BUILDING BLOCKS FOR A SCALABLE QUANTUM INFORMATION PROCESSOR BASED ON TRAPPED IONS

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We describe the underlying concept and experimental demonstration of the basic building blocks of a scalable quantum information processor architecture using trapped ion-qubits. The trap structure is divided into many subregions. In each several ion-qubits can be trapped in complete isolation from all the other ion-qubits in the system. In a particular subregion, ion-qubits can either be stored as memory or subjected to individual rotations or multi-qubit gates. The ion-qubits are guided through the array by appropriately switching control electrode potentials. Excess energy that is gained through the motion of ion-qubits in the array or other heating mechanisms can be removed by sympathetic cooling of the ion-qubits with another ion species. The proposed architecture can be used in a highly parallel fashion, an important prerequisite for fault-tolerant quantum computation.

1. Basic Concept

1.1. *Original Cirac/Zoller Architecture*

Quantum information processing with trapped ion-qubits was first proposed by J. I. Cirac and P. Zoller in 1995[1]. The original architecture consisted of a string of ions lined up in a linear quadrupole ion-trap. In each ion two long-lived electronic levels are used to implement a qubit. For all gate manipulations the ion-qubits are individually addressed with focussed laser beams. Single qubit rotations are performed with laser pulses exciting resonant transitions between the internal levels of the ion-qubit in question. Two-qubit gates use one normal mode of vibration of the ion string as a means to couple the possibly distant partners in the gate[1]. To this end all normal modes of vibration should be cooled close to the ground state before the algorithm starts.

This proposal stimulated a new field in trapped ion research, but it soon became clear that it is difficult to scale the original architecture to more than a few ions. In particular, confining a linear string of thousands of ions in one trap would lead to unrealistically high voltages on the endcap electrodes. Also, for a fixed value of the lowest normal mode frequency, the distance between neighboring ions decreases as the ion number increases. Keeping this distance above the diffraction limit of the addressing laser beam requires rather low motional frequencies for a large string. This is in conflict with other requirements, for example, ground state cooling, which has only been demonstrated at higher motional frequencies. Low motional frequency also limits gate speeds for the computation (In the original proposal the gate rate has to be below the lowest motional frequency). Finally, from a practical point of view, the emergence of $3N$ normal modes for N ions plus their sum and difference frequencies leads to an increasingly crowded excitation spectrum where components are difficult to identify and off-resonant coupling to parasitic transitions is hard to avoid.

1.2. *Multiplexed Trap Architecture*

In 1998 we proposed a multiplexed trap architecture[2,3] that might alleviate the problems described above and is modular, so scaling to higher qubit numbers seems to be more feasible. Other schemes have also been proposed The basic idea is to expand the orignal architecture to an array of many independently controllable subtraps that hold the ion-qubits in certain configurations at each stage of the algorithm (see Fig. 1). Qubits that do not partake in given step of the algorithm are stored in memory regions. To execute a gate on certain qubits, they are separated from other ions in the memory regions and shifted into a "processor" region. Moving ion-qubits around does not lead to decoherence in the computational Hilbert-space spanned by the qubits since the motion is only used for coupling two qubits during the gate. Once the gate is completed, the motion factors out and no entanglement with the computational Hilbert-space is left. Since the electrostatic forces controlling the ions in the array do not couple to the internal qubit states, the computation is not affected by the movement. The only relevant phases are brought about by the fact that the ions could be illuminated at different spatial positions in the array by the laser beams, but these phases depend only on the respective positions and not on the exact trajectory the ion took from one place in the array to another. Through movement in the array, the ion-qubits may gain some

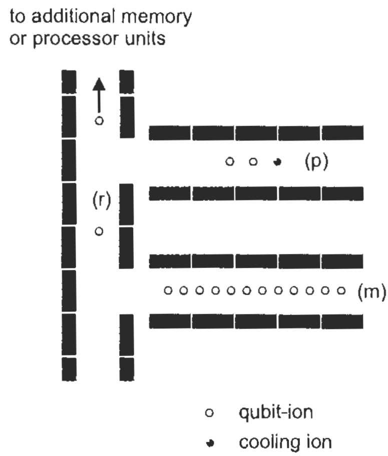

Figure 1. Multiplexed trap architecture. An array of independently controllable subtraps holds the ion-qubits. Qubits that are not involved in a given step are held in a memory region (m). Before performing a gate on a certain pair of qubits, they are shifted into a "processor" unit (p), and sympathetically re-cooled with another ion species. Single-bit rotations or ancilla readouts can be performed in any region of the array as long as the qubit in question is sufficiently isolated from the remaining qubits (for example in (r)).

