

Doppler cooling of Ca^+ ions in a Penning trap

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We have laser cooled a small cloud of $^{40}\text{Ca}^+$ ions stored in a Penning trap. The large Zeeman splittings that result from the presence of the imposed magnetic field necessitate the use of two cooling lasers tuned to the $^2S_{1/2}$ - $^2P_{1/2}$ transition near 397 nm (whereas only a single blue laser frequency is required in an rf trap). The 397 nm radiation is provided by a pair of blue diode lasers operated in extended cavities. Ions can escape from the cooling cycle by falling into a $^2D_{3/2}$ state. There is also a small probability that ions can be pumped into a $^2D_{5/2}$ state. The presence of large Zeeman splittings complicates the provision of repumper radiation to empty the D states. We describe two repumping schemes. The first scheme employs five infrared extended cavity diode lasers (ECDL's). The second scheme employs three infrared ECDL's, two of which have their injection current modulated to produce sidebands. An upper bound to the temperature of 1 K is inferred from the linewidth of the 397-nm fluorescence for a small cloud of $^{40}\text{Ca}^+$ ions in our Penning trap. This work is part of a program aimed at using atomic ions in a Penning trap for decoherence studies and quantum information processing.

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I. INTRODUCTION

There has been a great deal of work in recent years on laser cooling of trapped ions with a view to quantum information processing (QIP). All of the trapped ion work in this field so far has employed variants of the radio-frequency (rf) trap. In particular, following the suggestion of Cirac and Zoller [1], strings of ions held in a linear trap are being investigated (e.g., [2]), although much pioneering work has been done with more conventional three-dimensional miniature rf Paul traps (e.g., [3,4]). In an important recent development two groups have now demonstrated two-ion quantum gates [5,6]. A prerequisite for a practical ion trap quantum information processor is to laser cool the ions to the degree that they spend a substantial fraction of the time in the ground vibrational state of the trap [7–9].

One of the great experimental challenges facing any of the proposed quantum information processing schemes is decoherence. In the trapped ion system decoherence is thought to be due principally to the presence of fluctuating patch potentials on the electrodes and to uncontrolled Zeeman shifts resulting from stray magnetic fields. Heating of the ions in the trap is also a problem. The ions must be recooled between sequences of coherent operations. One major source of heating is the rf drive applied to the trap. The benefit of the linear rf trap is that a number of ions can be stored along a line where, in principle, the electric field is zero so that the heating effects should be rather small.

An alternative type of ion trap, the Penning trap, has been used extensively for the study of one-component plasmas [10], for precision measurements (e.g., [11]), for rf frequency standards [12], and for mass spectrometry [13]. The Penning trap does not rely on a radio-frequency drive to the trap

electrodes and as such may provide an interesting alternative for quantum information processing where the heating and decoherence problems may be less severe. The Penning trap employs similar electrodes to the rf Paul trap but now a dc potential is applied to the trap electrodes. The trap is located in a strong magnetic field of typically 0.3–6.0 T. In precision Penning trap experiments employing superconducting magnets, field stabilities in excess of 1 part in 10^8 are routinely achieved. The dc potential provides trapping along the axis of the trap electrodes while the magnetic field provides radial confinement. The axial motion is a harmonic vibration in the quadratic electrostatic potential. The radial motion consists of a fast circular orbit at a frequency near to the cyclotron frequency (the modified cyclotron frequency) superimposed upon a relatively slow circular drift of the center of this orbit around the center of the trap (the magnetron motion).

In fact the magnetron motion is unstable insofar as it describes motion around a potential hill. This leads to complications when one considers laser cooling in the Penning trap. The laser beam must not pass through the center of the ion trap but must be spatially offset in the radial plane so that there is an intensity gradient across the ion orbit [14,15]. If the beam placement is incorrect and the intensity gradient therefore has the wrong sign, the magnetron orbit will increase in size and the ion will be lost. For a single ion, the size of the radial orbit is limited by the waist size of the laser cooling beam. The result is that conventional Doppler laser cooling does not lead to very tight confinement in the radial plane. This is a significant drawback of the Penning trap; however, recently a technique which greatly improves the radial localization of ions in a Penning trap has been applied to single laser-cooled ions [16].

