Scalable quantum computing architecture with mixed species ion chains
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ABSTRACT

We describe our work on trapping, cooling and detecting mixed ion species for a scalable ion trap quantum information processing architecture. These mixed species chains in linear RF traps may help solve several problems with scaling ion trap quantum computation to large numbers of qubits. Initial temperature measurements of linear Coulomb crystals containing barium and ytterbium ions indicate that the mass difference does not significantly impede sympathetic cooling of normal modes that couple well to the coolant ions (Ba in our case). Average motional occupation numbers are estimated to be 10 to 20 quanta per mode for these well cooled modes for chains with small numbers of ions, consistent with the Doppler limit temperature. For normal modes that do not couple significantly to the coolant atoms, the occupation numbers are significantly higher, of order several thousand. Strategies for better cooling of these modes are discussed. Further, we are working to implement these techniques in microfabricated surface traps in order to exercise greater control over ion chain ordering and positioning.

Keywords: trapped ions, sympathetic cooling, normal modes, entanglement

1. INTRODUCTION

Trapped ion chains in linear RF traps are a promising candidate for quantum information processing, with demonstrated near-perfect initialization\(^1\) and detection efficiency\(^2\), high fidelity gates\(^3,4\), and high gate speed compared to their coherence times. Mixed species ion chains offer several advantages over using single species ions in achieving scalability in a quantum information processor. Crosstalk can be significantly reduced, and continuous cooling of the ion chain can be enabled that does not affect qubit coherence. The choice of ion species is very important. If the mass difference of the ion species is too large then the normal modes of motion will decouple, which would greatly reduce both the sympathetic cooling efficiency and motional entangling gate speeds.

We study Ba\(^+\) and Yb\(^+\) ion chains as the most promising system for such two species architecture\(^4\). Both ions are thoroughly studied experimentally as excellent qubit candidates\(^5\) and their mass difference of only about 25% makes them very suitable for efficient sympathetic cooling. Ytterbium-171 has a pair of ground state levels with excellent insensitivity to magnetic fields. These levels have very long coherence times and the state of the ion can be determined using a simple optical setup. Barium-138 has the advantage of having a strong transition at 493 nm, which is a long wavelength transition among ion species that can be laser cooled. This wavelength is transmitted through fibers easier than more ultraviolet transitions which will improve the rate at which remote entangled pairs can be generated.

This paper is organized as follows: first, we describe the experimental setup and procedures; we then present basic theory of normal modes in mixed species ion chains, and finish by discussing our measurement results.

2. EXPERIMENTAL DETAILS

Barium and ytterbium ions are trapped in a relatively standard millimeter-scale linear RF ion trap made from parallel 4 tungsten rods approximately 0.5 mm in diameter separated by approximately 1 mm radially. The axial confinement is enabled by two needle electrodes made from the same tungsten stock, separated axially by about 5 mm. This trap is based on design described in excruciating details in [6]. The trap is placed in a UHV chamber along with two small ovens, one loaded with metallic barium and the other with metallic ytterbium. Singly ionized Ba and Yb is produced by photoionization as described in [7]. Barium ions are Doppler-cooled using 493 nm and 650 nm lasers, while ytterbium ions are cooled in sympathy by the barium. No lasers are used to directly address the Yb ions; to study motional states of...
Ba ions, narrow-band laser spectroscopy is performed on the $6S_{1/2} - 5D_{3/2}$ transition. Relevant energy levels and transition wavelengths of Ba$^+$ are shown in figure 1.

![Energy Level Diagram](image)

Figure 1. Relevant energy levels and transitions in singly ionized barium. The ions are cooled on the 493 nm D1 line, with the 650 nm laser used to repump population from the metastable $5D_{3/2}$ state. The 1762 nm narrow band “shelving” laser is used for precision spectroscopy to determine the qubit state and the motional state of the ions. The 614 nm laser is used to deshelve the ion at the end of experimental cycle.

The 1762 nm laser is a fiber laser stabilized to a reference cavity with a finesse of 1000. The laser is pointed into the trap perpendicular to the trap axis, so only the radial modes of motion are observed in spectroscopy. This laser is used to perform both Rabi flops and the weak excitation sideband measurements. The 1762 nm light is focused to a 30 micron spot size centered on the ion chain, driving all ions in the chain with a comparable Rabi frequency. Spatially resolved state detection is performed using an EMCCD to count photons emitted from the cooling transition at 493 nm. The EMCCD was also used during each experimental cycle to ensure the correct ion chain configuration. To remove the ion from the shelved state, a pulse of 614 nm light was applied.