excess motional energy, but they can be sympathetically recooled close to the ground state with another ion species (a "refrigerator" ion) before the next gate is applied. Due to the strong Coulomb-coupling one can simultaneously laser cool all ions trapped in the same subtrap. The cooling laser interacting with the "refrigerator" ion can be far detuned from all qubit transitions and therefore cause negligible phase and spin-flip errors of the qubits, even if they are directly illuminated with the cooling light. Sympathetic recooling will also remove motional energy that the ion-qubits might acquire due to other heating mechanisms in the trap[6]. The heating time constant is estimated to be on the order of one quantum per second at our typical motional frequencies for the most benign source, blackbody radiation of the room temperature experimental apparatus[2]. In the small traps used in our experiments we empirically find a much larger heating rate with time constants on the order of several milliseconds[6]. With sympathetic recooling, an even larger heating rate would not limit computation time, so algorithms that run for much longer times could be implemented. In this case the time available for a computation would be limited only by the decoherence of the internal qubit states. The lifetime of hyperfine ground states is extremely long (many years), so the memory decoherence of qubits composed of such states is primarily due to phase errors induced by external perturbations, e.g. magnetic field fluctuations. In a carefully controlled environment decoherence timescales could theoretically be on the order of many days with experimentally demonstrated lower limits of several minutes (see, e.g., Ref. 7).

A final advantage of the array architecture is the ability to read out some qubits without perturbing other qubits (for example, ancillae within a round of error correction). Since the readout of an ion-qubit usually requires approximately 10^4 scattered photons and the fractional solid angle subtended by the scattering cross section of a neighboring ion is on the order of $\lambda^2/(8\pi^2 d^2) \geq 10^{-5}$ (assuming $\lambda \simeq 313$ nm is the wavelength of the scattered light and $d \leq 5\ \mu$m is the inter-ion distance) it is not possible to perform many ancilla readouts without compromising neighboring ion-qubits in a string through rescattered photons. In the array architecture these readouts might instead be performed in areas that are sufficiently spatially isolated from the remaining qubits.

All steps described above can be done in a highly parallel fashion, an important prerequisite for efficient error correction. Scaling to many, possibly thousands of ions is technically challenging, but seems possible without fundamental problems. To demonstrate the feasibility of this architecture one has to experimentally demonstrate the following basic building blocks:

(1) *Build trap arrays:* Arrays containing several independent sub-traps and eventually also crossings and/or "T"-junctions must be constructed in a precise and reproducible fashion. The dimensions and techniques used must be scalable to large arrays that are able to hold and control thousands of ions.
(2) *Move ions:* Ion movement in a trap array must be reliable and repeatable without gaining too much excess energy. The typical timescales of these movements should not substantially limit the speed of the algorithm.
(3) *Ability to separate and recombine ions:* To execute quantum logic gates, certain ions have to be picked out of the memory regions reliably and combined with another ion-qubit and the refrigerator-ion in the processor unit. The typical timescale of these processes should also not substantially limit the speed of the algorithm.
(4) *Sympathetic recooling:* Excess kinetic energy of the ion-qubits, brought about by their movement in the array, by external heat-

ing mechanisms, or by the recoil suffered in ancilla-readout steps, can be removed by sympathetic laser cooling with a second ion species (the refrigerator ion). Re-cooling must leave the ions sufficiently close to the motional ground state and should not disturb the qubit.

(5) *Robust single-qubit and two-qubit gates:* For extended algorithms it will be necessary to reach gate fidelities on the order of 0.9999. All single bit and two-qubit gate mechanisms considered should reach this fidelity with technically realistic improvements and still be compatible with the other features of the architecture, for example, the presence of a "refrigerator" ion during gate operation.

The experiments performed so far at NIST to implement these basic building blocks will be briefly described in the next section.

