Efficient Sympathetic Cooling of Trapped Atomic Ions

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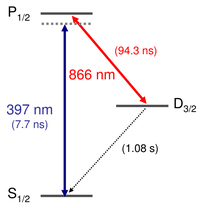
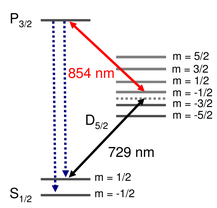
Sympathetic Cooling

A challenge of performing ion trap quantum computation with chains of ions is the heating of the trap vibrational modes. Trap heating can result in unwanted occupation of vibrational modes and a reduced fidelity for two ion gates. To combat this, specific ions within the chain can be tasked with cooling the entire chain via sympathetic cooling. The strength of the interaction between the cooling laser and cooling ions may have a significant effect on how efficiently the chain is sympathetically cooled. This interaction can be controlled via the intensity and detuning of the cooling beam as well as the time the cooling ions spend interacting with the cooling laser versus thermalizing with the ion chain. By using separate isotopes of Ca^+, we can construct a chain of cooling and information ions with each isotope interacting with its resonant cooling laser independently. By adjusting the aforementioned interaction parameters and measuring the sideband spectrum of the information ions, we will be able to find the most efficient sympathetic cooling parameters.

In these experiments, we trap two differing Ca^+ isotopes: $^{40}Ca^+$ and $^{44}Ca^+$. Initially, we hope to characterize and refine our techniques on this two ion system in a 3D Paul trap before eventually expanding to multi-ion chains in planar Paul traps in support of the MUSIQC collaboration. We have so far applied two techniques: spectroscopy of the $4^2S_{1/2} \leftrightarrow 4^2P_{1/2}$ transition and spectroscopy of the $4^2S_{1/2} \leftrightarrow 3^2D_{5/2}$ transition. In both cases, while the spectroscopy ion is probed, the second ion sympathetically cools the first and the effectiveness of this interaction can be evaluated through the spectroscopy ion's fluorescence.

Ca^+ Energy Levels and Isotope Shifts





Our two techniques require spectroscopy of specific transitions in Ca^+. In both cases, our collected signal is spontaneously emitted 397 nm photons generated by driving the $4^2S_{1/2} \leftrightarrow 4^2P_{1/2}$. In both cases, an 866 nm repumper laser is necessary to avoid trapping of the Ca^+ in the metastable $D_{3/2}$ state.

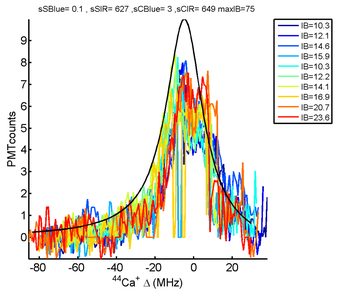
Additionally, for spectroscopy of the $4^2S_{1/2} \leftrightarrow 3^2D_{5/2}$, a 729 nm laser is necessary for shelving, while an 854 nm laser is necessary for pumping back to the ground state after measurement.

Due to the larger atomic mass of $^{44}Ca^+$, the atomic resonances experience isotope shifts with respect to the $^{40}Ca^+$ levels:

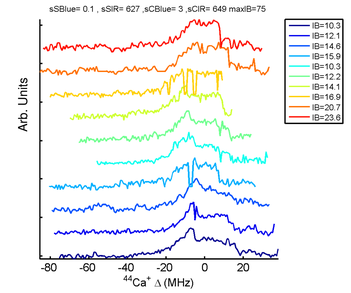
$$\Delta_{397} = 842 \text{ MHz} \qquad \Delta_{866} = -4.495 \text{ GHz}$$