The $6S_{1/2}$ Zeeman sublevels are split using a magnetic field coil producing a field of approximately 5 Gauss. Optical pumping to initialize the Ba qubits is done by directing the linearly polarized 493 nm cooling beam parallel to the quantization axis defined by the magnetic field and sending it through a quarter-wave plate to make it circularly polarized, achieving an optical pumping efficiency of over 95%.

We start the experiment by loading the desired number of Ba and Yb ions in the trap. First, barium ions are loaded and imaged on the EMCCD. Ytterbium ions are then added; as they equilibrate via sympathetic cooling interactions with trapped Ba$^+$, they crystallize and appear as dark gaps in the barium chain, as illustrated in figure 2. Orderings of ions are determined automatically by measuring the photon counts in a small area around each ion site. Positions of ion sites do shift slightly as the chain reorders, but this effect is small, owing to the small mass difference between barium and ytterbium. During the experiment the ion chain would occasionally spontaneously reorder due to background gas collisions or excess heating. Chain order is reestablished by turning off the Doppler cooling lasers, waiting several seconds for the crystal to melt, and then turning the cooling lasers back on. We would then check whether the ions were in the correct configuration and repeat the reordering cycle as necessary until the desired order is restored. This method scales poorly to larger numbers of ions and more diverse mixtures, however, and our future work will be done in microfabricated chip traps where ion ordering can be done deterministically.
Figure 2. Laser-cooled chain of 4 barium and 1 ytterbium ions. Barium ions are made visible by scattering 493 nm laser light, while Yb\(^+\) appears as dark gaps in the chain. All 5 possible configurations of ions are shown, produced stochastically by melting and recooling the crystal.

The experimental sequence for both the Rabi flops and the motional sideband scans is as follows. We first Doppler cool the Ba ions using the 493 nm and 650 nm transitions for approximately 50 ms; we then optically pump Ba\(^+\) to their initial \(m = +1/2\) state. The 493 nm and 650 nm beams are then extinguished, and the 1762 nm pulse is applied after a preset time delay. Afterward, the 493 nm and 650 nm lasers are turned on, and state detection is done using the EMCCD. The experimental sequence is repeated, with varying either the frequency of the 1762 nm during sideband scans, or the duration of the 1762 nm laser pulse length during Rabi flop experiments. Sideband scans are performed in the weak excitation regime, where the 1762 nm pulse duration corresponds to a small fraction of the \(\pi\)-pulse. If any EMCCD image is inconsistent with the chosen ion configuration, the experiment is halted and melting/recooling cycles occur until the correct configuration is achieved.

3. NORMAL MODES IN ION CHAINS

In order to analyze the temperatures of mixed species chains, we first need to understand the normal mode structure of a chain of ions with different masses. The normal modes for any given number of each species of ion and any ordering of those species can be calculated through classical mechanics techniques. When the dynamics are much slower than the RF period, the trapping potential \(V\) can be written as a simple harmonic oscillator:

\[
V = \sum_{i=1}^{N} \left\{ \frac{1}{2} m_i \omega_x^2 (m_i) x^2 + \frac{1}{2} m_i \omega_y^2 (m_i) y^2 + \frac{1}{2} m_i \omega_z^2 (m_i) z^2 \right\},
\]

Where the summation is over the total number of ions \(N\), \(m_i\) is the mass of the \(i^{th}\) ion, and \(\omega_{x,y,z}(m_i)\) is the \(i^{th}\) normal mode frequency for \(x\) \((y, z)\) direction. This potential is modified by the Coulomb repulsion between the ions:
\[ V_C = \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{q_i^2}{4 \pi \epsilon_0 |{\vec{r}_i} - {\vec{r}_j}|}, \]

Where \( q \) is the ion’s charge and \( r_i \) is the position of the \( i^{th} \) ion. Ignoring anharmonic terms, which is justified for small displacements, the coupled equations of motion for ions along the transverse (i.e. \( x \) and \( y \)) directions become:

\[ \ddot{x}_i + V_{ij} x_j = 0, \]

and similar for \( y \). Here:

\[ V_{ij} = \frac{1}{\sqrt{m_i m_j}} \frac{\partial^2}{\partial x_i \partial x_j} (V + V_C). \]

