Ion traps allow researchers to control the position and movement of charged particles with exquisite precision, and provide a powerful way to study many atomic phenomena

Atomic physics in ion traps

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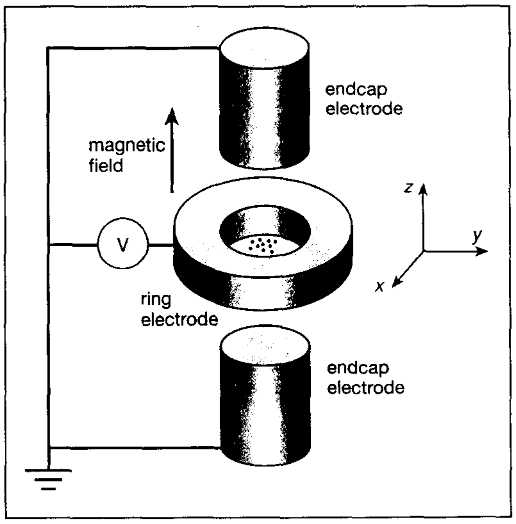
UNDER normal conditions, an atom hurtles from place to place. It can cross a room in mere milliseconds, and collides with other particles once every nanosecond or so. This motion, which is both random and unlimited in range, obscures many atomic properties. These include the internal structure of the atom, its interactions with radiation and other atoms, and its inherent quantum features.

To harness this frenzied motion, physicists have used techniques for trapping and cooling atoms with electromagnetic fields. In the case of neutral atoms, these techniques have led to the recent observation of Bose–Einstein condensation in a sample cooled to nanokelvin temperatures (see pp29–34). Charged atoms are more strongly confined by electromagnetic forces, and ion traps can be used to control the position and movement of individual particles with incredible precision.

The two main types of ion traps, Penning and Paul traps, were developed in the 1950s. In their simplest form, the ions are confined by applying a voltage between a "ring" electrode and a pair of "endcap" electrodes (figure 1). The Penning trap uses a static electric field and a uniform magnetic field to confine the ions, whereas the Paul trap uses time-varying electric fields, but no magnetic field.

The two trapping methods are complementary. The Paul trap allows strong confinement of a small numbers of ions, but the repulsive forces between the ions and the time-varying electric fields can heat the sample. The Penning trap, on the other hand, can trap larger collections of ions without inherent heating, but the confinement is limited by the strength of the applied magnetic field.

Recent experiments with trapped atoms have capitalized on the high degree of atomic control provided by ion traps. In this article we highlight how researchers have created exotic quantum states of an atom's motion, investigated the possibility of quantum computing, studied the interaction between two atoms and a laser field, measured the mass of individual atoms to high precision, and investigated the crystalline structure of a collection of trapped ions. Other notable areas of ion-trap research not covered here include high-resolution spectroscopy and frequency standards, and experiments with ion storage rings (see *Physics World* June pp40–44).



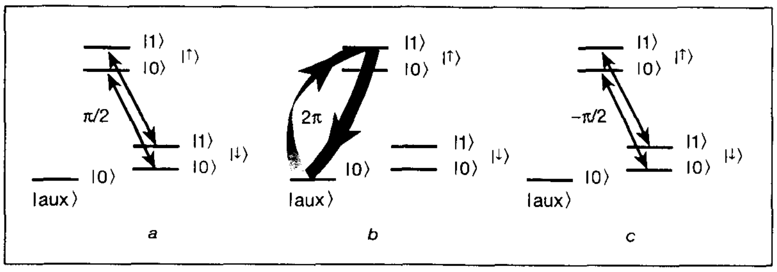
1 *An ion trap consists of a ring electrode and two endcap electrodes that provide a quadrupolar electric field distribution at the centre of the ring. For $V<0$, the electric field pushes positive charges together along the longitudinal z-axis and repels positive charges along the radial x and y axes. The Penning and Paul traps differ in the ways in which they confine particles in the x–y plane. The Penning trap uses a uniform magnetic field, B, that points along the z-axis to provide radial confinement. The Paul trap, also known as the rf trap, has a time-varying electric field that alternates between confinement along z (repulsion along x and y) and repulsion along z (confinement along x and y). For certain conditions, the time-averaged potential results in three-dimensional confinement.*

Quantum computers

A fundamental tenet of quantum mechanics is the phenomenon of superposition, which allows a physical attribute of a particle to be "smeared out" between two or more quantum states. These superposition states can become entangled when more than one attribute or particle is present. Entanglement means that the state of a particle can depend on the state of the other particles, even when there is no physical interaction.