Spectroscopy of the $4^2S_{1/2} \leftrightarrow 4^2P_{1/2}$ Transition

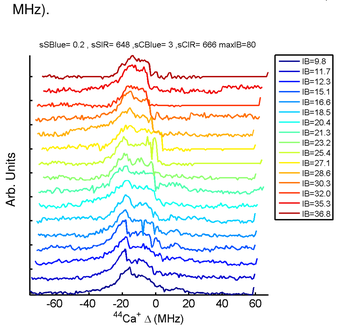
Initially, we trap $^{40}Ca^+$ and $^{44}Ca^+$ in a single harmonic well. We treat the $^{44}Ca^+$ as the spectroscopy ion while sympathetically cooling with the $^{40}Ca^+$. Both ions are continually addressed by their respective 397 nm cooling laser as well as their 866 nm repumper during the experiment. The spectroscopy ion's 397nm laser is swept across the transition resonance while the cooling ion's 397 nm laser is locked to a specific frequency detuning from resonance, Δ_{cool}, via the cooling ion's ion brightness (IB). Fluorescence is measured with a PMT and our measurement time is 5000 µs per trial at a given spectroscopy ion detuning ($^{44}Ca^+$ Δ). For a given set of IB values, the laser powers and thus saturation parameters, s_{spec} for the $^{40}Ca^+$ and s_{cool} for the $^{44}Ca^+$, are kept constant.



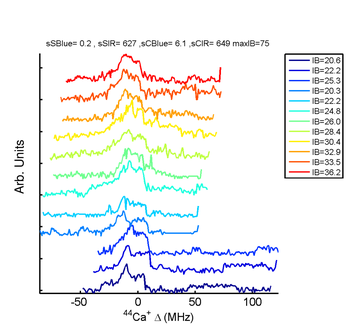
The spectroscopy ion's 397 nm spectrum for s_{spec}=0.1 and s_{cool}=3 values and various cooling ion IB values. The black line is a fit to the full transition width (~44 MHz).



The same data as to the left with the peaks shifted vertically. -55 MHz < Δ_{cool} < -32 MHz.



For this data, s_{spec} has been doubled to 0.2. -59 MHz < Δ_{cool} < -24 MHz.



For this data, s_{spec} and s_{cool} have been doubled. -48 MHz < Δ_{cool} < -30 MHz.

The Doppler broadened linewidth, Γ_D, of the $^{44}Ca^+$'s 397 nm transition can be used to estimate the temperature of the ion. In this preliminary data, the heating and cooling of the $^{44}Ca^+$ is too strong to accurately measure the sympathetically cooled ion temperature. Work is in progress to improve collection efficiency to measure the spectra at lower power.

$$\Gamma_D = \frac{\omega_0}{c}\sqrt{\frac{2k_BT}{M}}$$

We can clearly probe the blue side of the spectroscopy ion's transition due to sympathetic cooling between the two ions. For s_{cool}=3 scans as well as IB < 20, the Doppler broadened nature of the transition is clearly visible. For higher IB values, the spectroscopy ion appears to maintain fluorescence through resonance and onto the blue side of the transition and then rapidly drops to zero when the cooling laser overcomes the heating laser.

Spectroscopy of the $4^2S_{1/2} \leftrightarrow 3^2D_{5/2}$ Zeeman Levels

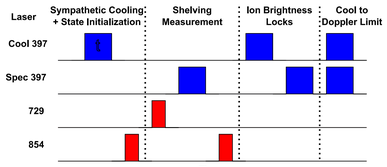
For spectroscopy Zeeman levels, we treat the $^{40}Ca^+$ as the spectroscopy ion and the $^{44}Ca^+$ as the cooling ion. In this case, we do not continually probe the spectroscopy ion and cool the cooling ion. The frequency of both 397 nm lasers are locked to their respective ions via ion brightness. Our measurement time is 1000 us and fluorescence is collected with a PMT.

For a given set of sidebands, the ratio, r, of the blue to red sideband height can be used to determine the number of quanta, n, associated with a given vibrational mode, ν.

