Two-ion Coulomb crystals of Ca⁺ in a Penning trap.

D. R. Crick, H. Ohadi, I. Bhatti, R. C. Thompson and D. M. Segal

Blackett Laboratory, Imperial College of Science, Technology and Medicine, Prince Consort Rd., London SW7 2AZ, UK. d.segal@ic.ac.uk

Abstract: Results demonstrating laser cooling and observation of individual calcium ions in a Penning trap are presented. We show that we are able to trap, cool, image and manipulate the shape of very small ensembles of ions sufficiently well to produce two-ion 'Coulomb crystals' aligned along the magnetic field of a Penning trap. Images are presented which show the individual ions to be resolved in a two-ion crystal. A distinct change in the configuration of such a crystal is observed as the experimental parameters are changed. These structures could eventually be used as building blocks in a Penning trap based quantum computer.

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References and links

- 1. J. I. Cirac and P. Zoller, "Quantum Computations with Cold Trapped Ions," Phys. Rev. Lett. 74, 4091, 1995.
- D. Leibfried, B. DeMarco, V. Meyer, D. Lucas, M. Barrett, J. Britton, W. M. Itano, B. Jelenkovic, C. Langer, T. Rosenband, and D. J. Wineland, "Experimental demonstration of a robust, high-fidelity geometric two ionqubit phase gate," Nature 422, 412, 2003.
- F. Schmidt-Kaler, H. Häffner, M. Riebe, S. Gulde, G. P. T. Lancaster, T. Deuschle, C. Becher, C. F. Roos, J. Eschner, and R. Blatt, "Realization of the Cirac-Zoller controlled-NOT quantum gate". Nature 422, 408–411, 2003.
- S. Gulde, M. Riebe, G. P. T. Lancaster, C. Becher, J. Eschner, H. Häffner, F. Schmidt-Kaler, I. L. Chuang, and R. Blatt, "Implementation of the Deutsch-Jozsa algorithm on an ion-trap quantum computer," Nature 421, 48–50, 2003.
- K.-A. Brickman, P. C. Haljan, P. J. Lee, M. Acton, L. Deslauriers, and C. Monroe "Implementation of Grover's quantum search algorithm in a scalable system," Phys. Rev. A.72, 050306R, 2005.
- M. Riebe, H. Häffner, C. F. Roos, W. Ha
 isel, J. Benhelm, G. P. T. Lancaster, T. W. Ko
 iber, C. Becher, F. Schmidt-Kaler, D. F. V. James and R. Blatt, "Deterministic quantum teleportation with atoms," Nature 429, 734, 2004.
- M. D. Barrett, J. Chiaverini, T. Schaetz, J. Britton, W. M. Itano, J. D. Jost, E. Knill, C. Langer, D. Leibfried, R. Ozeri and D. J. Wineland, "Deterministic quantum teleportation of atomic qubits," Nature 429, 737, 2004.
- J. Chiaverini, J. Britton, D. Leibfried, E. Knill, M. D. Barrett, R. B. Blakestad, W. M. Itano, J. D. Jost, C. Langer, R. Ozeri, T. Schaetz and D. J. Wineland, "Implementation of the Semiclassical Quantum Fourier Transform in a Scalable System," Science 308, 997, 2005.
- R. Reichle, D. Leibfried, E. Knill, J. Britton, R. B. Blakestad, J. D. Jost, C. Langer, R. Ozeri, S. Seidelin and D. J. Wineland, "Experimental purification of two-atom entanglement," Nature 443, 838, 2006.
- D. Leibfried, E. Knill, S. Seidelin, J. Britton, R. B. Blakestad, J. Chiaverini, D. B. Hume, W. M. Itano, J. D. Jost, C. Langer, R. Ozeri, R. Reichle, and D. J. Wineland, "Creation of a six-atom 'Schrödinger cat' state," Nature 438, 639–642, 2005.
- H. Häffner, W. Hänsel, C. F. Roos, J. Benhelm, D. Chekalkar, M. Chwalla, T. Körber, U. D. Rapol, M. Riebe, P. O. Schmidt, C. Becher, O. Gühne, W. Dür, and R. Blatt, "Scalable multiparticle entanglement of trapped ions," Nature 438, 643–646, 2005.
- D. J. Wineland, C. Monroe, W. M. Itano, D. Leibfried, B. E. King, and D. M. Meekhof, "Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions," J. Res. Natl. Inst. Stand. Technol. 103, 259, 1998.

