Trapped Atoms and Laser Cooling

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Physicists are often interested in investigating the energy-level structure of atoms with high accuracy. Perhaps the most important reason for this is the desire to test with precision the theories that predict this energy structure. If a deviation, no matter how small, occurs between the theoretically predicted structure and the experimental measurements, the theory must be modified. What is most interesting is to find the difference to be explained by some new physical effect which must then be incorporated into the theory.

Spectroscopy is an experimental procedure for measuring the energy-level structure of atoms. It involves measuring the energy differences between atomic states by observing the frequency f (or equivalently, the wavelength) of the radiation that is emitted or absorbed in transitions between atomic states. The energy difference between two particular states is $E_2 - E_1 = hf$, where h is Planck's constant (Equation 2-17). The energy levels of the atom can then be constructed from series of such energy differences.

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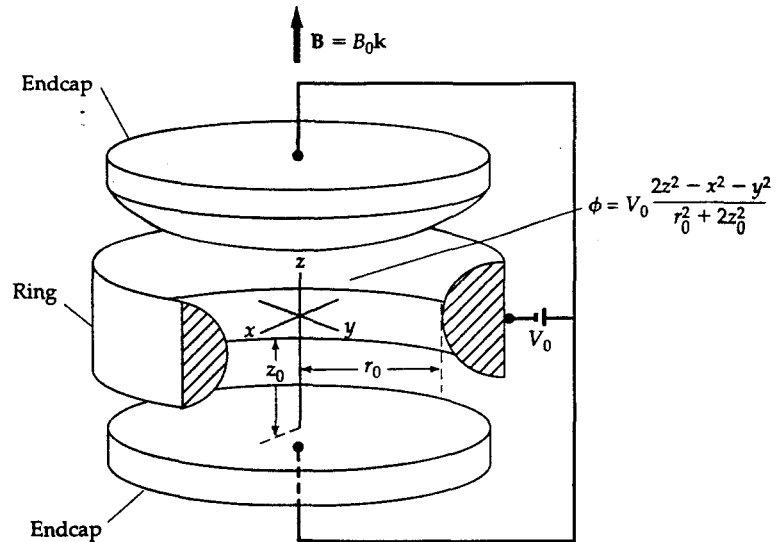
Measurements of energy differences $(E_2 - E_1)$ are always accompanied by some measurement uncertainty ΔE. In the case of absorption or emission spectra, the uncertainty in energy corresponds to the width of spectral lines: the smaller the uncertainty ΔE, the smaller the range of frequencies spanned, that is, the narrower the lines. Furthermore, the highest resolution (smallest ΔE) can be obtained when the time for transition between states Δt is as long as possible. This is a consequence of the time-energy uncertainty relation, which states that the time over which an energy is measured Δt and the uncertainty of that energy ΔE are related by $\Delta E \Delta t \sim \hbar$ (Section 3-3). In practice, Δt cannot be made arbitrarily long because processes other than emission or absorption—such as collisions with other atoms—can intervene and significantly alter the state of the atom. Such an intervention cuts short the time the atom has to emit or absorb in its undisturbed state, and therefore cuts short the time available for measuring the energy of such an emission or absorption.

The atoms in a sample being analyzed (for example, helium atoms emerging from a small hole in a helium reservoir) are normally moving relative to the radiation source (which is fixed in the laboratory), so the apparent frequencies of light emitted by the atoms are shifted by the doppler effect (Section 1-6). ^{4}He atoms at room temperature move with speeds of about 1.5×10^5 cm/s; therefore the apparent emission frequency of an atom moving toward the radiation source would be shifted to a higher value by the fraction $v/c = 5 \times 10^{-6}$. (The frequency of absorption would be shifted to a lower value by the same amount.) This is a significant amount in very high resolution studies.

