathbf{r}\hat{\boldsymbol{\epsilon}}\,E_0 \cos\big(kz - \omega_L t + \phi\big) = \tag{2}$$

$$= \hbar\Omega\big(S_+ + S_-\big)\Big\{\exp\big[i(kz - \omega_L t + \phi)\big] +$$

$$+ \exp\big[-i(kz - \omega_L t + \phi)\big]\Big\},$$

where $\mathbf{r}$ is the electron coordinate relative to the ion's core, e is the electron charge, $\hat{\boldsymbol{\epsilon}}$, E_0, and k are respectively the laser beam's electric field polarization, amplitude, and wave vector, z is the ion's position, ϕ is the electric field phase at the mean position of the ion, $S_+(=|e\rangle\langle g|)$ and $S_-(=|g\rangle\langle e|)$ are the internal-state raising and lowering operators, and $\Omega \equiv -\langle e|\mathbf{r}\cdot\hat{\boldsymbol{\epsilon}}|g\rangle\, eE_0/2\hbar$, with $|g\rangle$ and $|e\rangle$ denoting the ions ground and optically excited states. It is convenient to refer to the qubit states as spin states in analogy with the two states of a spin-1/2 particle; therefore, we will make the identifications $|g\rangle \leftrightarrow |\downarrow\rangle$ and $|e\rangle \leftrightarrow |\uparrow\rangle$. Thus, single-qubit "gates" correspond to rotations of the spin states on the Bloch sphere.

For the two-qubit logic gate scheme outlined above, we need to efficiently couple an ion's internal states to its motion. Laser beams provide a good means for this because the gradient of the laser beam's field, which is sensed by the ion's motion, has a length scale given by the laser wavelength λ. To treat a single trapped ion's motion quantum-mechanically, in Eq. (2) we write $z = Z + z_0(a + a^\dagger)$, where Z is the ion's mean position, $z_0 = \sqrt{\hbar/2m\omega_z}$ is the spread of the ground-state wavefunction, with m and ω_z the ion's mass and oscillation frequency, and a and $a^\dagger$ are the lowering and raising operators for the ion motion. If we go to the interaction pictures for the ion's internal states ($S_+ \to S_+\exp(i\omega_0 t)$) and motion states ($a^\dagger \to a^\dagger\exp(i\omega_z t)$) and assume $\omega_L \simeq \omega_0$, then neglecting terms that oscillate near $2\omega_0$ (rotating wave approximation), Eq. (2) becomes

$$H_I \simeq \tag{3}$$

$$\simeq \hbar\Omega S_+ \exp\Big\{i\big[kz - (\omega_L - \omega_0)t + \phi\big]\Big\} + H.C. \simeq$$

$$\simeq \hbar\Omega S_+ \exp\Big\{-i\big[(\omega_L - \omega_0)t - \phi\big]\Big\}\times$$

$$\times\Big\{1 + i\eta\big[a\exp(-i\omega_z t) + a^\dagger\exp(i\omega_z t)\big]\Big\} + H.C.,$$

where $H.C.$ stands for Hermitian conjugate and $\eta \equiv kz_0 = 2\pi z_0/\lambda$ is the Lamb-Dicke parameter, which we assume in the second part of the expression to be much less than unity. For an ion of mass 40 u (e.g., $^{40}Ca^+$) in a well with $\omega_z/2\pi = 3$ MHz and $\lambda = 729$ nm, we find $z_0 = 6.5$ nm and $\eta = 0.056$.