- D. Kielpinski, C. Monroe, and D. J. Wineland, "Architecture for a large-scale ion-trap quantum computer," Nature 417, 709–711, 2002.
- Q. A. Turchette, Kielpinski, B. E. King, D. Leibfried, D. M. Meekhof, C. J. Myatt, M. A. Rowe, C. A. Sackett, C. S. Wood, W. M. Itano, C. Monroe, and D. J. Wineland, "Heating of trapped ions from the quantum ground state," Phys. Rev. A 61, 063418, 2000.
- L. Deslauriers, S. Olmschenk, D. Stick, W. K. Hensinger, J. Sterk, and C. Monroe, "Scaling and Suppression of Anomalous Heating in Ion Traps," Phys. Rev. Lett. 97, 103007, 2006.
- W. M. Itano and D. J. Wineland, "Laser cooling of ions stored in harmonic and Penning traps," Phys. Rev. A 25, 35–54, 1982.
- H. F. Powell, S. R. de Echaniz, E. S. Phillips, D. M. Segal, and R. C. Thompson, "Improvement of laser cooling of ions in a Penning trap by use of the axialization technique," J. Phys. B: At. Mol. Opt. 36, 961–970, 2003.
- R. J. Hendricks, E. S. Phillips, D. M. Segal, and R. C. Thompson, "Laser cooling in the Penning trap: an analytical model for cooling rates in the presence of an axializing field," arXiv:0709.3817v1 [quant-ph] 2007, Accepted for publication in J. Phys.B. (in press).
- M. Brownnutt, G. Wilpers, P. Gill, R. C. Thompson, and A. G. Sinclair, "Monolithic microfabricated ion trap chip design for scaleable quantum processors," New J. Phys. 8, 232, 2006.
- 20. P. K. Ghosh, Ion Traps, (Oxford University Press 1995).
- M. König, G. Bollen, H.-J. Kluge, T. Otto and J. Szerypo, "Quadrupole excitation of stored ion motion at the true cyclotron frequency," Int. J. Mass Spectrom. Ion Proc. 142 95-116, 1995.
- J. R. Castrejón-Pita, H. Ohadi, D. R. Crick, D. F. A. Winters, D. M. Segal, and R. C. Thompson, "Novel Designs for Penning Ion traps," J. Mod. Opt. 54, 1581–1594, 2007.
- A. Barenco, C. H. Bennett, R. Cleve, D. P. DiVincenzo, N. Margolus, P. Shor, T. Sleator, J. A. Smolin, and H. Weinfurter, "Elementary gates for quantum computation," Phys. Rev. A 52, 3457–3467, 1995.
- G. Ciaramicoli, I. Marzoli, and P. Tombesi, "Scalable Quantum Processor with Trapped Electrons," Phys. Rev. Lett. 91, 017901, 2003.
- T. B. Mitchell, J. J. Bollinger, D. H. E. Dubin, X. P. Huang, W. M. Itano, and R. H. Baughman, "Direct observations of structural phase transitions in planar crystallized ion plasmas," Science 282, 1290–1293, 1998.
- D. Porras and J. I. Cirac, "Quantum Manipulation of Trapped Ions in Two Dimensional Coulomb Crystals," Phys. Rev. Lett. 96, 250501, 2006.
- 27. J. M. Taylor, T. Calarco, "Wigner crystals of ions as quantum hard drives," arXiv:0706.1951.
- 28. M. E. M. Storkey. "Studies of laser-cooled trapped ions," PhD thesis, Imperial College London, 2001.
- J. L. K. Koo. "Laser cooling and trapping of Ca⁺ ions in a Penning trap," PhD thesis, Imperial College London, 2003.
- G.P.T. Lancaster, H. Häffner, M.A. Wilson, C. Becher, J. Eschner, F. Schmidt-Kaler, R. Blatt, "Doppler cooling a single Ca⁺ ion with a violet extended-cavity diode laser," Appl. Phys. B 76 805, 2003.
- F. Diedrich, E. Peik, J. M. Chen, W. Quint, and H. Walther, "Observation of a Phase Transition of Stored Laser-Cooled Ions," Phys. Rev. Lett. 59, 2931–2934, 1987.
- S. Fishman, G. De Chiara, T. Calarco and G. Morigi, "Structural phase transitions in low-dimensional ion crystals," arXiv:0710.1831.
- D. Reiss, K. Abich, W. Neuhauser, Ch. Wunderlich, and P. E. Toschek, "Raman cooling and heating of two trapped Ba⁺ ions," Phys. Rev. A 65 053401, 2002.
- 34. D. G. Enzer, M. M. Schauer, J. J. Gomez, M. S. Gulley, M. H. Holzscheiter, P. G. Kwiat, S. K. Lamoreaux, C. G. Peterson, V. D. Sandberg, D. Tupa, A. G. White, R. J. Hughes and D. F. James, "Observation of Power-Law Scaling for Phase Transitions in Linear Trapped Ion Crystals," Phys. Rev. Lett. 85, 2466, 2000.
- D.J. Berkeland, J.D. Miller, J.C. Bergquist, W.M. Itano, and D.J. Wineland, "Minimization of ion micro motion in a Paul trap," J. Appl. Phys. 83 5025, 1998.
- R.C. Thompson and D.C. Wilson, "The motion of small numbers of ions in a Penning trap," Z Phys. D 42, 271–277, 1997.
- F. Mintert and Ch. Wunderlich, "Ion-Trap Quantum Logic Using Long-Wavelength Radiation," Phys. Rev. Lett. 87, 257904–1, 2001.