One of us (CM) and colleagues at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, have investigated quantum superposition and entanglement using trapped ions. We confined a single beryllium ion in a miniature Paul trap, allowing various nonclassical states of motion to be demonstrated, and also built a quantum logic gate that would be used for quantum computation (*Physics World* 1996 March p27; June p25).

A quantum computer is based on quantum "bits" that can store superposition states of 0 and 1. For N quantum bits, the most general state is an entangled superposition of 2^N states. Superposition means that all of these states can be occupied at the same time. A conventional com-



2 The quantum bits of a single trapped Be^+ ion are the vibration bit $|n\rangle$, with values $|0\rangle$ and $|1\rangle$, and the spin bit $|S\rangle$, which can be $|\downarrow\rangle$ or $|\uparrow\rangle$. An auxiliary level, $|aux\rangle$, is provided by the Zeeman effect, which shifts the energy level of the spin states when an external magnetic field is applied. The controlled-NOT (CN) quantum logic gate flips the spin if, and only if, $|n\rangle = |1\rangle$. This transformation is achieved with a sequence of three pulses of laser light. (*a*) A "$\pi/2$ pulse" transfers $|\downarrow\rangle$ states halfway to $|\uparrow\rangle$ states, and vice versa, while $|n\rangle$ remains the same. (*b*) A "2π pulse" transfers $|\uparrow\rangle|1\rangle$ to $|aux\rangle|0\rangle$ and back, reversing the sign of any component in the $|\uparrow\rangle|1\rangle$ state. The other three states are not affected by this step. (c) A "$-\pi/2$ pulse" then reverses step (*a*), transferring $|\uparrow\rangle$ states halfway to $|\downarrow\rangle$ states and vice versa, while $|n\rangle$ remains the same. If $|n\rangle = |0\rangle$, step (*b*) is inactive: the two $\pi/2$ pulses cancel out and the initial state is not altered. If $|n\rangle = |1\rangle$, then the sign change in (*b*) causes the two $\pi/2$ pulses to add, and the spin is flipped.

puter can only be in a single state, so quantum computers can provide an exponential gain in capacity. This improvement may appear dubious at first, because quantum mechanics says that any output from the computer will collapse the superposition and project only one of the possible values at random. However, some algorithms have been designed that allow only a few final states to be measured, allowing information on all 2^N states to be extracted with just a few repeated measurements.

The most notable of these algorithms, devised in 1994 by Peter Shor at AT&T Bell Labs, allows large numbers to be factorized efficiently. This is particularly important for data encryption schemes, since these often rely on the inability of conventional computers to factorize large numbers.

The physical requirements for quantum bits are extreme: many-particle entangled states must be created and preserved, reversible quantum logic gates must be made, and efficient measurement schemes must be developed. In 1995 Ignacio Cirac and Peter Zoller of the University of Innsbruck in Austria proposed that trapped ions could be an attractive system for quantum computation. They suggested that the quantum bits of information could be held in the electronic states of the ions, since these can store superpositions for long periods of time and can be measured highly efficiently. They also showed how such quantum bits could be "wired" together by exploiting the collective motion of the ions in the trap.

We have followed these ideas at NIST to demonstrate that a single trapped beryllium ion can act as a two-bit quantum logic gate. The electronic structure of Be^+ is particularly simple because it has only a single valence electron. The spin of this outer electron can be aligned parallel or antiparallel to the nuclear spin, resulting in two long-lived quantum spin states. These spin states provide one of the two quantum bits in the beryllium ion, and the spin bit, $|S\rangle$, is labelled $|\downarrow\rangle$ or $|\uparrow\rangle$. The other quantum bit is the vibration bit, $|n\rangle$. This represents the two lowest vibrational states of the ion's motion in the trap's harmonic oscillator potential, and can take the values $|0\rangle$ and $|1\rangle$.

In the experiments, the ion is first cooled to its vibrational ground state, $|n\rangle|S\rangle = |0\rangle|\downarrow\rangle$, using lasers. The ion can then be excited to other states using a pair of lasers. One laser is made resonant with the transition between the initial state and an "virtual" state, while another drives the transition between the virtual state and the final state, resulting in a so-called stimulated Raman transition between initial and final states. For example, the initial $|0\rangle|\downarrow\rangle$ state can be transferred to $|1\rangle|\uparrow\rangle$ by tuning the frequency difference between the lasers to this transition. The amount of population that is transferred between the states depends on the laser power and the duration of the pulse. A so-called π pulse transfers the whole population, while a $\pi/2$ pulse – which is applied for half the time – results in an entangled superposition of $|0\rangle|\downarrow\rangle + |1\rangle|\uparrow\rangle$. In this case, the spin state is correlated with the state of motion.