For $\omega_L = \omega_0$ and $\eta\Omega \ll \omega_z$, to a good approximation Eq. (3) becomes

$$H_I \simeq \hbar\Omega\exp(i\phi)S_+ + H.C..$$

This is the Hamiltonian for "carrier" transitions or single-qubit rotations about a vector in the $x - y$ plane of the Bloch sphere. (Rotations about the z axis can be implemented with two carrier "π" transitions ($\Omega t = \pi/2$) of different phase or AC Stark shifts from nonresonant beams [46–48]). If we assume $\omega_L = \omega_0 - \omega_z$ (laser tuned to the "red sideband"), the resonant term in Eq. (3) is

$$H_I \simeq \hbar\eta\Omega\exp\big[i(\phi + \pi/2)\big]S_+ a + H.C.,$$

which is the Jaynes-Cummings Hamiltonian from cavity QED [49] that exchanges quanta between the motion and spin. This interaction and the "blue sideband" interaction (for $\omega_L = \omega_0 + \omega_z$) provide a simple form of coupling between internal states and motion. When addressing a single ion amongst multiple ions confined in the same well, the qualitative features are as described above, but the motion corresponds to a particular motional mode that is selected by tuning the laser frequency ω_L appropriately [6,10-16]. As example applications of these interactions, the red-sideband interaction (applied for a duration $t = \pi/(2\eta\Omega)$) provides the internal-state qubit to motionstate transfer $(\alpha|\downarrow\rangle + \beta|\uparrow\rangle)|0\rangle \to |\downarrow\rangle(\alpha|0\rangle + \beta|1\rangle)$ corresponding to the first step in the Cirac/Zoller scheme, where $|0\rangle$ and $|1\rangle$ are the ground and first excited Fock states for the selected motional mode. The subsequent logic gate between the motion qubit and the internal-state qubit of the second selected ion is accomplished by implementing a 2π rotation ($\eta\Omega t = \pi$) on a $|\uparrow\rangle|1\rangle \leftrightarrow |aux\rangle|0\rangle$ transition, where $|aux\rangle$ is a third "auxiliary" internal state. This operation implements a $\exp(i\pi) = -1$ phase factor on the $|\uparrow\rangle|1\rangle$ component of the wavefunction thereby implementing a "π-phase gate" between the internal-state and motional-state qubits. The gate is then completed by returning the information in the motion to the first qubit with a reversing red sideband pulse.

Single-photon optical transitions have been used with great success, particularly by the Innsbruck group, for carrying out QIP operations on Ca^+ ions. For qubits based on hyperfine or Zeeman ground state sublevels, transitions can be driven by coherent two-photon stimulated-Raman transitions [11,20] with the use of two laser beams of frequency ω_a and ω_b and phases ϕ_a and ϕ_b at the mean position of the ion. The above expressions hold with the replacements $k \rightarrow k_b - k_a$, $\omega_L \rightarrow \omega_b - \omega_a$, and $\phi \rightarrow \phi_b - \phi_a$.

Somewhat more streamlined gates can be realized, in which multiple ions are addressed simultaneously by the same laser beam(s) [50–54]. These "geometric" gates can be viewed as arising from quantum phases that are acquired when a mode of the ions motion is displaced in phase space around a closed path; the phases accumulated are proportional to the enclosed area in phase space. The gates can be viewed in a common framework, the main difference being whether or not the forces act on the spin states in the z basis (eigenstates $|\downarrow\rangle$ and $|\uparrow\rangle$) or in the x, y basis (eigenstates of the form

$$\frac{1}{\sqrt{2}}\Big(|\downarrow\rangle + \exp(i\xi)|\uparrow\rangle\Big), \quad \frac{1}{\sqrt{2}}\Big(|\downarrow\rangle - \exp(i\xi)|\uparrow\rangle\Big),$$

[14]. The state-dependent forces required for the displacements are optical-dipole forces, which arise from spatial gradients of AC Stark shifts. Since the AC Stark shifts are usually different for the two qubit states, geometric phases lead to entangling gates. Two-qubit phase gates have been implemented in the z-basis [55,56] and in the $x - y$ basis [47,57–59]. In the Innsbruck experiment of [58] a state with fidelity of 0.993 with respect to a Bell state was produced, setting a standard for all QIP experiments.