1. Introduction

1.1. Quantum information processing with trapped ions

Laser cooled trapped ions represent one of the most promising candidate systems for quantum information processing (QIP). Inspired by the theoretical work of Cirac and Zoller [1], small 'crystallized' ensembles of ions held in radio-frequency (RF) traps have been used to demonstrate quantum gates, simple algorithms [2–9] and to generate multiparticle entanglement [10, 11]. The original scheme of Cirac and Zoller envisaged a quantum computer com-

prised of a long string of ions in a linear RF trap. Each ion would represent a qubit and entanglement would be engineered through the ions' collective quantised motion in the trap. It is now clear that this approach is not scalable to large numbers of qubits, so alternative strategies for scalability of trapped ion QIP have been suggested and are being investigated. In particular Wineland *et al.* and later Kielpinski *et al.* suggest a quantum computer made up of ions held in two dimensional arrays of miniature traps [12, 13]. Ions are brought together into a single miniature trap for gate operations and then separated and shuttled into other trapping zones for storage. Miniature traps and large RF voltages are required in order to provide tight confinement, leading to high motional frequencies which, in turn, give relatively fast gate operation times. However, the presence of time-varying patch potentials on the surface of the electrodes gives rise to decoherence effects in the trapped ions. In current traps this is at a tolerable level, however, this source of decoherence scales strongly with trap size [14, 15] and is likely to present challenges in the next generation of even smaller traps.

Unlike a radio-frequency trap, which uses a high voltage oscillating potential to realise ion confinement, the Penning trap uses entirely static electric and magnetic fields for this purpose. Although the oscillating drive potential in RF traps is not a major cause of decoherence at the scale of current traps (~ 0.1 -1 mm) its effects in the case of future generations of smaller traps are as yet unknown. In particular the RF potential may enter the problem indirectly through its influence on the less well understood problem of patch potentials [14].

The motion of an ion in an RF trap can be approximated as a superposition of three harmonic oscillations along three orthogonal axes. Laser cooling of ions in such a trap leads to tight confinement in all three dimensions. In a Penning trap the motion along the axis of the imposed magnetic field is simple harmonic motion, but the motion in the other two dimensions (the radial plane) is more complicated. As a result laser cooling is less straightforward in this system leading to relatively poor confinement in the radial plane [16]. In addition, the energy levels of atomic ions display large Zeeman splittings (tens of GHz for Ca^+ at B = 1 T) when held in the high magnetic field of a Penning trap. Thus a more complicated laser system is required when compared to cooling the same ion species in an RF trap. For these reasons ions held in Penning traps have not so far been employed in OIP experiments. However, better control over the radial motion (and tighter confinement) can be achieved through a process known as axialization [17, 18]. Also, modern laser diode and optical fibre technology allow a multiple-laser setup to be implemented relatively straightforwardly. The confinement in a Penning trap is largely provided by the magnetic field together with only moderate static voltages. Therefore, tight trapping and high motional frequencies can in principle be achieved with larger trapping structures eliminating some other possible disadvantages of very small RF traps such as excessive laser beam scatter and trap damage due to RF power dissipation or electrical breakdown [19] as well as the patch potential effect.