The singly ionized alkaline earth elements have a convenient atomic structure for laser cooling. Be^+ , Mg^+ , Ca^+ , Sr^+ , and Ba^+ have all been laser cooled in an rf trap whereas, of these, only Be^+ and Mg^+ have been cooled in a Penning trap (e.g., [10,17]). In fact, Be^+ and Mg^+ are the

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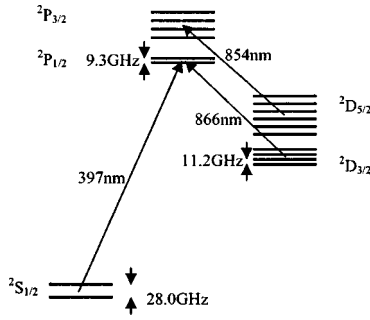


FIG. 1. Partial energy level diagram for Ca^+ showing Zeeman sublevels for a magnetic field of 1 T.

only ions that have been laser cooled in a Penning trap thus far. Among the singly ionized alkaline earths, these two ions are unique in that there are no metastable D states into which the ion can be optically pumped, removing the requirement for a repumper laser. Even with a magnetic field present, a closed-cycling transition can be driven by a single laser if σ -polarized light is used on the $2S_{1/2}$ - $2P_{3/2}$ transition. Both Be^+ and Mg^+ could be used for quantum information studies in a Penning trap but the presence of a large magnetic field and associated Zeeman shifts would lead to significant experimental complications, in particular in terms of the lasers required. In light of these considerations it is worth reassessing the potential of the other alkaline earth elements for use in a Penning trap, despite their more complicated level structures.

The relevant energy levels for $^{40}\text{Ca}^+$, the species studied in this work, are shown in Fig. 1. Doppler cooling of Ca^+ in a rf trap (i.e., in the absence of a magnetic field) requires two lasers. The branching ratio from the $2P_{1/2}$ state is approximately 16:1 in favor of returning to the ground state. Therefore, after of the order of 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 (see Fig. 1). The situation for the $2S_{1/2}$ - $2P_{3/2}$ transition is more complicated as the $2P_{3/2}$ state can decay to either of the metastable D states. 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 quantum information processing 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. In contrast, the relevant wavelengths for Be^+ or Mg^+ are usually accessed through the use of frequency-doubled dye lasers.

In order to perform Doppler cooling of Ca^+ in a Penning trap, 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. In this paper we report successful laser cooling of Ca^+ in a

Penning trap with repumper radiation driving four of the six 866-nm components as required. In terms of the Doppler cooling strategy, our system has some similarities to the rare isotope $^{43}\text{Ca}^+$ in a rf trap since the ground state of this isotope has a large hyperfine splitting. It is thought that $^{43}\text{Ca}^+$ may have a number of advantages over $^{40}\text{Ca}^+$ for QIP in rf traps.

Cooling $^{40}\text{Ca}^+$ in a Penning trap could, in principle, be accomplished with a single blue laser using the $2S_{1/2}$ - $2P_{3/2}$ transition, together with repumper lasers. For instance, if the ion is excited using the $m_J = -1/2 \rightarrow -3/2$ transition, reemission back to the ground state leaves it in the level $m_J = -1/2$ again. However, although this would simplify the requirements in terms of blue lasers, the repumping requirements would then be more severe since decay can occur from the $2P_{3/2}$ state to both D states.

II. EXPERIMENTAL METHOD

The trap used in these experiments is described in Ref. [18]. It is a conventional Penning trap for which the inner diameter of the ring electrode is 10 mm and the end cap separation is 7 mm. The vacuum tube containing the trap is located between the pole pieces of a conventional electro-magnet capable of providing a maximum magnetic field of 0.97 T. Ions are loaded into the trap by crossing an electron beam with an atomic beam.

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. A single plano-convex lens inside the vacuum chamber collimates the light which is then focused onto the PMT using a second lens outside the vacuum chamber. The single-photon PMT pulses are counted using a multichannel scaler (MCS) card housed in a PC.

We use two blue diode lasers in extended cavity arrangements to generate light at 397 nm (TUI Optics) to drive the π components of the Zeeman-split $S_{1/2}$ - $P_{1/2}$ transition. There are several options for providing repumping from the $D_{3/2}$ level. One is to drive the Zeeman-split components with separate lasers. To empty all four of the sublevels requires lasers to drive four of the six components of the $2D_{3/2}$ - $2P_{1/2}$ transition (see Fig. 2).