Qubits are typically composed of states separated by optical energies or two states in the electronic ground state hyperfine/Zeeman manifold [6,11]. Optical qubits have the advantage that single-photon transitions can implement gate operations, but have the complication that radiative lifetimes (e.g., ~ 1 s in Ca^+) limit long-term memory, and very good laser spectral purity is required. Hyperfine/Zeeman qubits have extremely long radiative lifetimes, implying potentially very good memory. Gates can be performed with coherent two-photon stimulated-Raman transitions, which require two laser beams having a frequency difference equal to the qubit frequency. These beams can typically be generated with a single beam of modest spectral purity and a RF/microwave frequency modulator to provide the required stable frequency difference between the beams. However, hyperfine/Zeeman transitions driven by stimulated-Raman transitions have the disadvantage of spontaneous emission decoherence, which can be reduced only by the use of high laser power and large detuning from allowed transitions [60–62].

The use of single- and multi-qubit gates has enabled the demonstration of several QIP algorithms, most of which are deterministic. These include the Deutsch-Jozsa algorithm [63], dense coding [64], qubit teleportation [65–67], quantum error correction [68], entanglement-assisted detection [69], the quantum Fourier transform [70], Grover's search algorithm [71], entangled state purification [72], entanglement swapping [73], the Toffoli gate [74], production of W states [75,76] and "spin-cat" states [77], logic gates with decoherence-free-subspace (DFS) qubits [78,79], random number certification through Bell's theorem [80], and realization of programable arbitrary two-qubit unitary operations [81]. A technique to generate arbitrary motional state superpositions [82] was demonstrated in [83]. Although the basic features of these algorithms were observed, in all cases, additional effort will be required to reach fault-tolerant error levels.

4. Towards applications

Although strong initial motivation for the field of QIP has been a factoring machine [1] and a device for performing unstructured searches [84,85], it is very likely that other applications will emerge first.

4.1. Spectroscopy and metrology

Some potential applications are motivated by the idea of using entangled states to improve spectroscopic sensitivity [86–91], and demonstrations of this increased sensitivity have been made [77,89,90,92,93]. These demonstrations were made in the limit that noise was dominated by "projection noise", the fundamental noise arising from the fluctuations in which state the system is projected into upon measurement [94,95]. However, if significant additional phase noise is present in either the atoms themselves [96], or the interrogating radiation [11,97], the gain from entanglement can be lost. This puts a premium on finding probe oscillators that are stable enough that the projection noise dominates for the desired probe duration.

Another interesting use of entanglement in spectroscopy was demonstrated in [90] and [98]. Here, a precise measurement of the quadrupole moment of $^{40}Ca^+$ was made by performing spectroscopy on an entangled state of two ions, in which the spectroscopy yielded the quadrupole moment, but was immune to perturbations from ambient fluctuating magnetic fields.

Some ions of spectroscopic interest may be difficult to detect because they either don't have a cycling transition, or lack a cycling transition at a convenient wavelength. In some cases, this limitation can be overcome by simultaneously storing the ion(s) of spectroscopic interest with a "logic" ion or ions whose states can be more easily detected. One technique is to detect the laser-induced heating of the spectroscopy ion by its effect on the logic ion's fluorescence [99]. Sensitivity can be increased with use of the internal-to-motion-state-transfer process of the Cirac/Zoller gate described above. Here, it is possible to transfer the states of interest in the spectroscopy ion to a mode of the ions' coupled motion and then transfer this information to the logic ion, which is subsequently measured [100,101]. This technique has been used to detect optical transitions in $^{27}Al^+$ ions by transferring the relevant state amplitudes to a $^9Be^+$ logic ion, which is then measured

[101]. It is now used routinely in an accurate optical clock based on $^{27}Al^+$ [102,103] and might also be extended to molecular ions [104].