1.2. Ions in a Penning trap

A conventional Penning trap consists of a set of electrodes, to which static electric potentials are applied, held in a region of a large homogeneous magnetic field in a vacuum. Typically three electrodes are used: a ring shaped electrode and two endcaps. For trapping positively charged ions the endcaps are held at a positive potential with respect to the ring. This leads to harmonic trapping along the axis between the endcaps. However the ions are attracted to the ring electrode by the inhomogeneous electric field. The magnetic field applied along the axis of the trap forces the ions into cyclotron orbits in the radial plane. The presence of the electric field means that the cyclotron motion is modified and occurs at a reduced frequency ω_c' compared to the true cyclotron frequency $\omega_c = eB/m$. Furthermore the ions perform a slow drift motion about the centre of the trap at the magnetron frequency $\omega_m = \omega_c - \omega'_c$ [20].

Laser cooling of ions in the Penning trap is complicated by the unstable motion in the radial plane. If energy is removed from the axial and cyclotron degrees of freedom these motions shrink as expected. On the other hand, if energy is removed from the magnetron mode this motion expands as the ions move down the sides of the radial potential hill. In order for laser cooling to improve three dimensional confinement, a strategy is required which simultaneously removes energy from the axial and cyclotron motion but pumps energy into the magnetron motion. Very soon after the first demonstrations of laser cooling in other systems such a strategy was devised for ions in a Penning trap [16]. It consists of positioning a focused, red-detuned laser beam slightly offset from the centre of the trap. If the beam is offset to the correct side of the trap, scattering occurs when the laser opposes the cyclotron motion but is in the same direction as the magnetron motion. This results in the amplitude of both motions being reduced. This strategy is effective but the radial confinement, although improved, is limited by the size of the laser beam focus, and the resulting motion is never as small as it can be for ions in an RF trap.

A second strategy (axialization) is available provided the trap is equipped with a ring electrode that is split into four segments. If a weak oscillating radial quadrupole potential is applied to the ring at the true cyclotron frequency $\omega_c = \omega'_c + \omega_m$ the effect is to couple together the two otherwise independent radial modes. In the absence of damping, the result is that energy is periodically transferred between these two motions. For our trap, simulations show that the frequency of this transfer of energy is approximately 10 Hz per mV of axialization drive voltage. If a source of damping is present the overall orbit size gradually shrinks [18]. This is essentially the same as a process called 'sideband cooling' (which is used in, for example, ion trap mass spectrometry) [21] with the exception that in axialization the damping is provided by laser cooling whereas in conventional sideband cooling it is provided by buffer gas collisions.

1.3. QIP in a Penning trap

A scheme for scalable Penning trap QIP has been suggested based on multiple miniature Penning traps made from planar electrode structures [22]. In this proposal ions would be moved between trapping zones, in directions perpendicular to the magnetic field, by using the electrodes to impose near-linear electric fields. The ions move from one trap to another via cycloid loops and if they start out at rest in one trapping zone they are automatically brought to rest as they arrive in the target trapping zone. Quantum gate operations could be accomplished by bringing ions together in a privileged trap which has multiple trapping zones along the axial direction. A two-ion crystal along the axis of a Penning trap behaves in the same way as a similar structure in a linear radio-frequency trap and the techniques developed in RF traps can be employed in this system. In theory, the combination of single qubit rotations and a universal two-qubit quantum logic gate is sufficient to build any quantum logic network [23]. Thus with the ability to control single ions and two-ion axial crystals, the Penning trap QIP scheme discussed in Ref. [22] should be possible. We note that the potential advantage of the Penning trap in terms of the ability to provide tight trapping with relatively distant electrodes only applies to the qubit storage aspect of the scheme outlined in [22]. The size scale of the individual planar electrodes in that scheme is not critical. Their role is simply to provide either the standard trapping field, or a nearly linear electric field in the radial plane to facilitate controlled movement of the ions. They do not need to be small enough to act as a wedge in the process of ion-pair separation – this operation would be accomplished in a multiple trap aligned along the magnetic field axis.