The energy resolution can be increased (ΔE made small) and the doppler shift reduced if the atoms are confined to a region of space. By holding the atoms, we can make the time for transition Δt large and ΔE small. As the atoms are held in a localized region, their velocity and associated doppler shift average to zero. The trick in this procedure is to hold the atoms in such a way that when they strike the walls of the container, the atomic states are not distorted to such a degree that the measurement is rendered inaccurate. Various methods are employed to do this; for atomic or molecular ions we can use special configurations of electric and magnetic fields that act on the charge of the ion to pro-

Figure 1 Schematic representation of the electrode configuration for the Penning or Paul trap. Electrode surfaces are figures of revolution about the z axis and are made as close as possible to be equipotentials of the quadratic potential ϕ discussed in the text.

$$\mathbf{B} = B_0\mathbf{k}$$

Endcap

$$\phi = V_0\frac{2z^2 - x^2 - y^2}{r_0^2 + 2z_0^2}$$

Ring

V_0

z_0 r_0

Endcap

vide confinement. It turns out that these electric and magnetic fields perturb the ion's internal structure very little, so that they do not limit the accuracy of the observation. The "walls" of the container provided by the fields are, in effect, very soft.

Ion Trapping

Several kinds of electromagnetic "traps" are used to confine ions. Cyclotrons and synchrotrons are used for accelerating and storing high-energy elementary particles. Here we'll briefly describe one kind of trap for atomic spectroscopy. This trap, shown in Figure 1, uses static electric and magnetic fields and is usually called a Penning trap, after F. M. Penning who reported the basic device in 1936.

Assume we are interested in confining positively charged ions, for example Be^+ or Hg^+, where one electron has been removed from the neutral atom. If we put a positive voltage V_0 on the two endcap electrodes and leave the central ring at ground potential, the ions experience a force in a direction toward the xy plane; in other words, they are confined as to how far they can travel up or down in the z direction. Unfortunately, this configuration of electrodes causes the ions to feel a radial electric force away from the z axis of the trap, so they accelerate rapidly into the ring electrode. This difficulty can be overcome if we superpose a static magnetic field B_0 whose field lines are parallel to the z axis. This axial magnetic field acting with the radial electric force causes the ions to orbit about the z axis of the trap and confines the ions in all three dimensions.

Let us analyze quantitatively the motion of an ion in a common type of Penning trap. One that is often used has electrode surfaces that conform to equipotentials of the potential (in cartesian coordinates)

$$\phi = V_0(2z^2 - x^2 - y^2)/(r_0^2 + 2z_0^2)$$

This is provided, to a good approximation, by the electrode shapes shown in Figure 2. The particular shape is that generated by rotating a hyperbola around the z axis. From this potential, we can find

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Cap electrode
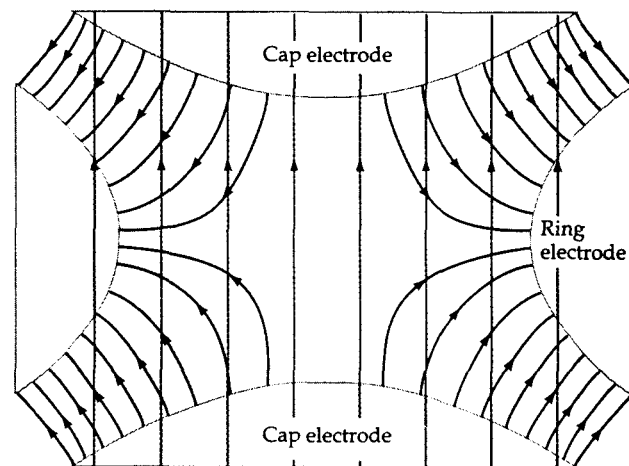
Ring electrode

Cap electrode

Figure 2 Electric (red) and magnetic (blue) field lines of trap shown in Figure 1.