We have tested two different repumping strategies. In the first of these, repumper radiation near 866 nm is generated using four homebuilt extended cavity diode lasers (ECDL's) and the frequencies of these lasers are set to coincide with four of the six possible components of the $2D_{3/2}$ - $2P_{1/2}$ transition. In the second scheme repumper radiation is generated using two ECDL's. Sidebands are imposed on these diode lasers by modulating their injection current. The carrier frequency is then tuned exactly halfway between a pair of the closely spaced σ components of the $2D_{3/2}$ - $2P_{1/2}$ transition (see Fig. 2). The carrier is therefore nonresonant and it is the sideband radiation that provides repumping. We use SDL

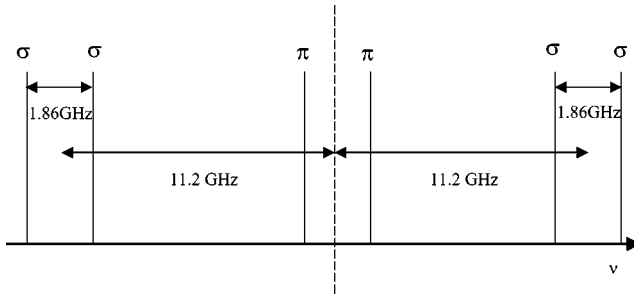


FIG. 2. The six transitions between $D_{3/2}$ and $P_{1/2}$. The splittings shown are for a magnetic field of 1 T.

5411 (100 mW) and Laser 2000 LD1377 (120 mW) single-mode diodes. The final output powers of the 866-nm lasers are ~ 12 mW.

We use a HP 8643A signal generator, running at 8 dBm, to modulate the current applied to the 866-nm lasers. The rf drive is split into two and each arm is connected to a bias T through a stub tuner, which is used for impedance matching. The output of the bias T is connected to a 10 cm length of rigid cable soldered directly to the diode pins. This produces sidebands of roughly 10% of the intensity of the carrier.

The radio-frequency drive significantly perturbs the operation of the extended cavity diode lasers. When the drive is switched on it is necessary to adjust the laser current and piezotransducer voltage in order to regain clean operation of the laser at the required frequency. These problems seem to be exacerbated at higher drive frequencies, so for this repumping scheme we employed a relatively low magnetic field of 0.78 T which required sidebands at 725 MHz.

The blue and infrared diode lasers are frequency locked to temperature-stabilized Fabry-Perot cavities. 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.

Since laser cooling of Ca^+ is much more straightforward in an rf trap than in a Penning trap, we initially trap and laser cool ions with our trap operating as a conventional rf trap. To do this the magnet is switched off and a drive voltage of ~ 300 V (peak to peak) at $\Omega/2\pi = 1.83$ MHz is applied to the ring electrode. When loading the trap in the rf mode, a weak axial magnetic field of 0.1 T is applied simply to guide the electrons into the trapping region. This magnetic field is switched off once the trap has been loaded. One laser at 397 nm is used to cool the ions on the $S_{1/2}-P_{1/2}$ transition and one laser at 866 nm is used to empty the $D_{3/2}$ level using the $D_{3/2}-P_{1/2}$ transition. The correct laser frequencies are set using a combination of a homemade hollow cathode lamp loaded with calcium and a Burleigh WA20 wavemeter which has been modified to enable reading of the 397 nm wavelength.

Due to background amplified spontaneous emission (ASE) light from the blue diodes at 393 nm, the $S_{1/2}-P_{3/2}$ transition is also driven very weakly. From the $P_{3/2}$ level the ion may spontaneously decay to the $D_{5/2}$ state. To empty this metastable state, an IR laser at 854 nm is used as a second

repumper on the $D_{5/2}-P_{3/2}$ transition. In the absence of the 854 nm light, the fluorescence signal of a cloud drops by a factor of 2 when the maximum available blue laser power is used. This implies that the ASE radiation causes about one jump per second per ion into the $D_{5/2}$ state.

In order to switch to operating the trap in the Penning mode, all of the required lasers ideally need to be preset to the appropriate wavelengths. In reality we adopt a different approach which is less laborious. Starting with an rf trap we switch on the extra lasers, tuned to their relevant zero-magnetic-field frequencies. We then increment the magnetic field and retune the lasers in order to reoptimize the fluorescence at each value of the magnetic field. During this process the trap acts as a “combined” (rf and Penning) trap. With the magnetic field switched on there are 12 Zeeman-split components of the 854-nm transition, six of which must, in principle, be addressed. In practice a single 854-nm laser continues to suffice even in the presence of a magnetic field. This is because even the now off-resonant clear-out rate is much greater than the rate of shelving in the $D_{5/2}$ state due to the ASE on the 397-nm lasers. Once the full magnetic field is reached, the rf drive is switched off. This results in a loss of the ion cloud. The trap is then reloaded as a pure Penning trap at the same magnetic field.