A number of other ideas for Penning trap QIP have also been put forward, including the use of trapped electrons with radio-frequency and microwave techniques [24]. More recently, inspired by images of large radial crystals in a Penning trap obtained using a rotating electric

field technique [25], the use of planar crystals of ions in a Penning trap has been proposed for QIP and as a quantum simulator [26, 27].

2. Single ions and quantum jumps

The trap used in this work has been described in detail elsewhere [28]. It is a conventional Penning trap whose electrodes have conical cross sections. The ring electrode is split into four segments to allow the application of an axializing potential. Light is sent into the trap through a gap between two ring segments and emerges through another diametrically opposed gap. In a direction at 90° to the laser beams the gap between the ring segments is enlarged to allow fluorescence to escape the trap. The fluorescence is collected by a plano-convex singlet lens held 19 mm away from the centre of the trap, inside the vacuum chamber. Ions are loaded into the trap by electron bombardment of a weak atomic beam of calcium. Electrons are generated using a thoriated tungsten filament placed behind one of the endcap electrodes. The endcap electrodes have small central holes to allow the electrons to pass through the centre of the trap. The background gas pressure in the trap vessel is $\sim 2 \times 10^{-10}$ mbar. A representation of the trap geometry is shown in Fig. 1.



Fig. 1. Schematic layout of the Penning trap used in this work.

A partial energy level diagram for ${}^{40}Ca^+$ is shown in Fig. 2. Two lasers near 397 nm are required to avoid optical pumping – one for each of the ${}^{2}S_{1/2}$ state Zeeman sub-levels. These wavelengths are provided by a pair of extended cavity diode lasers (ECDL).¹ Four home-made

¹Toptica DL100



Fig. 2. Partial energy level diagram of ${}^{40}Ca^+$ in a 0.98 tesla magnetic field.

ECDL's operating near 866 nm are used to repump ions from the ${}^{2}D_{3/2}$ metastable state to close the cooling cycle. Doppler cooling of Ca⁺ ions in a Penning trap had previously been achieved using a simpler repumping strategy that used two infra-red lasers near 866 nm with sidebands generated by direct modulation of the diode injection current [29]. However, the amount of power that can be generated in the sidebands at the high frequencies required is relatively low and so we have now opted for a more direct approach using four separate lasers.

The two blue laser beams are combined on a beam splitter and coupled into a polarisation maintaining optical fibre.² Similarly the four infra red beams are coupled into a second optical fibre.³ The outputs of the two fibres are then combined using a dichroic mirror and sent to the trap via a focusing lens.

Quantum jumps into the ${}^{2}D_{5/2}$ state can occur via excitation to the ${}^{2}P_{3/2}$ state. Normally this would not be populated but transitions to this state can be mediated by amplified spontaneous emission (ASE) present in either the 397 nm lasers (ASE at 393 nm) or in the 866 nm lasers (ASE at 850 nm). To avoid these quantum jumps, and to optimise the laser cooling, another laser at 854 nm may be used to repump ions in the ${}^{2}D_{5/2}$ levels back into the cooling cycle. In principle this laser should be broadband and cover all six of the required transitions from ${}^{2}D_{5/2}$ to ${}^{2}P_{3/2}$. However, the ASE only results in jumps into the ${}^{2}D_{5/2}$ level at a rate of a few events per second. In order to achieve a high fluorescence signal, the repumper laser only needs to bring the ion back into the cooling cycle at a rate comparable to this and so a single ECDL tuned centrally to the band of transitions suffices for this purpose. For future experiments where these unwanted quantum jumps must be avoided the laser outputs will be dispersed using gratings or prisms before being coupled into the optical fibres to prevent ASE from reaching the trapping region [30].