the electric field along the z axis as $E_z = -d\phi/dz \propto -z$. Thus the electric force on the ion is always in a direction toward the xy plane, and the strength of the force is proportional to the distance the ion is from the xy plane. The magnetic force on the ion can act only in a direction perpendicular to the direction of the magnetic field, meaning that in this case the magnetic force will act only in the xy plane. So the only force on the ion in the z direction is the electric force. Since $F_z \propto -z$, we know that the motion of the ion must be simple harmonic. It is in fact this property of an electrode shaped as a hyperboloid of revolution that makes it a popular one to use in an ion trap. In particular, the fact that the ion's motion is harmonic (in the z direction) means that its frequency of oscillation is independent of its amplitude of oscillation. From the properties of simple harmonic motion, we can work out the frequency of oscillation in the z direction, f_z, and find

$$f_z^2 = qV_0/\pi^2 m(r_0^2 + 2z_0^2)$$

where q and m are the ion's charge and mass respectively. To get an idea of the magnitude of this frequency, assume some typical values of parameters encountered in the laboratory. For $V_0 = 1$ V, $m \approx 9$ atomic mass units (e.g., $^9Be^+$ ions), $r_0 = z_0\sqrt{2} = 1$ cm, we find $f_z \approx 74$ kHz.

A charged particle in a magnetic field executes circular motion around the field lines at the cyclotron frequency $f_c = qB/2\pi m$. However the addition of the potential ϕ gives rise to a radial electric field whose strength is proportional to the distance of the ion from the z axis. As this radial electric field is perpendicular to the magnetic field, the center of the ions' cyclotron orbits drifts in a direction perpendicular to the magnetic and electric field lines. For the cylindrical geometry of the trap, this drift motion is a circular orbit about the z axis. Therefore the overall motion in the direction normal to the trap axis is a composite of circular motion at approximately the cyclotron frequency (which is actually shifted slightly by the presence of the radial electric field) and a circular motion around the z axis due to the crossed electric and magnetic fields. The latter is usually called the magnetron motion. The energy extracted from this motion in a "magnetron" tube is what provides heat in a microwave oven. The complete motion of the ion in the Penning trap is summarized in Figure 3a, b.

If the ions collide with background gas atoms, the radius of the magnetron motion gradually increases until the ions strike the ring electrode and stick to it. To prevent this, the trap apparatus is nor-
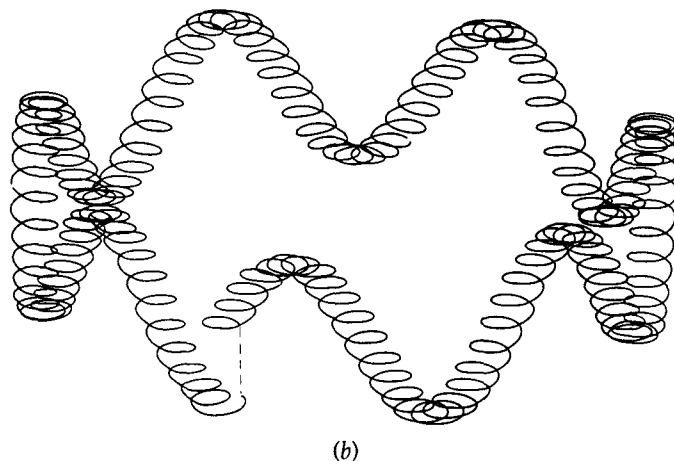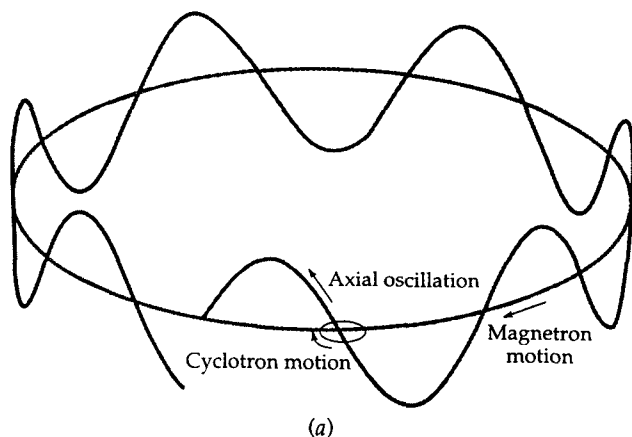

(a)

(b)

Figure 3 (a) Three modes of motion of the ion in the trap combine to yield a complex trajectory (b). The ion revolves rapidly in the cyclotron orbit; at the same time the center of the cyclotron orbit follows the much larger circular path of the magnetron motion; all the while the ion is oscillating along the axis of the trap.