Pairs of Raman pulses can be used to create a quantum logic gate called a two-bit controlled-NOT (CN) gate. This gate flips the state of one quantum bit depending on the state of the other one, and is a fundamental entangling operation of a quantum computer. Three pairs of Raman pulses can be used to set up a CN gate that only flips the spin if $|n\rangle = |1\rangle$ (figure 2).

The operation of the CN logic gate can be checked by studying the evolution of particular states as they "go through the gate". The spin bit $|S\rangle$ can be measured by applying a laser beam that causes a transition between the $|\downarrow\rangle$ state and an excited electronic state that will cause strong fluorescence if $|S\rangle = |\downarrow\rangle$. However, this measurement perturbs the vibrational motion of the ion, so the vibration bit $|n\rangle$ can only be measured by repeating the experiment with additional operations inserted prior to measuring the spin state. For instance, if the spin is first measured to be $|S\rangle = |\uparrow\rangle$, the experiment is repeated with the addition of a mapping π pulse to drive the transition from $|1\rangle|\uparrow\rangle$ to $|0\rangle|\downarrow\rangle$. If the spin is subsequently found to be $|S\rangle = |\downarrow\rangle$, the vibrational state must have been $|n\rangle = |1\rangle$, since the $|0\rangle|\uparrow\rangle$ state is unaffected by the mapping π pulse.

Although this experiment consists of only two quantum bits, it illustrates some of the basic operations and problems associated with building a quantum computer using a string of trapped ions (figure 3). According to Cirac and Zoller's scheme, each ion in the string would store a quantum bit in its internal electronic levels, and a collective mode of the ions' motion, such as the centre of mass, would act as a "data bus". This collective mode would first be cooled to its vibrational ground state, and then similar operations to those discussed above would allow logic gates to be created between the spin states of individual ions. Laboratories worldwide are now attempting to build

3 A string of about 40 mercury ions are trapped in a linear rf trap. The spacing between the ions is about 15 μm. The apparent gaps contain different isotopes of mercury, which do not fluoresce at the same wavelength as the others. (J D Miller, D Berkeland, J C Bergquist and D J Wineland, NIST.)

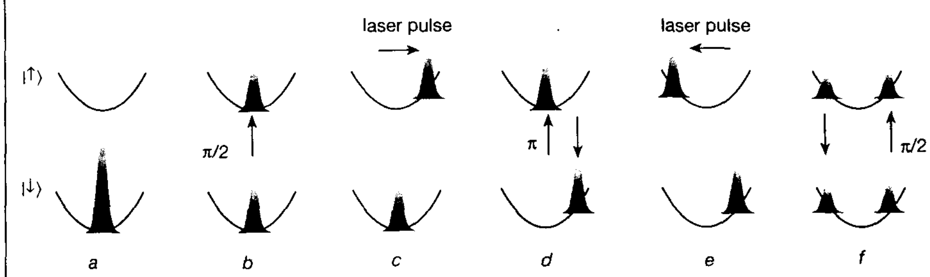
such extended quantum registers.

Another issue that affects the prospects of quantum computation is quantum decoherence, the collapse of superposition states due to external influences that effectively make a measurement of the system. The observed rate of decoherence is several times slower than the 20 kHz speed of the CN logic gate described above, implying a loss of coherence after about 10 gates. More complex computations will therefore need faster gate speeds and the development of methods to suppress decoherence.

The quantum bits in the ion-trap computer can be readily isolated from the environment – coherence times of over 10 minutes have been observed for electronic states of Be^+ – so decoherence will mainly affect the motion of the ions. To understand this motional decoherence, we have studied several nonclassical states of motion of a Be^+ ion, including a superposition state analogous to Schrödinger's cat.

To create this state the ion is first cooled to its ground vibrational state and a superposition of the spin states is created using the Raman beams. This internal superposition is then converted into a larger superposition of motional states by further laser pulses. These pulses effectively displace one part of the internal superposition in one direction and the other part in a different direction, creating a superposition of the atom in two widely separated locations (figure 4). This "big" superposition is analogous to Schrödinger's famous cat, which exists in the unlikely superposition of being both dead and alive. Although the separation in this experiment is by no means macroscopic, this version of Schrödinger's cat allows us to study the influence of the environment on motional decoherence.