The fluorescence collection lens attached to the trap forms part of a multi-lens imaging system, with the other lenses outside of the vacuum chamber. The photomultiplier tube (PMT) used for detection is adversely affected by magnetic fields and so it must be held \sim 50 cm from the trap centre. The light is focused onto the PMT using another two lenses, with an overall magnification of roughly unity. A 200 μ m aperture is placed in the image plane to cut down the

²Nufern PM-S350-HP

³Oz Optics SMJ-A3A-3AF-850-5/125

collection of stray light. A pair of filters is placed after the aperture to reduce other unwanted background light, e.g. room light, and light from the electron beam filament.

In order to obtain images of the trapped ions the light can alternatively be sent to an image intensified CCD camera.⁴ This is done by flipping a mirror into the optical path between the middle and final lens of the optical system. The light is then diverted at 90° to another lens system which forms an image which is then re-focused onto the camera using a commercial camera lens.⁵ The overall magnification is appoximately 4.

The trap is usually operated with a magnetic field of 0.98 ± 0.01 tesla, produced by a conventional electromagnet. Initially the wavelengths of the various lasers are set at their correct values using a home-made wavemeter and the beams are aligned centrally in the aperture formed by the gap in the ring segments. A large cloud of ions is loaded by running the atomic beam and electron filament simultaneously until some fluorescence signal is observed. Initially the fluorescence level may be low but fine adjustment of the six laser frequencies and the two beam positions (397 nm and 866 nm) allows this signal to be optimised. The optimum beam positions and laser detunings depend on the size of the cloud so we proceed to load a smaller cloud of ions (by lowering the current in the filament) and re-optimise the fluorescence level. For a very small cloud of ions the character of the noise on the fluorescence signal changes visibly due to the presence of quantum jumps. When this is the case we proceed to try to load a single ion by lowering the filament current still further and adopting a slightly different loading strategy.

The atomic beam oven is turned on for 60 seconds. After the first 30 seconds the electron filament is turned on for the remaining 30 seconds. Both are then switched off. At this stage there is usually no fluorescence detected, however an ion (or ions) may have been loaded into the trap. If the ion is in a large magnetron orbit, which is likely, then it spends very little of its time in the focused laser cooling beam. It can therefore take a significant time for the ion to cool. As the ion is slowly cooled it moves closer to the centre of the trap and the cooling rate and fluorescence level then increase dramatically. It is not uncommon to wait up to 5 minutes for the fluorescence from a single ion to become visible above the background level of scattered light. However, when this does happen the fluorescence increases to its maximum value very suddenly. Figure 3 shows the fluorescence rate during such a loading procedure. The trace begins just after the filament is switched off. After a waiting time of 35 seconds an ion cools to the centre of the trap and the fluorescence level rises to \sim 5000 counts per second. This count rate is somewhat lower than expected given the solid angle for fluorescence detection (0.16)steradians), the transmission coefficients of the filters, optics and window and the quantum efficiency of the detector (we calculate an overall detection efficiency of 1.2×10^{-3} which we would expect to lead to a count rate of $\sim 10^4$ s⁻¹). The lower than expected signal level per ion is probably due to the more complicated laser cooling scheme for Ca^+ in a Penning trap, which requires optimisation of the frequencies of six lasers, taking care to avoid the generation of unwanted 'trapped states'.

The fluorescence during a sequence where two ions are loaded into the trap is shown in Fig. 3. A second ion joins the first at $t \approx 70$ s. The number of cold ions in the trap can be checked by observing quantum jumps in the signal level when the repumper laser at 854nm is blocked. Figure 4 shows histograms of fluorescence rates corresponding to different numbers of ions in the trap. The example in Fig. 4(d) shows that the number of ions (two in this case) can be simply determined by eye in real time.

An interesting feature to note in Fig. 3 is the temporary loss of signal at $t \approx 70$ s. We interpret this as being due to the second (hot) ion coming into the centre of the trap and temporarily heating the cold ion that is already there. The two ions then re-cool resulting in the subsequent

⁴Andor DH534-18S-03

⁵Minolta MD 50mm F1.7



Fig. 3. Fluorescence rate after loading two ions. Time bins are 10 ms wide. Occasional brief quantum jumps can be seen even in the presence of laser light at 854 nm.