There are \( 3N \) solutions which take the form of independent harmonic oscillators. Each harmonic oscillator corresponds to motion along one of the eigenvectors \( \hat{e}_\alpha \) of the matrix \( V_{ij} \) with an angular frequency \( \omega_\alpha \) equal to the square root of the corresponding eigenvalue. We can write these solutions for each normal mode \( \alpha \) as:

\[ x_\alpha(t) = \hat{e}_\alpha \cos(\omega_\alpha t). \]

With this modification, the analysis of sideband transitions can be done in the usual fashion \(^7\), albeit with one small modification. The separate motional state operators for each ion and each mode now carry the corresponding eigenvector component as a scalar multiplier that attenuates the motion of each individual ion. This effect can be accounted for by defining the Lamb-Dicke parameter for each mode \( \alpha \) and ion \( i \) to be \( \eta_{\alpha,i} = \hat{e}_{\alpha,i} x_{\alpha 0} k_x \), where \( x_{\alpha 0} = \sqrt{\frac{h}{2 m \omega_\alpha}} \), \( k_x \) is the laser’s k-vector component along \( x \), and \( m \) is the ion’s mass.

4. RESULTS AND ANALYSIS

We can scan the frequency \( \omega \) of the 1762 nm laser over the radial modes frequencies for a chain of several Ba and Yb ions following the procedure described above. Since a PMT has no spatial sensitivity and cannot distinguish which ions in the chain are bright or dark, we developed software that integrates our experiment with the Andor Luca EMCCD camera and automatically performs this analysis. The ion chain length is short enough that we can achieve the correct ion ordering easily enough to take reasonable amounts of data. We are most interested in how effectively the ytterbium ions can be cooled by only Doppler cooling the barium ions.

We limit the exposure time of the 1762 nm laser such that the shelving probability \( P \) does not exceed \( \sim 35\% \) allowing us to fit each peak in the sideband scan to the weak excitation limit:

\[ P(\omega) = \frac{1}{4} \eta_{\alpha,i}^2 \bar{n}_\alpha \Omega_\alpha^2 \sin^2\left(\frac{((\omega - \omega_\alpha) t / 2)}{(\omega - \omega_\alpha)^2 / 4}\right), \]

where \( \bar{n}_\alpha \) is the average occupation number of the given mode, and \( \Omega_\alpha \) is the carrier Rabi frequency for the given ion, determined separately. (Due to spatial variation of the 1762 nm beam intensity, ions in the middle of the chain have slightly higher Rabi frequency than those on the periphery.)

A sample of our results is shown in figure 3. Preliminary analysis indicates that the normal modes occupied predominantly by the lighter Ba ions (typically, the higher frequency modes) are very well cooled to \( \bar{n}_\alpha \) of order 10 to 20, corresponding to the Doppler cooling limit for our typical trap frequencies of order 1 MHz. The lower frequency normal modes, occupied predominantly by the Yb ions, should not be visible on the scans if cooled to near Doppler limit. However, we do observe these modes rather being very strong even in barium ions, for which the eigenvectors are very small (order 0.01), indicating that these modes are very hot, with \( \bar{n}_\alpha \) of several thousand. The good news is, not all
modes that couple well to ytterbium are hot. Depending on the ion arrangement, some modes are cooled very well, even if their coupling to Ba ions is weak.

Figure 3. Carrier Rabi flops (top) and radial sideband scans for a chain of 5 barium and 1 ytterbium ions. The ion chain arrangement is indicated on the left of the graphs. The measured Rabi frequency is lower for the peripheral ions due to lower 1762 nm laser beam intensity. In the radial sideband scan, the lower frequency modes are those to which the heavier Yb ions are better coupled, while the higher frequency modes are mostly occupied by the Ba ion. Large amplitudes of the lower frequency sidebands for the two Ba ions surrounding the Yb ion indicate that these modes are poorly cooled. The line width of the sideband transitions is broadened by the slow frequency drifts of the 1762 nm laser on the order of 10 kHz.
To summarize, we are studying the cooling and sorting of mixed species ion chains, composed of Ba and Yb ions. Our preliminary results indicate that successful sympathetic cooling of the heavier Yb ions by Ba ions can be achieved, at least for some normal modes, by interspersing the coolant ions among the qubit ions in the chain. Roughly equal mixture of the two species should provide sufficient cooling. In the future we plan to perform these experiments in microfabricated surface traps where sorting of ions in the chain can be done deterministically.

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