The field of quantum computation and "big" superpositions is still in its infancy, and theorists and experimentalists are beginning to investigate its limits. Theorists are developing new algorithms to exploit the parallelism of quantum computers, although the factoring problem might prove too difficult to implement, and they are also inventing quantum error-correction codes that could reverse decoherence. Experimentalists, including those at NIST, the University of Innsbruck, Los Alamos, IBM Almaden, the University of Oxford and the Max Planck Institute for Quantum Optics in Garching, Germany, are attempting to generate larger superpositions and longer strings of quantum logic gates, with the eventual goal of a producing a working quantum computer.



4 A Schrödinger cat state is created by modifying the atomic wavepackets associated with the spin states |↓⟩ and |↑⟩. The idealized wavepackets are snapshots in time, taken when the atom is at the outer limits of its motion in the trap, as represented by the parabolas. The area of the wavepackets corresponds to the probability of finding the atom in a given internal state. (*a*) After laser cooling, the Be^+ ion is initially almost at rest in the ground state, $|S\rangle = |\downarrow\rangle$. (*b*) A $\pi/2$ pulse splits the wavepacket into a superposition of |↓⟩ and |↑⟩. (*c*) Laser beams are used to excite the |↑⟩ wavepacket into a coherent state that oscillates from one side of the trap to the other like a pendulum. The polarization of the laser beams are set to only affect the |↑⟩ wavepacket, so the internal spin states and the motional states become entangled. (*d*) The |↓⟩ and |↑⟩ wavepackets are then exchanged using a π pulse. (*e*) The new |↑⟩ wavepacket is excited to a coherent state by another laser pulse that is out of phase with the pulse used in (*c*), so the oscillations of the two spin states are also completely out of phase. The two wavepackets are separated by a maximum distance of 84 nm, larger than the 7 nm spread of each wavepacket, and this state is analogous to Schrödinger's cat. (*f*) The |↓⟩ and |↑⟩ wavepackets are combined by a $\pi/2$ pulse, as in step (*b*). The relative direction of the two laser pulses in (*c*) and (*e*) can be varied to change the relative positions of the two wavepackets. This gives rise to an interference signal in the measured |↓⟩ population, and this signal allows the spatial separation of the wavepackets and the degree of coherence to be determined.

Two atoms in a trap

When studying atomic interactions in the lab, we must usually rely on averaging the microscopic variables of interest, such as the number of atoms, their individual velocities and the spacings between them. However, this averaging process can mask many effects that are important on an atomic scale. Ion traps allow researchers to study these effects.

In 1996 Ralph DeVoe and Richard Brewer at IBM Almaden in California confined two barium ions in an ion trap and studied their interaction with an applied laser field. The laser excited the ions to a higher electronic state, and the radiation emitted by the ions as they decayed was recorded. The researchers found that the emitted radiation depends on the distance between the ions, thus demonstrating of a pair of interference phenomena called superradiance and subradiance that were first described in 1954 by Robert Dicke. In most systems, where an average must be taken over an ensemble of atoms, this interference effect cannot be observed.

Superradiance and subradiance occur when radiation emitters are closer together than the radiation wavelength, λ. Atomic radiators can be treated as classical oscillating dipoles, which means that the emission from each dipole interferes with the others in a way that depends on the initial phases of the dipoles. In particular, when two dipoles are much closer together than λ, their initial phases can be set such that the net radiation either vanishes (subradiance) or is four times the radiated power of a single dipole (superradiance).

The IBM group trapped and laser-cooled barium (Ba^+) ions in a Paul trap formed by three planar electrodes. This trap tightly confines the ions, counteracting their Coulomb repulsion and squeezing them to an interatomic spacing of 1 μm. The electronic transition of interest has a radiation wavelength of about 0.5 μm, so the atoms are close enough together to exhibit superradiant and subradiant effects.

The IBM researchers excited the ions using a rapid laser pulse that is weak enough to maintain the coherence of the dipoles. The relative phase of the dipoles is determined by the angle between the wavevector of the laser light and the direction of atomic separation. A photon released by the ions during the decay is detected, and the time between the initial laser pulse and the emission of the photon is measured. A histogram of photon arrival times after many repeats of the experiment shows an exponential decay, providing a measure of the lifetime of the excited state (figure 5*a*).

When a single atom is loaded into the trap, the signal-to-noise ratio of such measurements compares favourably with conventional experiments using atomic beams or cells. (We might expect better results with more atoms, but the detection of more than one photon causes a systematic shift in the measurement.) Indeed, the IBM group has measured the lifetime of a particular excited state of a single Ba^+ ion with a precision of 0.2% after just a few minutes of collecting data.