Fig. 4. Histograms from 40 seconds of data collection with 30 ms time bins show discrete levels of fluorecence rate for small numbers of trapped ions. (d) shows ten seconds of fluorecence (10 ms time bins) from two ions; two levels of signal (plus the background level) can clearly be seen.

two-ion fluorescence level.

3. Phase transition

If two ions are trapped they can undergo a number of distinct types of motion. When they are hot the motion of the two ions is effectively uncorrelated and the ions collide with each other at random times. When the ions are cold they can form a two-ion 'crystal' such that the separation of the ions remains approximately constant. Earlier work with small numbers of ions in RF traps showed that the change between these two types of motion is abrupt and may be thought of as a phase transition [31]. Recently interest in these sorts of phase transition has intensified [32] and we note that structural changes in ion crystals have been studied previously in the RF trap [33, 34]. The orientation of the crystal that forms at low temperature will depend on the external trap parameters. For a relatively high axial potential the ions will form a dumbbell shape in the radial plane (radial crystal). Due to the magnetic field this dumbbell shape will rotate about the trap centre at a frequency close to ω_m (the Coulomb repulsion between the pair of ions leads to a shift in ω_m). Strong cooling brings the ions closer together but their orientation does not change. On the other hand for trap voltages below some critical value (5.4 volt in our case), and as long as the magnetron motion is cooled effectively, it is energetically favourable for the dumbbell shape to form along the axis of the trap (axial crystal) [36]. In this case, especially under the influence of axialization, each ion can be expected to have its radial motion in the trap minimised.

Since we collect fluorescence in the plane of the ring electrode and since an image can only be obtained by our CCD camera over times which correspond to many magnetron orbital periods, we must expect images of a radial crystal to be blurred into an elongated shape in the radial plane. On the other hand an axial crystal should appear as two well-resolved spots in the image plane. Figure 5 shows images of two ions under the two different conditions, together with a single ion for comparison.

Figure 5(a) is a radial structure taken at a trapping potential of 3.5 V. Operating at our normal applied magnetic field this leads to $\omega_m = 21.8$ kHz, $\omega_z = 125$ kHz and $\omega'_c = 357$ kHz. Although the axial trapping potential is below the critical voltage needed to align two ions along the axis, the radial confinement/cooling is not strong enough to form an axial crystal. Note that although the image is somewhat blurred the fluorescence forms two bright zones. This can simply be explained by projecting the fluorescence of an individual ion in a circular orbit onto the radial plane. The ion spends more time at the extrema of the projected motion and so the fluorescence appears brighter here. If the size of the ion orbit has a constant radius, *r*, and the fluorescence rate is constant, then the intensity incident on a pixel of the camera should be

$$I \propto \sin^{-1}\left(\frac{X + \frac{\Delta X}{2}}{r}\right) - \sin^{-1}\left(\frac{X - \frac{\Delta X}{2}}{r}\right),\tag{1}$$

where X is the position of the pixel relative to the centre of the image, and ΔX is the width of a pixel. The pixel size of the camera is 13 μ m, with a minimum spatial resolution quoted as 22 μ m (~4 μ m and ~6 μ m respectively with our magnification). Figure 5(b) shows a theoretical image obtained by convolving the pattern given by Eq. (1) at an ion separation of 20 μ m with a Gaussian to add some simple aberration.

Figure 5(c) shows two ions with a trap potential of 2.0 V. With the application of a weak axialization drive (50 mV peak-peak at 376 kHz) the ions form an axial crystal and the two spots apparent are genuinely the fluorescence from two different ions. In both cases the fact that two ions were present in the trap was corroborated by observing two-ion quantum jump traces using the photomultiplier (e.g. Fig. 4(d)) before flipping the mirror to send light to the



Fig. 5. Images of ions taken at a magnification of \sim 4. Magnetic field axis is vertical.

CCD camera. We have found that it is possible to form an axial crystal without an axialization drive but that the crystal formed in this way is much more sensitive to the positions of the laser beam foci than in the axialized case.

