Towards Quantum Information Processing with Atomic Ions in a Penning Trap

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Abstract

We describe experiments aimed at assessing the suitability of ions held in a Penning trap as a candidate system for quantum information processing (QIP). In an experiment employing $^{24}Mg^+$ ions we have demonstrated a method that improves Doppler cooling in the Penning trap, resulting in ions that are more tightly localised than would otherwise be the case. Our measurements show that cooling of the magnetron motion is improved using this novel scheme. All the singly charged alkaline-earth anions apart from Be^+ and Mg^+ have metastable D states that cause complications for laser cooling. As a result, up until now, only these two species have been laser cooled in a Penning trap. In a separate experiment we have performed Doppler cooling of $^{40}Ca^+$ ions in a Penning trap for the first time.

Introduction

We report on progress in experiments aimed at assessing individually addressable laser cooled ions held in a Penning trap as a candidate system for Quantum Information Processing (QIP). The Penning trap employs static electric and magnetic fields as opposed to the oscillating electric field employed in the more familiar radio frequency Paul or linear traps. As a result, the decoherence rate may prove to be significantly lower in this system. The motion of an ion in a Penning trap consists of a harmonic oscillation in the electrostatic potential well along the axis of the trap and an epicyclic superposition of two circular motions in the radial plane: the modified cyclotron motion and a slower **E**×**B** drift around the centre of the trap, the magnetron motion. As a result of the rather complicated motion of ions in a Penning trap, laser cooling is less straightforward than it is in a radio frequency trap. One consequence is that the cooling laser beam must be offset from the centre of the trap. The magnetron motion is particularly difficult to minimize so that single ions are not usually as well localized as they are in a radio frequency trap. Our experiments are carried out using either $^{24}Mg^+$ ions or $^{40}Ca^+$ ions.

Axialisation

Axialisation is the process by which particles in a Penning trap are driven towards the central axis of the trap [1]. It occurs when the efficient cooling of the cyclotron motion is effectively extended to the magnetron motion by means of a coupling between the two. Axialisation has been used in conjunction with buffer gas cooling to increase storage times in Penning traps and to increase the density of ion clouds. Combined with laser cooling, very low temperatures should be reached. The process of axialisation is driven by a radial quadrupole field at ω_c generated by a split ring electrode. The excitation causes the quantum number of the cyclotron motion to increase by 1 and that of the magnetron to decrease by 1. This *reduces* the magnetron radius r_m and *increases* the cyclotron radius r_c. The excess energy in the cyclotron motion is then rapidly removed by the laser cooling. The process can be described by the following equations:

$$dr_c/dt = \delta r_m - \gamma_c r_c, \qquad dr_m/dt = -\delta r_c - \gamma_m r_m$$

where γ_c and γ_m are the cooling rates for the two motions and δ is the coupling rate due to the rf field. Various solutions to the equations can be found: in Figure 1 we show simulations of (a) oscillation between magnetron and cyclotron motions when the damping rates are zero; (b) axialisation when $\delta^2 > -\gamma_c\gamma_m$; and (c) a stable orbit with finite radius when $\delta^2 = -\gamma_c\gamma_m$. The situation in (c) arises with laser cooling if the damping rates are large and of opposite sign; the orbit then expands, reducing the interaction with the laser beam, until the equality is satisfied. Note that with laser cooling the values of the damping coefficients can be varied by changing the laser frequency and position.

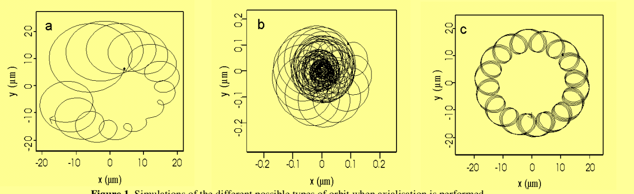


Figure 1. Simulations of the different possible types of orbit when axialisation is performed.