The information transfer and readout process employed in [101,102] typically had a fidelity of about 0.85, limited by errors caused by the ions' thermal motion in modes not used for information transfer (so-called "Debye-Waller" factors [11]). However, this detection process is a quantum-nondemolition (QND) type of measurement in that it doesn't disturb the detected populations of the $^{27}Al^+$ ion. It can therefore be repeated to gain better information on the $^{27}Al^+$ ion's state. By use of real-time Bayesian analysis on successive detection cycles, the readout fidelity was improved from 0.85 to 0.9994 [105]. This experiment shares similarities with those of the Paris cavity-QED group, where successive atoms are used to perform QND measurements of the field in a cavity [106]. In [105], the same atom ($^9Be^+$) is reset after each detection cycle and used again. Also, because the detection was accomplished in real time, the procedure was adaptive, requiring on each run a variable number of detection cycles to reach a certain measurement fidelity.

4.2. Tests of quantum correlations and entanglement

With the continued interest in testing Einstein-Podolsky-Rosen correlations [107] and Bell-type inequalities [108], trapped ions have been able to probe these fundamental aspects of quantum mechanics in some new regimes. By producing entangled pairs of ions, Bell's inequalities of the CHSH form [109] have been measured. Since the pairs are produced deterministically, correlation measurements can be performed in every experiment, as opposed to, for example, photon-based experiments where not every pair produced results in a measurement. This feature enabled experiments that showed a violation of Bell's inequalities and overcame the "detection loophole" [110,111]. These experiments also provided the first such tests on massive particles that employed a complete set of correlation measurements. Some experiments have explored other aspects of entanglement such as size, by production of an 8-qubit W-state [75] and a 6-qubit "spin-cat" state [77]. Entanglement longevity has been explored with the production of decoherence-free subspace Bell states [78,111] with coherence lifetimes of 7 s in [112] and 34 s in [75]. In [113], Bell's inequalities were violated for entangled states between an ion and a photon. Distance scales for entanglement of massive qubits have been explored by producing entangled spins over length scales from sub-millimeter [6] to ~ 1 m [17,114]. The highest fidelity (0.993) of deterministic entanglement in any system has been reported in [58]. A recent verification of contextuality in quantum mechanics has been made in [48]. By transferring entanglement from spin states to the motion of ion pairs held in different locations, entanglement has been created between separated mechanical oscillators [115].

4.3. Quantum simulation

In the early 1980's, Richard Feynman proposed that one quantum system might be used to efficiently simulate the dynamics of other quantum systems of interest [116,117]. This is now a highly anticipated application of QIP, and will likely occur well before useful factorization is performed. Of course, the universality of a large-scale quantum computer will allow it to simulate any quantum system of interest. However, before such a device is built, it may be possible to use the built-in available interactions in a quantum processor to simulate certain classes of physical problems. For trapped ions, it has been possible to use the interactions employed in the various gates to simulate other systems of interest such as nonlinear optical systems [118] or the motional quantum dynamics as in an electron's Zitterbewegung [119] or the properties of a "quantum walk" [120,121].

Currently, there is considerable interest in, and efforts are underway in several laboratories to use QIP interactions to simulate various dynamics including those of condensed matter systems. Some of the basic ideas for how this might work with ions have been outlined in [122–133]. Here, one can take advantage of the fact that logic gates between ions i and j invoke a spin-spin like interaction of the form $\sigma_{\hat{u}i}\sigma_{\hat{u}j}$, where $\hat{u} \in \{\hat{x}, \hat{y}, \hat{z}\}$. Spin rotations about a direction $\hat{u}$ act like magnetic fields along $\hat{u}$. In [59,134–136], these basic interactions have been implemented on a few ions and efforts are underway to scale to much larger numbers. One interesting outcome is the study quantum phase transitions by varying the relative strengths of the (simulated) spin-spin and magnetic field interactions. Under appropriate conditions, the effects of spin "frustration" are now becoming apparent [135,136].