Figure 4 Electrodes for a small Paul trap mounted on a penny to give the size. In the experiment, these electrodes are mounted inside a quartz vacuum enclosure where the vacuum is about 10^{-8} Pa or about 10^{-13} atm. The electrodes on either end are held at ground potential and a potential of about 500 V which oscillates sinusoidally at a frequency around 20 MHz is applied to the center ring electrode. The quartz vacuum enclosure allows the ultraviolet light scattered from the ion to pass and be photographed.
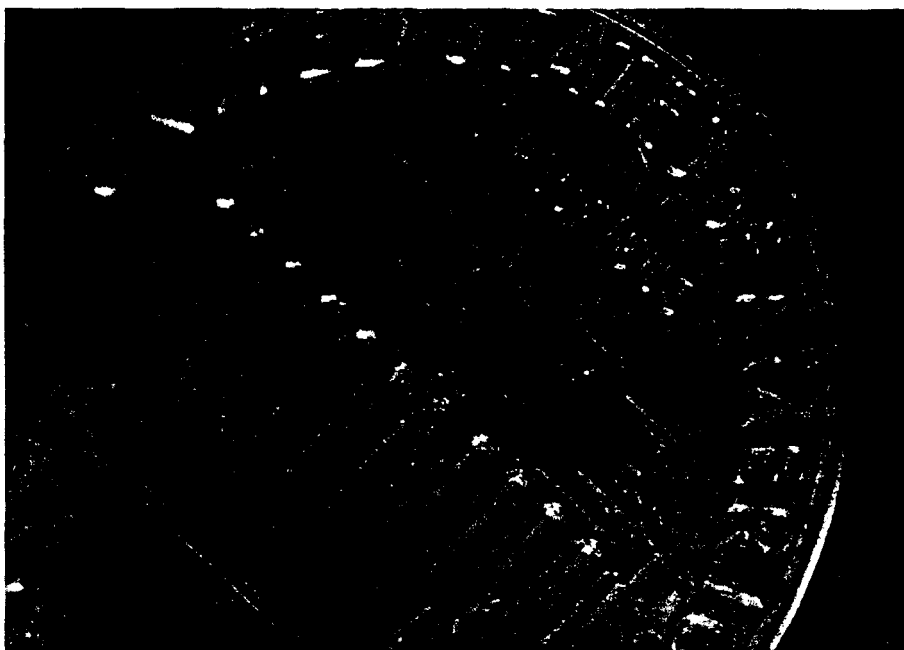
mally installed in an evacuated envelope (for example, a sealed glass tube) where the pressure inside the envelope is on the order of 10^{-8} Pa (about 10^{-13} atm). Under these conditions, the ions can be stored in the trap for many days.

Another kind of ion trap uses the same electrode shapes as the Penning trap but confines ions by the action of an oscillating electric potential $V_0 \cos \omega t$ applied between the endcaps and ring electrode. This trap is called the Paul trap after Wolfgang Paul who proposed it in the early 1950s (Figure 4). Figure 5 shows an ultraviolet photograph of a single Hg^+ ion confined in a miniature Paul trap. The high degree of localization obtained with the trap allows this kind of photograph to be made.

With both kinds of traps, ions, electrons, and even more exotic particles such as positrons or antiprotons can be confined for such long times that the resolution of energy measurements is no longer limited by the residence time of the ions in the trap.