Demonstration of Axialisation

We report a study of the axialization and laser cooling of single $^{24}Mg^+$ ions and small clouds of $^{24}Mg^+$ ions in a Penning trap. Our set-up consists of a Penning trap with an internal radius of 10 mm in an electromagnet generating a field of roughly 1 T [2]. The ring electrode is split into four segments. Magnesium ions are trapped and laser cooled with light at 280 nm. The fluorescence is detected by a photomultiplier which feeds pulses to an MCA (to measure the fluorescence rate) or a TAC (for photon correlation studies). Some of the light can be imaged on an ICCD with a pixel size of 13 μm and a magnification of ~ 1. If the fluorescence signal is monitored by the photo-multiplier an increase is observed immediately when the cyclotron drive is applied, as the size of the cloud is reduced and the ions are more strongly cooled. Figure 2 shows the fluorescence signal as the drive frequency is scanned around the resonance. When the laser beam is in its normal position (offset from the trap centre) a broad resonance is observed (a) but when it is moved so that it goes through the centre of the cloud (making γ_m negative) a much more narrow resonance is seen (b) as cooling can now only take place when the drive is resonant [3].

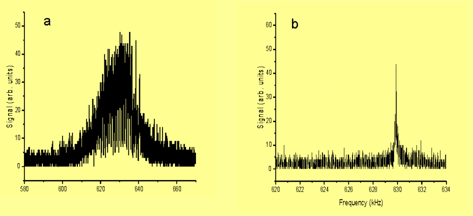


Figure 2. Plots of fluorescence as a function of the axialisation drive frequency. Axialisation enables laser cooling to be performed in the Penning trap with the laser beam centred on the ion orbit .

Images of the cloud

The ICCD images (Figure 3a) show a large cloud before and after the drive is turned on (but before optimisation of the axialisation conditions has been performed), showing that compression of the cloud has been achieved. Figure 3b shows an image of an optimised single ion. The measured size of the orbit is determined to be of the order of 10 μm or less after allowing for the finite resolution of the camera. The equivalent temperature for the single ion is of order 10 mK [3]. Finally, Figure 3c shows the cloud size and shape for various detunings of the rf drive.

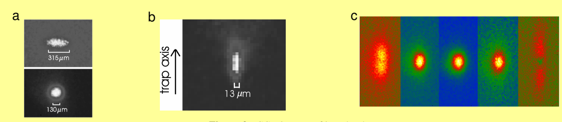
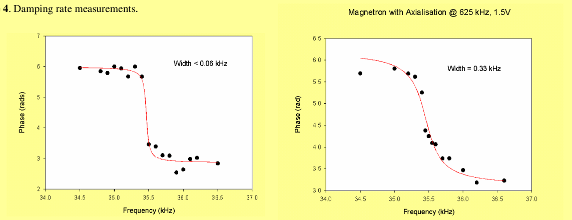


Figure 3. ICCD images of ion clouds.

Measurement of Damping Rates

We have measured the cooling rates for the ion motions using an rf-photon correlation technique [see 4]. By driving the ions with a weak rf field close to a motional resonance, the phase difference between the drive and the driven motion can be found. Moving through the resonance, this phase difference changes by π (as for any driven harmonic oscillator) and the width of the curve gives the cooling rate. In earlier experiments we measured this rate for both cyclotron and magnetron motions and found the magnetron cooling rate to be very low, as expected from calculations. We have now measured the rate in the presence of axialisation (see Figure 4) and we find that the magnetron cooling is enhanced due to the axialisation, confirming that the strong cyclotron cooling is extended to the magnetron motion by this technique.

Figure 4. Damping rate measurements.



Doppler cooling of Ca^+ in a Penning Trap

The relevant energy levels for Ca^+ are shown in Figure 5. In contrast to Be^+ and Mg^+, the Doppler cooling of Ca^+ in an rf trap (i.e. in the absence of a magnetic field) requires two lasers. This is because the branching ratio from the $^2P_{1/2}$ state is approximately 16:1 in favour of returning to the ground state. Therefore, after of order 16 optical cycles the ion will fall into the metastable $D_{3/2}$ state and laser cooling will be turned off. Doppler cooling therefore requires one laser on the 397 nm $^2S_{1/2}$ – $^2P_{1/2}$ cooling transition and one at 866 nm to repump ions that fall into the $^2D_{3/2}$ state back into the cooling cycle. Clearly, due to the far greater number of levels and transitions, laser cooling of Ca^+ will be significantly more complicated in the Penning trap than in an rf trap.