5. Future

5.1. Scaling to many ion qubits

Very large crystalline arrays of ions have been observed in traps [137–139]. These arrays have recently been used to demonstrate strong coupling with photons [140] and as a model quantum memory for studying the error-suppressing capabilities of dynamical-decoupling pulse sequences [141,142]. In large crystals, the ions are relatively well separated implying that individual qubit addressing can be accomplished with appropriately focused and steered laser beams. However, for almost all of the gates that have been demonstrated, information is transferred through one mode of motion. The modes generally have different frequencies and therefore can be spectrally isolated; but as the numbers of ions increase, the mode spectrum becomes more dense and it becomes difficult to isolate the mode of interest, or the gate speeds must become very slow to maintain this isolation.

To mitigate this problem and to ease the task of single-qubit addressing by laser beam focussing, smaller groups of ions could be distributed over arrays of individual trap zones. In each zone the number of ions would be kept relatively small. Single qubit addressing could be accomplished by first spatially separating the ion(s) of interest [115,143]. One way to transfer information throughout the array would be to physically move the ions between zones [11,27,33,39,81,115,143–152]. Alternatively, the ions could be coupled through common electrodes [153,154] or optical cavities [155,156]. Another way to transfer information would be to first create entangled pairs where the individual qubits in each pair are strategically distributed to different locations in the array. Subsequently, information is transferred and gates are performed between separated qubits by teleporting [8,17,157–161]. The initial entangled-pair distribution could be created by physically transporting the ions or through projective entanglement as demonstrated in [17,114]. In these latter experiments, each ion is entangled with a second quantum system, its emitted photon, after which a projective measurement of the the photons in an entangled basis projects the atoms into the desired Bell state. A related idea would be to transfer quantum information between ions and other quantum systems [11,150,162,163] that might have advantages for certain tasks.

Multi-zone arrays are currently being explored in several laboratories, as summarized in [164]. Transport of ions in linear arrays has been studied in [66,81,115,143,144,149,152,165] and methods to deterministically order ions in [115,150,166]. For efficient computation, we want to perform multi-qubit gates between ions selected from arbitrary locations in the processor. This can be accomplished with 2-D arrays [33,39,151,167] as for example shown in Fig. 4, or with the ability to swap ion positions in a linear array [166]. It will be important to separate and move ions with minimal increase in kinetic energy while preserving coherence [66,149,151].

Currently, durations required for detection through state-dependent fluorescence are relatively long ($\sim 200\ \mu$s or longer). Most experiments use relatively large multi-element optics; therefore development of simpler, high-efficiency detection is important. A disadvantage of current systems is that the field of view is rather limited, and because of the large size of the optics it becomes difficult to detect ions in zones separated by distances between approximately 0.1 and 50 mm. Therefore several labs are investigating the use of micro-optics for efficient multiplexed detection [168–172].