Various types of traps can be used for neutral atoms. These provide trapping by electric and magnetic fields but (because of the overall charge neutrality of the atom) the fields must act on the electric or magnetic dipole moment of the atom.

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Figure 5 False-color image of a *single* Hg^+ ion (small isolated dot near the center) stored in the Paul trap shown in Figure 4. The other shapes are due to light reflected from the trap electrodes. The inner diameter of the ring electrode in this trap was about 0.9 mm. The ion is actually confined to a region of space much smaller than indicated by the size of the dot but the lens used in this experiment limited the resolution obtained.

High Accuracy Atomic Spectroscopy

Accuracies of energy measurements in certain atomic spectroscopy experiments are now better than 1 part in 10^{13}. This means that when we measure the frequency of an atomic transition, we know all of the environmental perturbations on the atom to such an extent that we can tell you the frequency at which the atom would absorb the radiation if it were isolated and at rest in space. If the accuracy is 1 part in 10^{13}, the inaccuracy of our prediction of the frequency is only 10^{-13} of the value of the frequency. As a comparison, if we could measure the distance between two points on the east and west coasts of the United States to an accuracy of 1 part in 10^{13}, the error in our measurement would be about 5×10^{-5} cm (the distance of one wavelength of visible light).

With such high accuracies in atomic spectroscopy, we must consider a number of effects that are typically small enough that we do not ordinarily worry about them. One such effect is called the second-order doppler shift. It can be derived by expressing Equation 1-24a or 1-24b in a power series in V/c. The term proportional to V/c is the same as the classical expression for sound. The second-order doppler shift is the term proportional to $(V/c)^2$. This is the effect caused by relativistic time dilation; because the ions (or atoms) are moving with respect to our radiation source, which is stationary in the lab, time moves more slowly for them. Hence, when we measure the frequencies of their transitions, we measure a value which is slightly lower than the frequency we would measure if they were at rest. This is not a particularly big effect—for $^9Be^+$ ions stored in a trap where the kinetic energies are near room temperature (about 300 K), the magnitude of this shift is fractionally $V^2/2c^2 \approx 5 \times 10^{-12}$. However, it is a difficult shift to measure accurately as it is hard to measure the ions' velocity distribution precisely. One approach to this problem is to reduce the temperature of the ions; an effective method is laser cooling.

Laser Cooling

We are familiar with the use of lasers to provide heat (e.g., laser surgery, welding, and inertial confinement fusion). However, as explained below, laser light has now also been used to cool small samples of trapped ions and atoms to very low temperatures—in some cases to about 1 μK. This cooling results from the mechanical momentum imparted to the atoms when they scatter light; by suitable arrangement of the laser beam's frequency and position, the atoms can be made to scatter light only when this scattering causes their momentum to be reduced.

That electromagnetic radiation can impart momentum to matter was known to James Clerk Maxwell in the late nineteenth century. Albert Einstein used the discrete momentum changes imparted to atoms by electromagnetic radiation in his theoretical studies of thermal equilibrium between radiation and matter. In 1933, Otto Frisch demonstrated experimentally the transfer of momentum from photons to atoms by deflecting a beam of sodium atoms with resonance radiation from a lamp. With the development of tunable lasers in the 1970s, such effects could be much more pronounced. Recently, the narrow spectral width of lasers has also allowed cooling of atoms by these mechanical forces. The simplest form of laser cooling, and the one most commonly used, is called doppler cooling. It relies on the high spectral purity of lasers, the fact that atoms tend to absorb light only at particular frequencies, and the frequency shift of the light (as viewed by the atom) due to the doppler effect.

First, suppose we use a tunable laser to measure the absorption spectrum of an atom near one of its optical transitions. If we could hold the atom stationary, the absorption would be strongest at a particular frequency f_0 and have a narrow range Δf over which it absorbs most strongly. For the transition of interest in $^9Be^+$ ions, $f_0 \approx 10^{15}$ Hz and $\Delta f \approx$ 20 MHz.