A pair of Ba^+ ions was then loaded into the trap, and the lifetime of the same excited state was measured as the spacing between the ions was varied (figure 5*b*). In some cases the measured lifetime is about 1.3% longer than that observed for a single ion, corresponding to subradiance, and in others it is 1.3% shorter, indicating superradiance. The data agree with Dicke's original theory, provided that they are modified to include the Zeeman effects involved in the emission of a photon and the residual motion of the ions.

The researchers plan to use a different atomic excitation scheme and to squeeze the ions even closer together. This should produce a much larger effect, and they expect to make accurate measurements of superradiance and subradiance at the ±5% level. This degree of resolution may lead to precise tests of quantum electrodynamics, including the effects of higher multipoles on the emitted radiation.

Precision mass measurements of atoms

An important application for Penning ion traps is the precision measurement of the masses of atoms and stable atomic particles. Indeed, the accuracy to which some of the lighter atomic masses are known has improved by several orders of magnitude over the last few years.

The basic idea is to measure the motion of particles in the trap. The strong magnetic field in the trap (about 6 T or more) causes charged particles to circulate perpendicular to the field. This cyclotron motion has a frequency given by $\nu_c = qB/2\pi m$, where q is the charge, B is the magnetic field and m is the mass. Thus the mass of a particle can be found by comparing its cyclotron frequency to that of a reference mass in the same magnetic field.

These measurements are generally most accurate when they are performed on single ions, and the cyclotron frequencies of the two ions are measured alternately. However, it can take about 20 minutes to switch the ions, and fluctuations in the magnetic field over this timescale has limited the accuracy of current measurements to a few parts in 10^{10}.

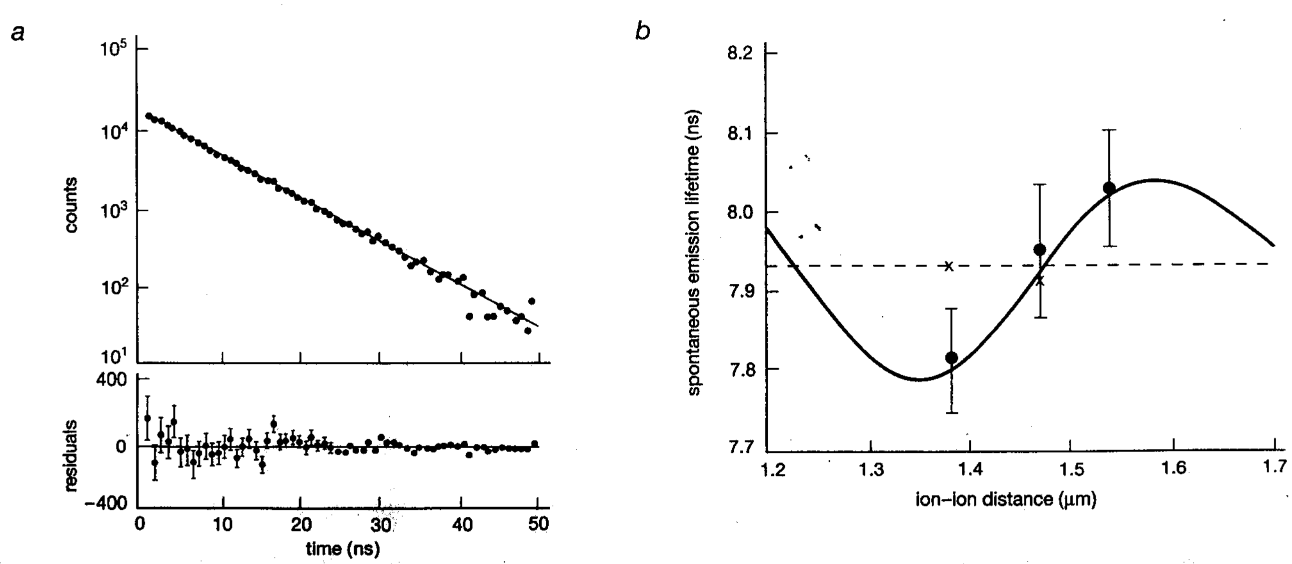
This is the basic idea, but the reality is much more complex. A single ion in a Penning trap undergoes motion at three different frequencies (figure 6). First, the fast cyclotron motion is shifted to a frequency, ν'_c, by the electrostatic fields in the trap. Second, $\boldsymbol{E}\times\boldsymbol{B}$ drift causes a slow circular motion perpendicular to the magnetic field – this "magnetron" motion has a frequency ν_m. Finally, the electrostatic fields in the trap cause the ion to oscillate along the axis of the magnetic field at a frequency ν_z.