For QIP studies in Ca^+, the metastable $^2D_{5/2}$ state can act as the upper level of the qubit transition. This state has a lifetime of 1.1 s. The $^2S_{1/2}$– $^2D_{5/2}$ single photon quadrupole transition at 729 nm can conveniently be accessed using a Ti:Sapphire laser. For the purposes of Doppler cooling, the 397 nm and 866 nm transitions can be accessed using diode lasers. One major complication for Ca^+ in a Penning trap is that *two* lasers near 397 nm are required to cover the two Zeeman-split components of the $^2S_{1/2}$ – $^2P_{1/2}$ transition. At the same time, the 866 nm transition splits into six components (see Figure 6). In this poster we report successful laser cooling of Ca^+ in a Penning trap with a magnetic field of 1 T, by driving all of the required components directly with optical radiation.

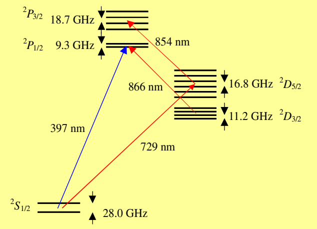


Figure 5. Partial energy level diagram for Ca^+ showing Zeeman sub-levels for a magnetic field of 1 T.

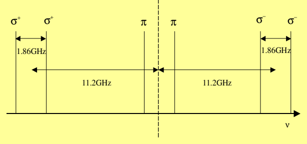


Figure 6. The six transitions between $D_{3/2}$ and $P_{1/2}$.

Experiment

The trap used in these experiments is a conventional Penning trap for which the inner diameter of the ring electrode is 10 mm and the endcap separation is 7 mm. The trap is located between the pole-pieces of a conventional electromagnet providing a maximum magnetic field of 0.98 T. The magnetic field is applied along the axis of the trap between the two endcaps. With the magnet switched off it is possible to run the trap as a conventional Paul (rf) trap. The laser beams enter the trapping region through a hole in the ring electrode and pass out through a diametrically opposed hole. Fluorescence from the ions is detected through a third hole in the ring electrode at 90° to the laser access holes. Fluorescence light from trapped ions is imaged onto the photocathode of a photon-counting photomultiplier tube (PMT) situated outside the magnetic field above the trap.

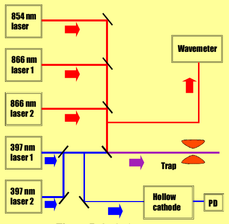


Figure 7. Optical set-up.

Figure 7 shows the optical set-up used for the experiment. We use two blue diode lasers in extended cavity arrangements to generate light at 397 nm. These lasers produce up to ~ 1 mW of useful output power. When focused to a ~ 100 μm spot in the trap this amount of laser power can easily saturate the cooling transition (the saturation power is around 30 μW). The blue laser polarisation is set to excite the π-components of the 397 nm transition. The 866 nm light is generated using home-built extended cavity diode lasers with final output powers of 12 mW. The injection current to these infra-red lasers is modulated to impose sidebands on the laser output. The carrier of each laser is then tuned half way between a pair of the σ transitions shown in figure 6. The sidebands provide the required repumping radiation.The blue and IR beams are mixed on a dichroic mirror. Beam splitters are used to mix laser beams of similar wavelength. All light entering the trap is focused through a single lens into the middle of the trap. All the laser beams can be moved in unison in the trap using a single mirror before the lens.

Results

One blue laser is scanned from below resonance up to resonance in 1 s and the fluorescence recorded. Figure 8 shows a fluorescence trace for a small cloud of ions laser cooled in this way. The minimum temperature of the ions is limited by the difficulty associated with effectively cooling the magnetron motion. In general therefore one would not expect to achieve cooling to the Doppler limit in the Penning trap. An upper bound on the temperature of the ions can be estimated from the width of the trace. For the trace shown in Figure 8 this is found to ~ 1 K.

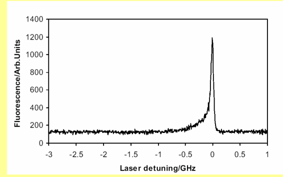


Figure 8. Fluorescence intensity vs. detuning of one of the blue lasers.

Conclusions

We have demonstrated that axialisation can be used in conjunction with laser cooling to give very tight confinement of a single ion to the axis of a Penning trap. The laser cooling rate for the magnetron motion is enhanced by this process. We have also demonstrated the trapping and laser cooling of Ca^+ in a Penning trap. We have therefore overcome some of the major objections to using single ions held in Penning traps as a resource for QIP. The next step in this research will be to trap and laser cool a single Ca^+ ion in our Penning trap and perform axialisation in this system. We are also developing a narrow linewidth 729nm laser system which we will use to perform sideband cooling and also as a means of measuring the decoherence rate in our system.

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