Suppose we now release the atom and subject it to a laser beam coming from the left. Assume this laser has frequency f_L where $f_L < f_0$. If the atom moves to the left with velocity V, then in the atom's reference frame, the laser light appears to have a frequency approximately equal to $f_L(1 + V/c)$ due to the doppler frequency shift (Section 1-7). For a particular value of V, $f_L(1 + V/c) \approx f_0$, and the atom absorbs and re-emits photons at a high rate. On absorption, the photon's momentum is transferred to the atom and thereby reduces the atom's momentum by approximately h/λ where λ is the wavelength of the laser radiation (see Equation 2-29). However, the photon re-emission is spatially symmetric, so on the average, there is no net momentum imparted to the atom by re-emission. Hence, on the average, the atom's momentum is reduced by h/λ for each scattering event. This is really no different than in collisions of macroscopic bodies, since all we need to take care of is conservation of energy and momentum.

If, instead, the atom moves to the right, each scattering event increases the atom's momentum by h/λ. However, the scattering rate is much less for atoms moving to the right because the frequency of the radiation (in the atom's frame) is now $f_L(1 - V/c) < f_L < f_0$ and the laser appears to be tuned away from the atom's resonance. This asymmetry in the scattering rate, and in the accompanying transferred momentum, for atoms moving left or right, gives rise to a net cooling effect. If an atom is subjected to three mutually orthogonal, intersecting pairs of counterpropagating laser beams tuned to $f_L < f_0$, the atom feels a damping or cooling force independent of which direction it moves. Such a configuration has been called "optical molasses."

The randomness in the times of absorption and the randomness in the direction of photon re-emission act like random impulses on the atom, which counteract the cooling effect. These random impulses, which cause heating, reach a balance with the cooling when the effective temperature of the atoms reaches a minimum value equal to $h \, \Delta f/2k$ (k = Boltzmann's constant). For many atoms, this temperature is around 1 mK or less. At 1 mK, the second-order doppler shift of $^9Be^+$ ions is about 1.5×10^{-17}, so by the use of laser cooling we significantly reduce the perturbation to the measured frequency caused by the second-order doppler shift.

Other Applications of Trapping and Cooling

In the above, we have discussed how the techniques of atom trapping and cooling can be used for precision atomic spectroscopy. It appears that these techniques can also be used to advantage for other purposes. Some examples are briefly discussed here.

Atomic Clocks   The regular oscillations or vibrations of atoms and molecules can be likened to the oscillations of the pendulum in a grandfather clock. To make a clock based on atoms, we can tune the frequency of a radiation source until we drive a particular transition in an atom with maximum probability. If we then count the oscillations of the radiation source and wait until a certain number of cycles have elapsed, we define a unit of time. The nice thing about atoms is that, as far as we know, all atoms of a particular kind (such as $^9Be^+$ ions) are the same. No matter where two people are in the universe, if they agree to synchronize their radiation sources to a particular transition in a partic-

ular atom, when they count a given number of cycles, the unit of time they measure will be the same independent of a direct comparison. This is to be contrasted to pendulum clocks where no matter how much care is taken in their construction, they will oscillate at slightly different frequencies as it is hard to make the length of the pendula the same. Eventually we hope that, with the aid of trapping and cooling techniques, we will be able to make a clock that will be accurate to 1 second over the age of the universe. Accurate clocks are very useful in satellite and deep-space navigation systems.

Collision Studies   Atomic collision studies at extremely low energies are now possible. At very low temperatures, the atom's de Broglie wavelength is long and quantum-mechanical effects are very important in describing the collisions. If the atom's de Broglie wavelength is large compared to the attractive region near a material surface, the atom may experience only the repulsive part of the surface and elastically bounce rather than stick. This may help provide nearly ideal atom "boxes."