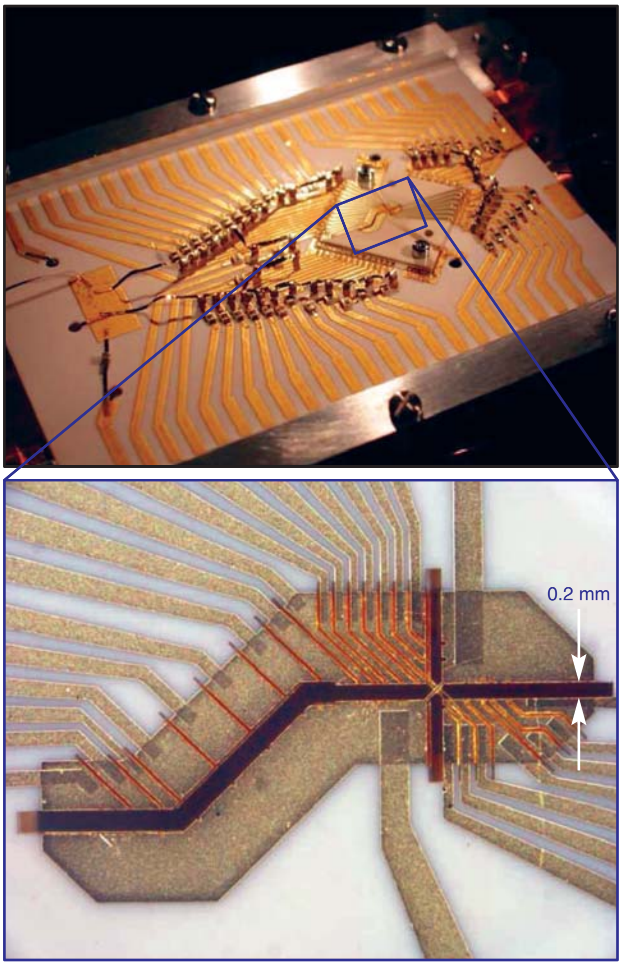

Figure 4 (online color at www.lphys.org) Photographs of a multi-zone trap that incorporates an “X” junction [151]. The trap is formed from two gold-coated alumina wafers similar to that described in [149]. An array of interconnected trap zones that includes junctions will enable two ions selected from arbitrary locations in the array to be transported to a common zone with time dependent potentials applied to the segmented electrodes, in order to perform two-qubit logic gates

5.2. Uncontrolled electric fields

A ubiquitous problem that affects trapped-ion QIP is ion heating. For example, the fidelity of the Cirac/Zoller gate is significantly affected by absorption of a single quantum of motion during the gate, since the operations depend on the exact motional quantum state. Some types of gates are relatively insensitive to heating (as long as the Lamb-Dicke limit is maintained) [50–53,173], but at some point, it compromises all types of gates. Heating can be caused by thermal electronic noise. In free space, this noise is manifested as blackbody radiation, but for typical trapped-ion conditions, it can be described as coming from Johnson noise in any resistive elements associated with the trap electrodes [11,174,175]. It has typically been small enough not to cause significant errors. However as noted above, to increase gate speeds in QIP we want high motional frequencies, which can be obtained, in part, by using very small trap structures. Unfortunately, at smaller trap dimensions ($\ll 1$ mm), additional electric-field noise has been observed. Representative data compiled from several groups, expressed as electric-field noise spectral density at the position of the ions, are contained in [33,176,177]. Observed heating rates are anomalously high, typically orders of magnitude higher than predicted for thermal noise heating. A model that seems to approximately represent this anomalous heating assumes that electric field noise is due to randomly fluctuating potentials on patches located on the electrode surfaces, where the size of the patches is small compared to the electrode-ion spacing [178]. There is evidence from some groups that the noise may be due to surface contamination, because its strength depends in part on electrode cleaning and vacuum processing. Importantly, it has been observed that the heating drops more quickly with ambient temperature than would be expected for thermal electronic noise [29,30,179]. The anomalous heating appears to be caused by a thermally activated process and is dramatically reduced near liquid helium temperatures [29,30]. Of course, ion trappers hope to identify and eliminate the cause, but in the meantime, it may therefore be possible to suppress the heating by operating at low temperature.

Even if very low heating rates are achieved, it will likely be necessary to provide some sort of qubit cooling for lengthy computations. Since cooling implies dissipation, the qubits themselves can't be used as the cooling elements, due to decoherence. However, cooling can be performed "sympathetically" [3,180–187], where one ion or group of ions is used as a refrigerator to cool the qubit ions. In QIP, the refrigerator ions might be identical to the qubit ions [183,186], a different isotope [180,184,187], or an entirely different species [3,81,115,143,181,185]. Even with the use of sympathetic cooling, during a multi-qubit gate the cooling must be interrupted to avoid errors from fluctuations in the motion. (This restriction might be relaxed in certain circumstances where the change in ion temperature is slow compared to the gate dynamics [188].)

Typically, stray static electric fields are also present at the sites of the ions. The source of these fields might be electrode patch potentials or stray electric charge that deposits on nearby insulating surfaces. The charging might originate from electrons used to create ions by impact ionization or they might be created by photo-emission when the laser beams that manipulate the ions, or those that create ions via photo-ionization, strike the electrode surfaces [189]. These fields will generally push the ions away from the RF-field null point, leading to RF micromotion, which can lead to various deleterious effects. If these fields are constant they can be detected by various means (see e.g., [34,190]) and overcome by applying compensating fields.