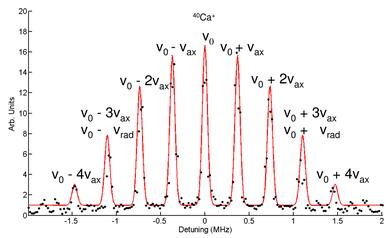
$$\nu_{ax} \approx 370 \text{ kHz} \quad \nu_{rad} \approx 1.04 \text{ MHz}$$

$$n_{ax} \approx 29 \quad @ \quad T_D \approx 527\ \mu\text{K}$$

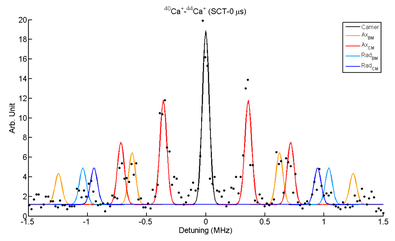
$$r = \frac{n+1}{n} \qquad T_n = \frac{h\nu}{k_b}(n + \tfrac{1}{2})$$



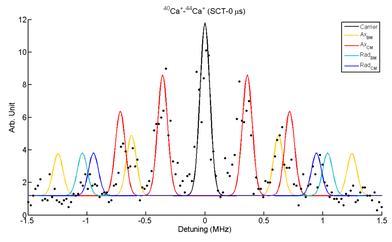
The 729 nm and 854 nm pulse times are on the order of 10^{-5} s. The 397 nm times are all 1 ms. We can vary t, the sympathetic cooling time, to increase the ion thermalization time.



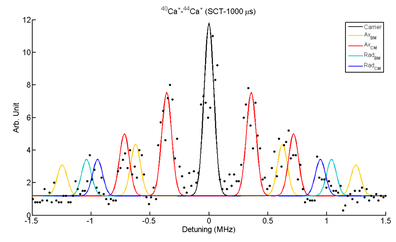
Sideband spectra of the $4^2S_{1/2}$, m_J = 1/2 ↔ $3^2D_{5/2}$, m_J = 5/2 for a single $^{40}Ca^+$.



Sideband spectra for two trapped ions in which the cooling ion's 397 nm laser is blocked. The splitting of the sidebands into center of mass and breathing modes is apparent and t = 0 us. The sideband linewidth < 30 kHz.



Sideband spectra for two trapped ions in which the cooling ion's 397 nm laser is unblocked but t = 0 us. The sideband linewidth has widened to 70 kHz.



Sideband spectra for two trapped ions in which the cooling ion's 397 nm laser unblocked and t = 1 ms. There is little obvious change in the sideband spectra. For higher t, significant heating or loss of the spectroscopy ion can occur.

Further Work

Our initial experiments with spectroscopy of the $4^2S_{1/2} \leftrightarrow 4^2P_{1/2}$ transition continuously probed both ions and the resulting peak shapes were difficult to analyze. By increasing collection efficiency, we will be able to use even lower s_{cool} values resulting in less cooling of the spectroscopy ion and better measurement of the temperature.

Currently, for spectroscopy of the Zeeman levels it is not obvious that there is any change in n for an increase in t, Δ_{cool}, or s_{cool} , but this may be due to high values of n which requires very good resolution of our sideband heights (for example, r = 1.034 for n = 29). In the multi-ion data we include, we see values of r implying n ~ 4 due to noise.

To increase the reliability of our sideband data, we will implement increased averaging of sideband spectra, only probe the first sidebands at a higher resolution to more cleanly image the peak, and switch which isotope we use for cooling and which we use for spectroscopy. Another approach would be to initially sideband cool both ions such that increases in n would result in a larger r. When we have refined these techniques, we will move onto larger ion chains as well as testing sympathetic cooling in planar ion traps.

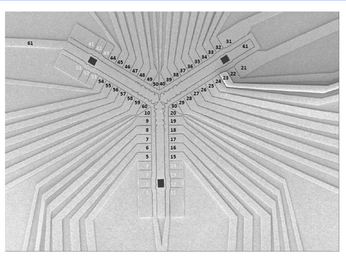


Image of planar ion trap that we will use in further studies. Fabricated by Sandia National Laboratories.

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