Micromotion Reduction and Barium-Ytterbium Ion Chains

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Abstract

The purpose of this REU project was to compensate for micromotion to reduce ion temperature and to trap and retain barium-ytterbium ion chains. Having cold ion chains allows us to implement quantum gates, which is a necessary component to any quantum computer. Micromotion is a constant issue that frequently needs to be compensated for because the electric fields within our trap are prone to drifting. We could adjust for it visually and we could "measure" it by checking how well we were driving the ion from $S_{1/2} \rightarrow D_{5/2}$ energy levels (used a 1762 nm laser for this transition). After compensating micromotion we were able to trap mixed ion chains and retain them for relatively long times.

1 Introduction

Quantum computers provide exciting possibilities for allowing for certain problems to be solved with efficient solutions, such as Shor's algorithm for getting the prime factorization of large integers, Grover's search algorithm, and even simulation of quantum mechanical systems [1].

In order to actually build a quantum computer, the following must be met (known as DiVincenzo criteria):

1. A scalable physical system with well characterized qubits
2. The ability to initialize the state of the qubits to a simple fiducial state, such as |000…>
3. Long relevant coherence [sic] times, much longer than the gate operation time
4. A "universal" set of quantum gates
5. A qubit-specific measurement capability [2]

All of these are satisfied using a trapped ion implementation: Energy states with long lifetimes play the role of the qubits. Scalability (though difficult) may be achieved via mixed ion chains, and entangling ions in multiple traps [3] [4] [5]. We can use optical pumping to initialize the state [3]. Ytterbium has long coherence times as compared to quantum operations [5] [6]. It also has "fast readout"[5] and "entangling ion-ion gates"[5]. Ytterbium also has "magnetic-field-insensitive hyperfine levels" [4] that are ideal for storing quantum information. Barium has similar properties in that it has energy levels that could act as qubits; but these are magnetically sensitive, therefore would make bad qubits [4]. Barium also can be pumped to specific states, has long coherence times, can be used for implementing quantum gates, and has easy readout [4]. Hence, ytterbium is used to store the quantum information while barium is used as a way of cooling ytterbium and transferring its entanglement to the ytterbium ions [4]. Otherwise, trying to perform cooling or entanglement on ytterbium would cause a collapse of the stored quantum information [4].

2 Experimental Setup

We use a linear RF trap to confine the ions in three dimensions.

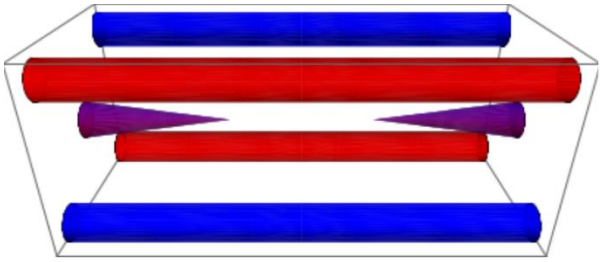

Figure 1: Linear RF trap (fig. courtesy of John Wright)

Figure 1 depicts the trap: the blue rods are grounded, while the red rods are at an RF voltage. The voltages on the red rods are shifted in a continuous manner from a negative voltage to a positive voltage and back, which provides the changing electric field that confines the ion in the radial direction. The resulting electric field looks like a saddle that flaps as the voltages on the rods change, but the time average of this field is effectively a harmonic potential well. The purple needles confine the ion along the axis of the trap by having a constant dc voltage applied to them [4].

This allows us to trap ions, which we get from the following process. Ions are produced by bombarding the flux of neutral atoms coming from our barium oven with a 791 nm laser that brings the atom to an excited state. Then hitting those excited atoms with a nitrogen pulse laser ionizes the atoms by stripping away an electron. We have a similar process for ytterbium in which we blast the neutral ytterbium atoms from the oven with a 399 nm light to excite them, then use the nitrogen pulse laser to ionize the excited ytterbium atoms. Both processes leaves the ions fairly hot which is not ideal for experiments.

To address this issue we use Doppler laser cooling for our barium ions, and we use sympathetic cooling from the barium ions to cool our ytterbium ions. Doppler laser cooling is done via lasers whose frequencies are detuned slightly lower from the desired transition so as to only affect ions moving in the direction toward the laser. As ions absorb this light they emit light in random directions; they lose momentum when they absorb photons and their emissions amount to a net momentum gain of zero. Therefore, the ions are cooling overall. We use the 493 nm laser to drive the main cooling transition (see figure 2 for transition structure for a barium ion). The $P_{1/2}$ state has a 25% chance to decay into the $D_{3/2}$ state, so we use the 650 nm laser to drive the transition back to being cooled by the 493 nm laser. Cooling ytterbium sympathetically has to do with the ytterbium transferring its energy to the barium which is then laser cooled. It is important that ytterbium is not laser cooled because that would cause system decoherence [5].

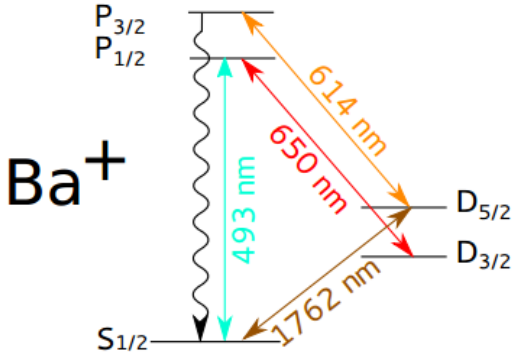

Figure 2: barium ion transitions (fig. courtesy of John Wright, et. Al)

3 Experiment

3.1 Micromotion

Micromotion, driven directly by the RF field, exists throughout the linear RF trap, however it is at a minimum when the ion is in the center. It is much larger when the ion is off-center in the trap because the ion then moves with the flapping of the electric field (as shown in figure 3).