Atom Manipulation   Optical forces, such as those used in laser cooling, have been used to slow neutral atoms, steer atomic beams, and make atom "traps." The traps provided by optical forces are typically shallow (trap depths corresponding to a few kelvins). Therefore atoms from an atomic beam can be first slowed by overlapping them with a counterpropagating laser beam whose cooling force can stop the atoms at the position of the trap. In one trap called "optical tweezers," which uses the forces of a focused laser beam, the trapped atoms can be moved to different spatial locations by simply moving the laser beam. Applications of atom traps may include storage and manipulation of atomic antimatter, which must avoid contact with ordinary matter to prevent annihilation.

Condensed Matter   Collections of atomic ions contained in ion traps (for instance, Figure 6) can be viewed as plasmas. At the very low temperatures provided by laser cooling, the Coulomb potential energy between adjacent ions exceeds their kinetic energy and the ions show regular spatial structure. In Figure 7, this regular spatial structure takes the form of shells of

Figure 6 Photograph of the Penning trap used to confine the $^9Be^+$ ions shown in Figure 7. In this trap, which has cylindrical geometry (inner diameter of the cylinders ≈ 2.5 cm), the sections at either end have the function of the endcaps of the trap shown in Figure 1. They are at a positive potential with respect to the central electrodes. A uniform magnetic field from a superconducting magnet (not shown) is parallel to the axis of the cylinders. This trap is also mounted in a quartz vacuum enclosure. Photographs of the ions are made by viewing along the axis of the cylinders.
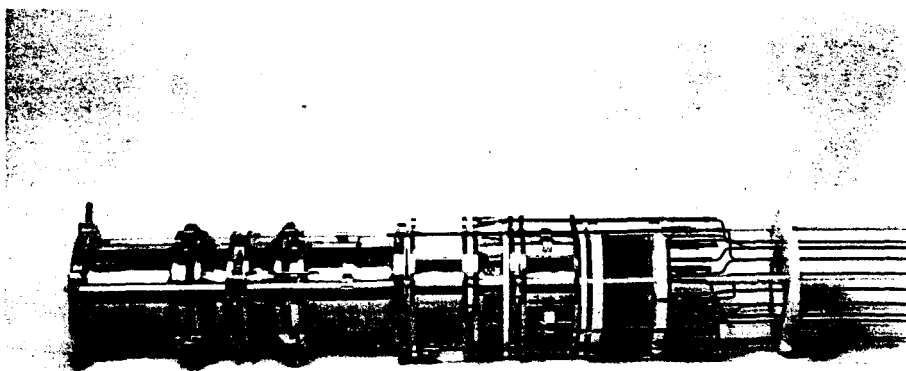
ions. If a sample of weakly interacting atoms (e.g., atomic hydrogen) is trapped and sufficiently cooled, it may be possible to observe a transition to a state where the wave functions of the atoms are all the same and occupy the same region of space. This phenomenon, which has yet to be observed, is called Bose–Einstein condensation.

These topics have been developed in more detail by P. Ekstrom and D. Wineland, "The Isolated Electron," *Scientific American*, August 1980, pp. 104–121; D. J. Wineland and W. M. Itano, "Laser Cooling," *Physics Today* vol. 40, no. 6, June 1987, pp. 34–40; W. D. Phillips, and H. J. Metcalf, "Cooling and Trapping Atoms," *Scientific American*, March 1987, pp. 50–56. J. J. Bollinger and D. J. Wineland, "Microplasmas," *Scientific American*, January 1990, pp. 124–130. C. Cohen-Tannoudji and W. D. Phillips, *Physics Today*, vol. 43, no. 10, October 1990, pp. 33–40.

Figure 7 Ultraviolet photograph of a small Be^+ ion plasma which has been stored in the Penning trap shown in Figure 6 and laser cooled to about 10 mK. This picture was taken by viewing the ion plasma along the z axis through one of the endcaps. At low temperatures, plasmas become "strongly coupled" and show spatial structure. Here, this structure takes the form of cylindrical shells, which have been partially illuminated by a laser beam. The diameter of the outer shell in this picture is about 150 μm.