Applying the full power of the blue lasers as described above will oversaturate the $S_{1/2}-P_{1/2}$ cooling transition. For large ion clouds, despite saturation, higher laser power *does* lead to increased signal since ions in the outer regions of the laser focus will contribute significantly to the overall fluorescence level. Therefore, the full available 397-nm laser power is used in initial experiments using large clouds. However, it is clear that high 397-nm laser intensities will lead to significant power broadening of the transition for ions near the center of the beam. The Doppler-limited temperature is given by $k_B T = \hbar \Gamma / 2$ where Γ is the spontaneous decay rate. If the linewidth is broadened, effectively increasing Γ , this will increase the minimum temperature of the ions. To avoid this, the power of the blue lasers is attenuated using neutral density filters. For small clouds this does not greatly affect the fluorescence intensity since all of the ions are near the center of the beam.

III. RESULTS

Figure 3 shows a fluorescence trace for a small cloud of laser-cooled Ca^+ ions in a Penning trap. This trace was obtained at a magnetic field of 0.97 T using the repumping scheme that employs four independent 866-nm lasers. One of the blue lasers is scanned from 3.6 GHz below resonance up to resonance in a time of ~ 1 s and the fluorescence recorded. Scanning the entire line shape is not possible since blue detunings lead to laser heating rather than cooling. Figure 3 is the sum of the results of 50 consecutive scans.

The minimum temperature of the ions is limited by a number of effects. Of these the greatest is probably the difficulty associated with effectively cooling the magnetron motion. Optical pumping effects will also play a role. In general therefore one would not expect to achieve cooling to the Doppler limit in the Penning trap. An upper bound on the

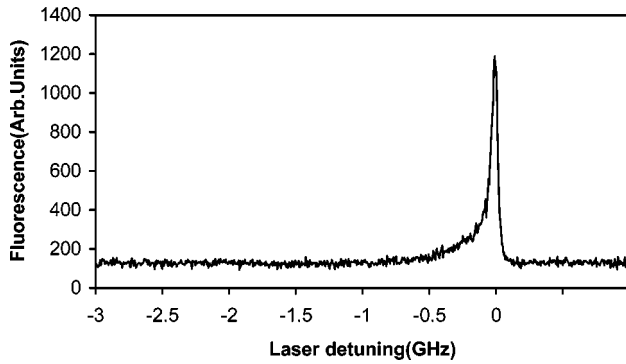


FIG. 3. Fluorescence as a function of 397 nm laser detuning for a small cold cloud of $^{40}\text{Ca}^+$ ions.

temperature of the ions can be obtained by fitting the fluorescence trace with half a Gaussian line shape. The maximum possible temperature of the Doppler-broadened ions can be found from

$$T = \frac{\Delta\nu^2 A}{[(7.16 \times 10^{-7}) \nu_0]^2}, \quad (1)$$

where A is the atomic weight, ν_0 is the resonance frequency, and $\Delta\nu$ is the full width at half maximum, which is roughly twice the width of the peak shown in Fig. 3. In fact the peak shown in Fig. 3 includes the fly-back of the sawtooth laser scan. Taking this into account we find $\Delta\nu$ to be 82 MHz which implies an upper limit on the temperature of ~ 1 K. No allowance has been made for natural broadening which gives a linewidth of 22 MHz. In the past we have performed a number of studies of laser-cooled Mg^+ in a Penning trap. The temperature we have inferred for small clouds of Ca^+ is comparable to the temperature we would expect to find for a similar sized cloud of Mg^+ .

The repumping scheme employing two lasers with sidebands gives essentially identical results. Since this repumping scheme requires fewer lasers, we have now routinely adopted it. Eventually we intend to operate a trap with a

higher magnetic field of up to 2.5 T provided by a superconducting magnet. This will require sidebands to be imposed at a higher frequency.

IV. CONCLUSION

We have demonstrated the trapping and laser cooling of $^{40}\text{Ca}^+$ in a Penning trap. $^{40}\text{Ca}^+$ has a fundamentally different level structure as compared to the only other ions so far cooled in a Penning trap (Mg^+ , Be^+). Two cooling lasers of equal strength and a repumping scheme are required for $^{40}\text{Ca}^+$. Effective Doppler cooling of the $^{40}\text{Ca}^+$ ions has been achieved, giving an upper bound of 1 K on the temperature.