These frequencies are independent of the amplitude of each type of motion as long as the electrostatic potential in the trap varies as the square of the axial and radial coordinates (i.e. it is quadratic). The electrodes in the traps used for mass spectroscopy are therefore hyperbolic to maximize the volume in which there is a quadratic potential. Extra electrodes, called compensation electrodes, are used to control the size of the nonquadratic contribution to the potential.

Lowell Brown at the University of Washington and Gerry Gabrielse at Harvard University in the US have shown theoretically that the unperturbed cyclotron frequency can be obtained from $\nu_c^2 = \nu_c'^2 + \nu_m^2 + \nu_z^2$, which means that all three frequencies must be measured. However, the magnetron frequency is typically much less than the frequency of the axial motion, which in turn is much less that the perturbed cyclotron frequency. This means that the axial and magnetron frequencies do not need to be known to the same precision as ν'_c.

Many groups worldwide have used Penning traps for mass spectroscopy (see Bergstrom *et al.* in Further reading). In many of these experiments the axial motion is detected from the currents that the ion's oscillation induces in the endcap electrodes. The cyclotron and magnetron frequencies are measured by coupling these motions to the axial motion.

Two groups in particular have reported impressive

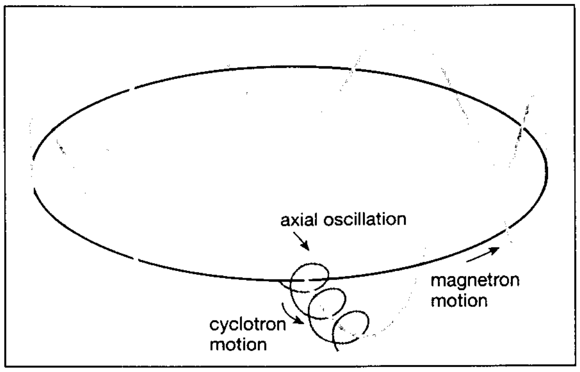


5(a) Arrival times recorded for the spontaneous emission of photons from two Ba^+ ions separated by 1.380 μm and initially excited with a weak laser pulse. The histogram yields a lifetime of 7.820 ns. (*b*) The spontaneous emission lifetime of two Ba^+ atoms was measured when the ions were separated by 1.380, 1.470 and 1.540 μm. The solid curve is theoretical, and the dashed line is the measured lifetime of a single Ba^+ ion. At 1.540 μm, the measured lifetime is about 1.3% longer than that of a single ion, corresponding to subradiance, while at 1.38 μm it is shorter, indicating superradiance.

improvements in these measurements over the last four years. Robert Van Dyck and colleagues at the University of Washington have determined the masses of eight atoms with an accuracy of about 2 parts in 10^{10}. They used a C^{6+} ion as the reference mass, and made consistency checks by comparing the cyclotron frequencies of different charge states of the same element. They have also obtained the most accurate measurement to date of the proton–electron mass ratio, at 3 parts in 10^9.

David Pritchard and colleagues at the Massachusetts Institute of Technology have determined nine atomic masses with an accuracy close to 1 part in 10^{10}, and the measurements are consistent with those of the Washington group. The MIT group has also measured the mass ratios of a variety of molecular ions, and these can be combined in a number of ways to determine the atomic masses.

Certain mass measurements have important implications for physics. In metrology, for example, they are needed to define an atom-based mass standard, to calibrate γ-ray wavelengths and to determine fundamental constants. One of the most important constants in particle physics is the proton–antiproton mass ratio. Gabrielse and colleagues have recently compared the cyclotron frequencies of the proton and antiproton, and found that their charge-to-mass ratios are identical to 1 part in 10^9. This is the most accurate confirmation of charge–parity–time (CPT) invariance in a baryon system. They are planning to compare the cyclotron frequencies of an H^- ion and an antiproton. This will allow them to determine the proton–antiproton mass to an accuracy of about 1 part in 10^{10}, given that we know the values of the electron–proton mass ratio and the binding energy of H^-.



6 A particle in an ion trap moves in three different ways. The strong magnetic field causes cyclotron motion, a rapid circulation perpendicular to the magnetic field. The $\boldsymbol{E}\times\boldsymbol{B}$ drift generates magnetron motion, typically a much slower circulation with a larger radius, again perpendicular to the magnetic field. Finally, the particle oscillates in an axial motion around the magnetic axis of the trap.