2. Experimental Demonstrations

2.1. *Building Trap Arrays*

In the last two years we have built and characterized three multi-zone traps, two of them with the ability to load and hold $^{9}Be^{+}$ and $^{24}Mg^{+}$ simultaneously. The sub-traps are aligned along one common axis and the traps had 3, 5 and 6 trapping zones respectively. The two larger arrays had a dedicated loading zone to shield the other zones from plating with neutral Be and Mg from the ovens. We were able to cool Be^{+} to the ground state in all three traps and observed heating rates of 1 quantum in 10 ms at 2.9 MHz axial trap frequency for the 3-zone trap[8], 1 quantum in 1 ms at 4.5 MHz for the 5-zone trap, and 1 quantum in 5 ms at 4.1 MHz for the 6-zone trap.

2.2. *Moving Ions*

We transferred a single ion between two traps 1.2 mm apart by continuously changing the potentials on five pairs of control electrodes [8]. We initially prepared the ion in the motional ground state. Using numerical solutions for our trap geometry, trap potentials were designed so that during the transfer all motional frequencies would be held constant. After a hold period in the target trap the transfer process was reversed. Following the transfer back to the starting trap, we measured the average gain in occupation number of the axial motional mode. For a transfer time of 28 μs and a trap frequency of 2.9 MHz, about half a quantum on average was gained from the transfer. From a numerical integration of the classical equations of motion, we expected that the ion should gain an amount of energy equal to one motional quantum for a 30 μs transfer duration. This estimate indicates approximately when the transfers are no longer adiabatic and agrees reasonably well with our observations. Overall, this transfer process is robust in that we have not observed any ion loss due to transfer. We also verified that the coherence of the internal qubit-states was not affected by the transfer[8].

2.3. *Separating Ions*

We separated two ions from a common trap-well into two separate wells 300 μm apart by continuously changing the potentials on five pairs of control electrodes. For separation, the common trap potential is relaxed, so the Coulomb repulsion drives the ions apart until a distance is reached where an external electrostatic "wedge" can be ramped up between the two ions to separate them into independent sub-traps. At one point during this process the external potential is essentially flat, leading to rather small motional frequencies of the ions. At this point the ions are most susceptible to external heating and to field errors due to imperfect trap geometry and stray charges. It is therefore essential to keep this minimum frequency as high as possible. Ideally one would like to have a very sharp wedge, but that is only possible if the trap electrodes are small and close to the ion. In the 6-zone trap we included a pair of electrodes with a width of 100 μm and about 140 μm distance from the ion. Ramping the potential on this electrode pair creates the electrostatic wedge that separates the ions into two adjacent zones over two electrode pairs 200 μm wide. In preliminary experiments in this array we were able to separate two ions in about 2 ms reliably. The time varying potentials on all electrodes were designed to be in the adiabatic regime with a minimum oscillation frequency of about 350 kHz. A heating measurement after separation yielded that the motional energy increased by less than 10 quanta during the separation. Current efforts are devoted to increasing the speed and reducing the heating during separation.

2.4. *Sympathetic Recooling*

Sympathetic recooling could be a crucial step to extend the capability of quantum information processing with trapped ions to timescales much longer than the time constant for motional heating in the ion traps. It can also serve to remove the excess kinetic energy of ion-qubits that might be produced by their movement in the array or by the recoil suffered in ancilla-readout steps. Recooling must leave the ions sufficiently close to the motional ground state so that quantum gates are not limited in fidelity by the fluctuations of the thermal state produced by cooling. For the gate mechanism used in the two-ion experiment described below, 99% ground state cooling on all modes will lead to a fidelity of about 0.9999.

Sympathetic cooling has previously been demonstrated using "refrigerator" ions that are the same as the qubit ions[9] or an isotope of the qubit ions[10]. In order to gain higher immunity from decoherence caused by stray cooling light, we have chosen a different ion species for the refrigerator ion. In our sympathetic cooling experiment we trapped and Doppler cooled one $^{9}Be^{+}$ and one $^{24}Mg^{+}$ ion in one trap, with 2.0 MHz and 4.1 MHz axial normal mode frequencies. We then cooled either the Mg^{+} or the Be^{+} ion close to the ground state using interspersed red-sideband Raman pulses and resonant repumping pulses[11]. Finally the average occupation number $\bar{n}$ was determined by comparing red and blue sideband strengths of both modes on the Be^{+} ion. When cooling on the Mg^{+} ion we were technically limited by our Raman-detuning and achieved $\bar{n} = 0.19(6)$ and $\bar{n} = 0.52(7)$ on the two normal modes, respectively. This result will be improved in the future by implementing higher Raman-detuning. Cooling the two ions through the Be^{+} ion (where the detuning is large) yielded a limit of $\bar{n} = 0.03(2)$ and $\bar{n} = 0.04(3)$[11].