Unfortunately, tracking the evolution of a given pair of ions through the transition from one orientation to the other as the trap voltage is changed is not straightforward. This is because the effective centre of the trap shifts as a function of applied voltage, probably as a result of trap misalignments and contact potentials due to deposits on the electrodes from the atomic beam oven. Changing the voltage requires lengthy re-optimisation of the laser beam parameters in order to recover a high level of fluorescence. For very low applied voltages this becomes a more significant problem so that we are unable to operate the trap effectively below 1.7 V (for which $\omega_m = 10.3$ kHz, $\omega_z = 87.0$ kHz and $\omega'_c = 369$ kHz).

Similar effects occur in RF traps and are usually counteracted by the inclusion of dedicated compensation electrodes to which dc potentials are applied so that the electrical and geometrical centres of the trap can be made to coincide [35]. This procedure is essential in RF traps in order to minimise unwanted micromotion. Since micromotion is not an issue in Penning traps we did not include such electrodes in our current trap. Compensation is in principle possible by the application of extra dc potentials to the four ring segments and two endcaps or to other structures such as the atomic beam oven. In RF traps the success of compensation is gauged by

various methods of monitoring the (reduced) micromotion. By initially operating our trap as an RF trap it may be possible for us to apply similar methods. It is clear that, in order to extend the work presented here, we will have to implement some form of stray potential compensation.

Although it is difficult to follow the shape of the ion cloud as function of trap voltage, it is interesting to vary the strength of the axialization drive without changing the laser or trapping parameters. In another experimental sequence we have loaded two ions into the trap at a trapping bias of 2.0 V, which corresponds to an axial frequency of 94 kHz (compared to the effective radial frequency of 177 kHz). We have then obtained images of the ions at intervals as the strength of the axialization drive is changed in steps. The results of this process are shown in Fig. 6 and even more clearly in the supplementary animation. At low axialization amplitude the ions move in the radial plane and their separation, which is related to the rotation frequency, is relatively large. As the axialization drive strength is increased, the ions move closer together radially as expected. At a certain drive strength it becomes energetically favourable for the ions to change their orientation while keeping their separation constant [36]. Once the ions are aligned along the axis of the trap, their separation is fixed and does not change as the drive strength is increased further. The transition is not expected to be abrupt as a stable motion at an intermediate alignment is possible. The images seen are all consistent with the expected evolution of the system as the strength of cooling is increased, and the minimum observed separation in the images corresponds roughly to the expected value of 27 μ m, although uncertainties in the precise value of the magnification make an exact comparison impossible.



Fig. 6. Images of a two-ion crystal as the axialization voltage is varied. Magnetic field axis is vertical. Also see supplementary animation.

4. Conclusions

Recent theoretical work suggests the use of large planar crystals in a Penning trap for applications in QIP [26]. The structures discussed so far in this theoretical work are very large crystals in which only a small fraction of the ions near the centre of the structure would be used for the

quantum simulations. In light of the work presented here it is interesting to speculate that one may be able to adopt a 'bottom-up' approach where small ion crystals are loaded into a Penning trap and used for this purpose.

The number of ions that can be held in an axial crystal depends on the radial confinement. If a superconducting magnet were used with a magnetic field in the region of 10 T, then axial crystals of perhaps 10 ions seem feasible. This compares unfavourably with linear RF traps where longer strings of ions can readily be made. On the other hand, it is generally believed that very long strings of ions are unlikely to find application in QIP (with the possible exception of a novel scheme employing strings of ions in a magnetic field gradient subject to microwave excitation [37]).

Engineering a set of individual trapping zones along the magnetic field axis of a Penning trap should be straightforward and moving ions in this direction is not expected to present any problems not already encountered in RF traps. On the other hand, a scalable quantum computer based on shuttling ions from trap to trap requires T and X junctions, so at some stage moving ions perpendicular to the magnetic field is essential. A strategy for overcoming this problem involving novel trapping geometries has been put forward so that scaling this system to larger numbers of qubits appears possible [22].

To conclude, we have trapped and laser cooled individual ⁴⁰Ca⁺ ions in a Penning trap for the first time. We have obtained images of ordered structures of two ions in a Penning trap. We have demonstrated the effect that axialization has on the orientation that these structures adopt in the trap, and shown that using this technique we are able to produce axial ion crystals. Small axial crystals in a Penning trap could in principle be used to demonstrate many of the building blocks of QIP including quantum gates, using the procedures pioneered in radio-frequency traps.

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