Further improvements in the accuracy of these measurements will require the ions to be switched more quickly, or perhaps longer experiment times to average out the magnetic field fluctuations. The MIT group has even thought about trapping the two different ions and measuring their cyclotron frequencies at the same time.

Other sources of uncertainty will become important once accuracies of 5×10^{-11} have been achieved. For example, thermal noise can alter the amplitude of the cyclotron motion, which will degrade the measurement if the trap potential is not quadratic. The MIT group has demonstrated a way of reducing the effect of this noise.

Trapped ions form crystals

Charged particles in a trap can effectively form one of the simplest types of plasma, a classical one-component plasma (OCP). This consists of a single type of charged particle in a uniform background of opposite charge, provided in this case by the trapping fields. The thermodynamic state of an OCP depends only on the "coupling" of the plasma, Γ, essentially a measure of the potential energy between neighbouring ions divided by their thermal energy.

Plasmas with $\Gamma > 1$ are said to be strongly coupled, and theory suggests that such plasmas should exhibit complex behaviour, even though they are conceptually simple. For example, a bulk OCP is predicted to change from a liquid to a solid crystal lattice at $\Gamma \sim 172$. Such high values of Γ can be achieved by laser cooling to temperatures of few millikelvin and increasing the density of the trapped ions to over 10^8 cm^{-3}.

Strongly coupled OCPs in ion traps could serve as models of dense astrophysical matter. The outer crust of a neutron star is thought to be a strongly coupled OCP, with values of Γ between about 10 and 1000. These neutron star plasmas can thus be modelled in an ion trap by producing strongly coupled OCPs with similar Γ values, even though the outer crust of a neutron star is about 20 orders of magnitude more dense than the densities achieved in ion traps.

Paul traps, with their heating problems, can typically only be used to cool small plasmas, typically less than about 10 interparticle spacings across. However, they have been used to produce clusters of a few ions at low temperatures. These strongly coupled clusters were first observed in 1987 by groups at the Max Planck Institute for Quantum Optics in Garching, Germany and NIST. As the number of ions in the cluster was increased, it was found that the ions form concentric shells in a shape that roughly follows the curved boundary of the plasma. This shell structure is ordered only over short length scales, and is caused by the small size and curved boundary of the plasma.

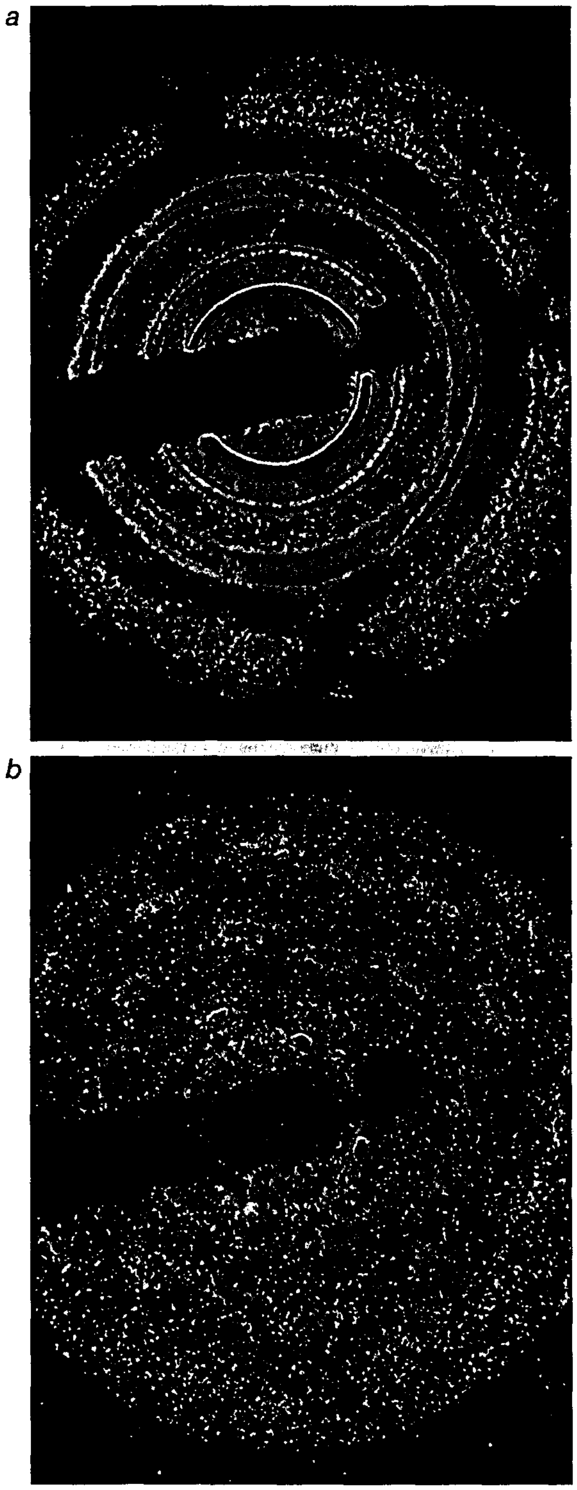
These shell structures have been observed both in linear radio-frequency traps and in roughly spherical plasmas of around 20 000 ions in a Penning trap. Calculations by Dan Dubin of the University of California at San Diego and by Rainer Hasse of the GSI laboratory in Darmstadt, Germany, indicate that the plasma must be larger than 60 interparticle spacings in any direction for a crystal to form in the plasma interior. This corresponds to about 100 000 trapped ions for a spherical plasma.