5.3. Alternative logic gates

So far, most of the multi-qubit gates that have been demonstrated rely on addressing a single mode of motion. Their speed is limited in part by the requirement that the the pulse be not so short as to couple to other modes. Generally, this is aided by use of high mode frequencies, which implies very small traps, and thereby puts a premium on suppressing the anomalous heating (above). However, use of a single mode for multi-qubit gates is not a requirement [8,188,191,192]. For example, "push gates" [193–196], which could be implemented with quasi-static dipole forces, can be viewed as geometric phase gates in the limit of large detuning where all modes participate. Here, the same basic ideas for the gates apply, but by utilizing multiple modes the gate speeds can be increased and the number of ions in a given zone could be made substantially larger than when single-mode addressing is used [188]. For small numbers of ions, the use of multiple modes for gates has already been implemented [59,135,136,143] and efforts are currently underway to extend this to much larger numbers of modes [188].

In addition, most demonstrated gates have used CW lasers that are applied for a specified duration. But [59,135,136] demonstrate the implementation of multi-qubit gates with the use of pulse trains derived from a mode-locked laser. Important technical advantages of this technique include the relative simplicity of spanning a large frequency difference when driving stimulated-Raman transitions and the efficient generation of short wavelengths via nonlinear techniques without the need for build-up cavities, due to the high peak powers of the pulses. Extremely fast stimulated-Raman-transition single-bit rotations (π-pulse duration ≤ 50 ps) have been implemented between hyperfine levels in Yb^+ ions with very short pulses [197]. This points the way to multi-qubit gates whose duration is shorter than the period of the modes involved [188,191, 192].

Magnetic field gradients can be used to implement gates. If an array of ions is placed in a static magnetic field gradient, the individual ion qubit frequencies are position-dependent; therefore the qubits can be addressed for single-qubit gates without the need for the qubit excitation fields (microwave or optical) to be focussed onto the ions [11, 122,198–200]. In addition, under these conditions, sideband transitions and multi-qubit gates can be implemented with uniform RF fields. If the two qubit states have different magnetic moments, their confining wells are displaced relative to each other in a static gradient field; therefore, Franck-Condon-type overlap factors allow simultaneous change of spin and motional states [122,133,198,199,201]. This basic scheme has recently been realized with neutral atoms where the different spin states experience displaced optical lattice wells [202]. On the other hand, in a uniform static magnetic field, it should be possible to use inhomogeneous AC magnetic fields for sideband transitions and multi-qubit gates on hyperfine qubits [129,203,204], similar to Dehmelt's AC Stern-Gerlach effect for electrons [205,206]. The potential advantages of RF fields for gates include significantly reduced laser power requirements (low power lasers would suffice for Doppler cooling, optical pumping, state detection) and the absence of spontaneous emission decoherence [60–62] during the gates. However, the advantage of qubit addressing with focused laser beams would be

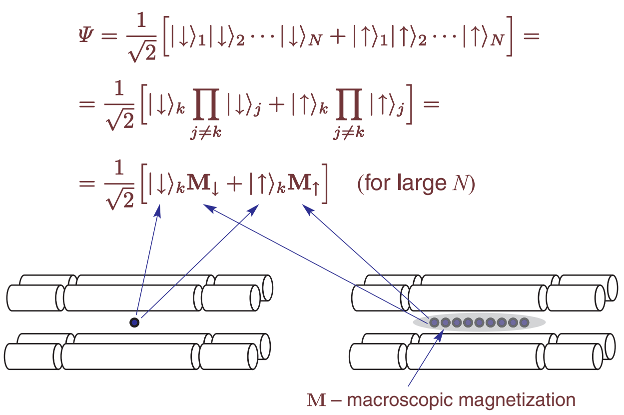

Figure 5 (online color at www.lphys.org) Experimental configuration that mimics the conditions of Schrödinger's cat [207]. From a large number of ions in the state Ψ, we select the k-th ion and transport it to a separate location (on the left) while the remaining ions are located in the right-hand trap zone. For large N, these remaining ions compose a large spin and associated macroscopic magnetic moment M. We associate the k-th ion with the single radioactive particle in Schrödinger's example; we associate the macroscopic magnetic moment pointing up or down with Schrödinger's cat being dead or alive