2.5. *Robust One and Two-qubit Gates*

Single qubit rotations can be executed in any region of the array where the selected qubit is sufficiently isolated from all other qubits. For one-qubit spin-flip gates we use stimulated Raman transitions where the two laser beams have a parallel wave-vector. This makes these rotations highly immune to the motional state of the ions and to any common fluctuations of the beam path of the two Raman beams. We have demonstrated π-rotations with a lower fidelity limit of 0.99. Higher fidelity seems possible with improved intensity stability of the Raman-beams (currently fluctuating by about 1%) and by reducing the magnetic field sensitivity of our qubit states. Beryllium ions offer a qubit transition that is first-order magnetic field independent at about 120 G. Working at this field should reduce the sensitivity to fluctuating magnetic fields by at least two orders of magnitude. One ion-phase gates (z-rotations) need not be executed by laser pulses; they can be incorporated by adjusting the phase of subsequent spin-flip gates.

We recently demonstrated a two-qubit geometric phase gate utilizing a state-dependent dipole force. In our implementation, we coherently excited the motion of two ion-qubits along a closed path in motional phase space if they were in different internal states, while they were not excited if they were in the same state[12]. For different internal states the total state of the ions picked up a phase proportional to the phase-space area circumscribed, leading to the following truth table ($|\downarrow\rangle$ and $|\uparrow\rangle$ denote the qubit logical states):

$$\begin{aligned} &|\downarrow\downarrow\rangle \rightarrow |\downarrow\downarrow\rangle \\ &|\downarrow\uparrow\rangle \rightarrow e^{i\phi}|\downarrow\uparrow\rangle \\ &|\uparrow\downarrow\rangle \rightarrow e^{i\phi}|\uparrow\downarrow\rangle \\ &|\uparrow\uparrow\rangle \rightarrow |\uparrow\uparrow\rangle . \end{aligned} \tag{1}$$

The gate is universal and can be converted into a π-phase gate or a CNOT-gate with single bit rotations for $\phi = \pi/2$.

Starting with the state $|\downarrow\downarrow\rangle$ and sandwiching this gate between $\pi/2$ and $3\pi/2$ pulses applied to both ions, we were able to produce maximally entangled states of the form $|\psi\rangle = 1/\sqrt{2}(|\downarrow\downarrow\rangle + i|\uparrow\uparrow\rangle)$ with a fidelity of 0.97. Under the reasonable assumptions that the error of the gate operating on $|\downarrow\uparrow\rangle$ is of equal magnitude to the one on $|\uparrow\downarrow\rangle$ and much larger than the errors on $|\downarrow\downarrow\rangle$ and $|\uparrow\uparrow\rangle$ (which are not excited by the gate pulse), the fidelity of producing the maximally entangled state can be shown to be equal to the gate fidelity. Individual ion addressing is not required during this gate and the accumulated phase depends only on the path area, not on the exact starting state distribution, path shape, orientation in phase space, or the time it takes to traverse the closed path. Thus within the Lamb-Dicke regime, ground state cooling is not required for accurate gate operations. The main sources of gate error in our experiment are fluctuations in the trap frequency and fluctuations in the Raman-beam intensity, both roughly at the 1% level, and a spontaneous emission probability of about 2.2% for each gate operation. If frequency drift and intensity errors could be reduced to order 10^{-3} and spontaneous emission suppressed (i.e., by using a different ion species[13]), the expected gate fidelity is on the order 0.9999. In the future, with a refrigerator-ion present in the processor trap, the normal-mode amplitudes of each ion will be different, making it technically more difficult to obtain equal laser beam couplings, as required in the Sørensen/Mølmer gate[14]. Equal coupling is not required for a general geometric phase gate since the extra phases on each qubit can be absorbed into previous or subsequent single-qubit rotations.

3. Conclusions and Outlook

In the last two years, all basic building blocks for a scalable architecture of a quantum information processor with trapped ion-qubits have been individually experimentally demonstrated. Although it will be a nontrivial technological challenge, no fundamental problems seem to prohibit scaling to many qubits. It also appears technically feasible to reach the fault tolerant level with the demonstrated one- and two-qubit gates. Therefore trapped ion-qubits remain a promising candidate for the implementation of large-scale quantum information processing.

Acknowledgments

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