Such large plasmas have only been cooled in a Penning trap. Since 1994 researchers at NIST have been laser-cooling up to 500 000 Be^+ ions to millikelvin temperatures in a cylindrical Penning trap. And in 1995 one of us (JB) and colleagues found that one or more crystals with long-range order could form in these large plasmas.

The crystals were detected using Bragg scattering, which is commonly used to determine the crystal structure of solid materials. In the ion trap experiment, a laser beam of wavelength 313 nm is sent along the magnetic axis of the trap. The intensity of the light scattered by plasma is measured as a function of the scattering angle, θ, which is the difference in angle between the incident light and the scattered light. For a crystal lattice, the scattering angle depends on the distance between the crystal planes as $n\lambda = 2d\sin\theta/2$, where n is an integer, λ is the wavelength of the light and d is the interplane spacing.

The Bragg scattering pattern from a stationary crystal would consist of a pattern of dots. However, plasmas in a Penning trap rotate about the magnetic field axis, and hence the laser beam direction, with a frequency of about 100 kHz. This means that the scattering pattern for one or more crystals should consist of a series of rings (figure 7*a*).

Each ring corresponds to Bragg scattering from a different set of crystal planes. The width of the rings tells us that



7(*a*) This Bragg scattering pattern of a laser-cooled plasma of 500 000 Be^+ ions was generated with a 313 nm laser beam. This wavelength is small compared with the particle spacing (~ 10–15 μm), so the Bragg pattern forms within a scattering angle of about 5.4°. The rings indicate that one or more crystals have formed in the plasma. The image was obtained after reflecting the Bragg pattern from a mirror with a hole in it – here the hole is positioned on the second ring. The light that escapes through the mirror was recorded, and the variation in the light intensity with time provides an excellent measure of the frequency at which the plasma rotates. (*b*) The camera recording the pattern was strobed so that it took a snapshot of the pattern when the crystal was in certain orientations. The resulting pattern of dots is then similar to that recorded for a stationary crystal, and it indicates the presence of a single body-centred cubic crystal.

the crystal, or crystals, are larger than 10 interparticle spacings across, but probably not by much. Simulations by John Schiffer at the Argonne National Laboratory in the US suggest that there might be 20 layers of boundary shells and that the crystals could lie within these.

If the Bragg scattering is caused by a single crystal, or a small number of crystals, the intensity at any point on the Bragg rings should vary as the plasma rotates. The time variation in the light intensity can be recorded, providing an accurate measure of the rotation frequency of the plasma. It is also possible to take a "snapshot" of the Bragg scattering pattern when the crystal is in a specific orientation, and in this case a pattern of dots is observed (figure 7*b*). Most of these patterns indicate that a single crystal is seen, but occasionally it seems that more than one is observed.

The type of crystal lattice that has formed can be determined from the scattering angle of the Bragg rings and the ion density, which can be obtained from the rotation frequency of the plasma. Experiments with plasmas of more than 200 000 ions indicate that a body-centred cubic lattice has formed, which is predicted to be the minimum energy state for a bulk OCP. This suggests that these plasmas could be large enough to study bulk strongly coupled OCPs. Indeed, we hope to observe a sudden melting of the crystals as the ion temperature is increased, corresponding to the predicted phase transition.

Controlling the future

Both Penning and Paul traps have become powerful tools in the study of atomic physics. Although many of the techniques for trapping ions were developed decades ago, recent advances have led to renewed interest in experiments that allow the position and motion of individual atoms to be controlled with the utmost precision. This control enables researchers to investigate atomic properties that cannot be probed in free atoms, and is sure to provide many more insights into the physics of atoms.

Further reading

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