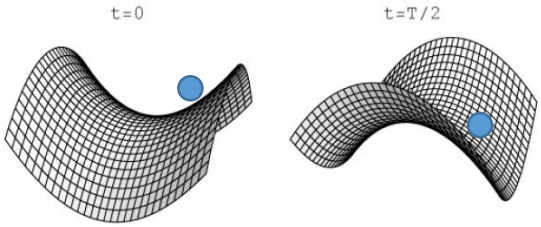

Figure 3: depicts the flapping of the E field, ion is blue dot off center of trap (fig. courtesy of Mostafa on http://physics.stackexchange.com/questions/82291/quadrupole-potential-generation-in-paul-traps)

This causes the excess motion of the ions which makes them "hotter". These hot ions can cause issues with maintaining the order of the chain. Hot ions also will cause issues for implementing the Mølmer-Sørensen gates.

In order to reduce micromotion the constant dc offset voltages were adjusted (these are actually

applied to one of the RF rods and one of the grounded rods, see figure 1). We had two methods of measuring the size of the micromotion: one used the camera, and the other used the 1762 nm laser (see figure 2).

The camera method involved changing the trap depth and watching how the ion moved on screen, then compensating by altering the constant voltages on our rods, then changing trap depth to see if it is still moving on the camera. This way was less involved, but also less precise than using the 1762 nm laser.

We use the 1762 nm laser for this because the width of its transitions are so narrow we can see the carrier and the sidebands in its spectrum. When using the 1762 nm laser, we would lock the laser to a frequency about 10MHz away from the carrier transition (this drives the internal states of the ion rather than its motional states, which is the micromotion sideband. Then we would "shelve" the ion using the 1762 nm laser into the $D_{5/2}$ state (outside the cooling cycle). Then deshelve the ion to the $P_{3/2}$ state using the 614nm laser which it decays from back into the $S_{1/2}$ state, thus into the cooling cycle once more (figure 2). This process gave us information on the amount of micromotion present by giving us a measure of how well we are shelving while locked to a micromotion sideband. Then we would adjust the voltages and do the shelving experiments again to see if we had reduced the amount of shelving produced. This was repeated multiple times, with varying voltages. Then we would set the voltages to those which produced the minimum shelving efficiency.

3.2 Barium and Ytterbium ion chains

This involved first trapping as many barium ions as we desired (in this case 2). Then reducing micromotion as much as possible to reduce the possibility of chain reordering. Then trying to trap ytterbium ions.

When trapping ytterbium we were having issues with how much 399 nm light (as mentioned above) was necessary to excite the atom. We actually needed more light through our fiber coupling than we initially thought. But, we also needed to reduce the current on the ytterbium oven because the ions were coming in with enough force to eject the barium ions from the trap. I had to find a medium point between producing ions at a decent pace, while not losing all the ions in the trap. The final current settled on produced single ytterbium ions approximately every 5 minutes moving slowly enough not to knock barium ions out of the trap.

4 Results

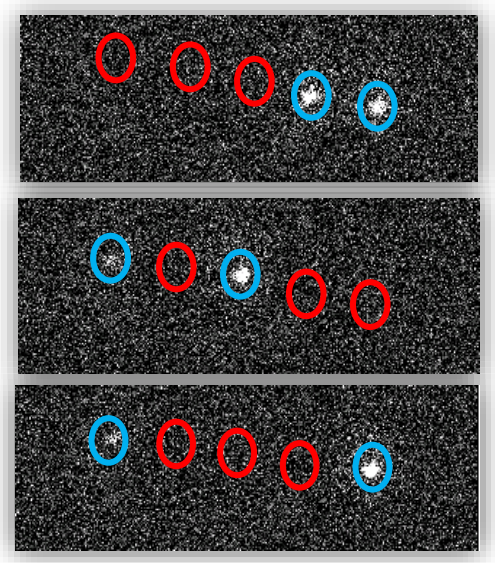

Figure 4: Barium(visible): blue, Ytterbium(dark): red – pictures were taken within 15 minutes of each other

We were able to trap barium and ytterbium chains and hold them for a few hours. As can be seen in figure 4 we had barium and ytterbium ions in a chain together. The blue circles are where the fluorescing barium ions are, and the red circles are where the ytterbium ions positions are; we can tell these positions are where ytterbium ions are located by taking a series of pictures such as those in figure 4 and compare the distances and positions the bright ions take. Because of their larger mass ytterbium ions coming into the chain and moving around cause the whole chain to shift positions. The other way of confirming that they are ytterbium is that before turning on the ytterbium

oven there were no dark spots between our ions even after turning the cooling lasers on and off to get the ions to rearrange.

5 Future work

Now that we can trap mixed barium-ytterbium ion chains, we need to get a good temperature measurement. Then we can move on to implementing Mølmer-Sørensen gates. These rely on changes to motional states in the ions, so we need cold ions to do this. Which will lead to doing remote entanglement experiments with multiple traps.

6 Acknowledgements

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7 References

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