The next step in this research will be to trap and laser cool a single $^{40}\text{Ca}^+$ ion in our Penning trap. We will do this in a different trap with a number of improved features. First, it will have an imaging system optimized for $^{40}\text{Ca}^+$ so that our signal per ion should be higher (the imaging optics in the trap used at present are optimized for the Mg^+ wavelength). Second, it will have a ring electrode which is split into four sections. This will allow us to apply the technique described in Ref. [16] which improves the localization of single-laser-cooled ions in a Penning trap and, importantly, removes the extreme sensitivity to beam position normally encountered in the Penning trap. We are also currently developing a narrow (linewidth $\sim$ a few kHz) Ti:sapphire laser which we will use to interrogate the 729-nm qubit transition and perform sideband cooling in our trap.

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- [1] J.I. Cirac and P. Zoller, *Phys. Rev. Lett.* **74**, 4091 (1995).
 - [2] H.L. Naegerl, Ch. Roos, D. Liebfried, H. Rohde, G. Thalhammer, J. Eschner, F. Schmidt-Kaler, and R. Blatt, *Phys. Rev. A* **61**, 023405 (2000).
 - [3] C. Monroe, D.M. Meekhof, B.E. King, W.M. Itano, and D.J. Wineland, *Phys. Rev. Lett.* **75**, 4714 (1995).
 - [4] Ch. Roos, Th. Zeiger, H. Rohde, H. Naegerl, J. Eschner, F. Liebfried, F. Schmidt-Kaler, and R. Blatt, *Phys. Rev. Lett.* **83**, 4713 (1999).
 - [5] F. Schmidt-Kaler, H. Häffner, Mark Riebe, S. Gulde, G.P.T. Lancaster, T. Deuschle, C. Becher, C.F. Roos, J. Eschner, and R. Blatt, *Nature (London)* **422**, 408 (2003).
 - [6] D. Leibfried, D. DeMarco, V. Meyer, D. Lucas, M. Barrett, J. Britton, W.M. Itano, B. Jelenkovic, C. Langer, T. Rosenband, and D.J. Wineland, *Nature (London)* **422**, 412 (2003).
 - [7] C. Monroe, D.M. Meekhof, B.E. King, S.R. Jefferts, W.M. Itano, D.J. Wineland, and P. Gould, *Phys. Rev. Lett.* **75**, 4011 (1995).
 - [8] F. Schmidt-Kaler *et al.* *J. Mod. Opt.* **47**, 2000 (2000).
 - [9] J. von Zanthier, J. Abel, Th. Becker, M. Fries, E. Peik, H. Walther, R. Holzwarth, J. Reichert, Th. Udem, T.W. Hänsch, A.Yu. Nevsky, M.V. Skvortsov, and S.N. Bagayev, *Opt. Commun.* **166**, 57 (1999).
 - [10] T.B. Mitchell, J.J. Bollinger, D.H.E. Dubin, X.-P. Huang, W.M. Itano, and R.H. Baughman, *Science* **282**, 1290 (1998).
 - [11] R.S. Van Dyck, Jr., P.B. Schwinberg, and H. Dehmelt, *Phys. Rev. Lett.* **59**, 26 (1987).
 - [12] J.J. Bollinger, D.J. Heinzen, W.M. Itano, S.L. Gilbert, and D.J. Wineland, *IEEE Trans. Instrum. Meas.* **40**, 126 (1991).
 - [13] R.E. March and R.J. Hughes, *Quadrupole Storage Mass Spec-*

- troscopy* (Wiley Interscience, New York, 1989).
- [14] W.M. Itano and D.J. Wineland, Phys. Rev. A **25**, 35 (1982).
- [15] R.C. Thompson and J. Papadimitriou, J. Phys. B **33**, 3393 (2000).
- [16] H.F. Powell, D.M. Segal, and R.C. Thompson, Phys. Rev. Lett. **89**, 093003 (2002).
- [17] P.L. Knight, I.C. Percival, R.C. Thompson, and D.C. Wilson, J. Mod. Opt. **40**, 1663 (1993).
- [18] D.J. Bate, K. Dholakia, R.C. Thompson, and D.C. Wilson, J. Mod. Opt. **39**, 305 (1992).