lost, and crosstalk between zones, particularly for single-qubit rotations, could be problematical (these effects could be mitigated by use of composite pulses [15] and proper shielding between zones). Of course, in the future, it may be that a combination of several of these strategies will be used for efficient, large-scale processing.

5.4. Lasers

A significant source of decoherence in many experiments stems from the laser beams that drive the transitions. For qubits based on optical transitions, errors can be due to the radiative lifetime of the excited state and laser phase fluctuations. For hyperfine qubits driven by two-photon stimulated-Raman transitions, a fundamental limit is caused by spontaneous emission from the weakly coupled optically excited states [60–62]. In practice, decoherence is often dominated by classical noise. Phase noise in the laser beams can be caused by phase noise in the lasers themselves and by fluctuations in beam path lengths. Intensity noise might be caused by power fluctuations, or fluctuations between the relative positions of the beams and the ions due to air currents or mechanical vibrations. Operation at shorter wavelengths can be especially troublesome because of poorer-quality optics, degradation of beam qualities when they are produced by nonlinear conversion, and inability to purify beam quality with mode cleaners such as single-mode fibers.

Laser beam switching is typically accomplished with RF-driven acousto-optic modulators, but in many cases the on-off ratio is not sufficient, due to scattering in the modulators. Moreover, the RF drive can lead to temperature-dependent index effects in the modulators that cause time-dependent beam steering and mode quality degradation. This becomes a particular problem in algorithms with intermediate measurements and logical branching, where the duty cycle of switching is generally not constant. In principle these classical fluctuations have straightforward solutions, such as better passive control and active feedback using power and position sensors, but may be difficult to implement in practice.

5.5. Fundamental tests

As trapped-ion experiments become more refined, we should be able to provide more stringent tests of certain quantum phenomena. For example, a long-sought goal is to perform a "loophole-free" test of Bell's inequalities. Following the recent successes of producing remote entanglement in ions with good memory qualities via photons in fibers [7–9,17,114], it should be possible to perform such a test. With anticipated technical improvements, QIP systems will become larger, more complex, and more entangled. This will press issues such as the measurement problem and fundamental sources of decoherence, and may enable the possibility of realizing situations like Schrödinger's cat [207]. As an example of this latter possibility, trapped-ion experiments [77,89,208] have been able to make small-N approximations to the state

$$\Psi = \frac{1}{\sqrt{2}}\Big[|\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N + |\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N\Big], \qquad (4)$$

where N is the number of ions. If these states can eventually be produced for very large N, it should be possible to realize a situation like that depicted in Fig. 5. Unless there might be some as-of-yet undetected mechanism that prevents the formation of large entangled superpositions [209], and if we can overcome the (admittedly formidable) technical challenges, we should therefore be able to realize analogs of Schrödinger's cat. Moreover, as is often the case, as the field progresses, new unanticipated fundamental phenomena will hopefully emerge.

Acknowledgements The trapped-ion work at NIST involves the contributions of many people; current and recent past group members include Jason Amini[1], Jim Bergquist, Sarah Bickman[2], Mike Biercuk[3], Brad Blakestad[4], John Bollinger, Ryan Bowler, Joe Britton, Kenton Brown, James Chou, Yves Colombe, Hua

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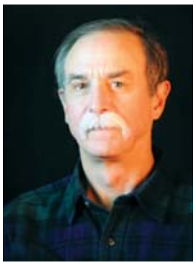

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