Microplasmas

Two or more atoms—stripped of their outer electrons, trapped by electromagnetic fields and cooled to temperatures near absolute zero—array themselves in structures that behave like both liquids and solids

by John J. Bollinger and David J. Wineland

In 1973 a container whose "walls" were built from electric and magnetic fields trapped a single electron. Then in 1980 a similar device confined a single atom. The technology enabled physicists to measure the properties of electrons and atoms in unprecedented detail. The workers who initiated these experiments, Hans G. Dehmelt of the University of Washington and Wolfgang Paul of the University of Bonn, shared the 1989 Nobel prize in physics. Employing the same control over the temperature and position of atoms, we and our colleagues are investigating fundamental theories of atomic structure by trapping as many as 15,000 ions (atoms stripped of one or more of their electrons). The result is called a microplasma, by extension from the large groups of ions and electrons known as plasmas.

A microplasma is made by first applying electromagnetic fields to confine the ions to a specified region of space. A technique called laser cooling can then cool the trapped ions to temperatures of less than a hundredth of a kelvin. Because microplasmas can be built up practically one ion at a time, they provide an excellent opportunity to explore mesoscopic systems, that is, collections of ions too small to behave like a familiar, macroscopic system and yet too complex to be identified with the behavior of a single ion. Furthermore, microplasmas can serve as models for the dense plasmas in stellar objects.

Like the atoms in liquids, the ions in some cold microplasmas can diffuse through a somewhat ordered state. In other cases, the ions can resemble the atoms in solids, diffusing very slowly through a crystal lattice. Yet the nature of microplasmas is quite different from that of conventional liquids and solids. Whereas common liquids and solids have densities of about 10^{23} atoms per cubic centimeter, microplasmas have concentrations of about 10^{8} ions per cubic centimeter. Consequently, the average distance that separates ions in a microplasma is about 100,000 times greater than the distance between atoms in common liquids or solids. Furthermore, whereas internal attractive forces between the atoms hold a conventional liquid or solid together, external electric and magnetic fields hold the trapped ion microplasmas together. Indeed, the ions, which all have the same charge, actually repel each other and tend to disperse the microplasma.

The first investigations of these cold plasmas began more than a decade ago. In 1977 John H. Malmberg and Thomas M. O'Neil of the University of California at San Diego suggested that a collection of electrons or ions in an electromagnetic trap would resemble a type of matter known as a one-component plasma. In such a plasma, a rigid, uniform background of charge confines mobile, identical particles of opposite charge. The specific heat, melting point and other thermodynamic properties of a one-component plasma depend greatly on the density and the temperature of the mobile particles.

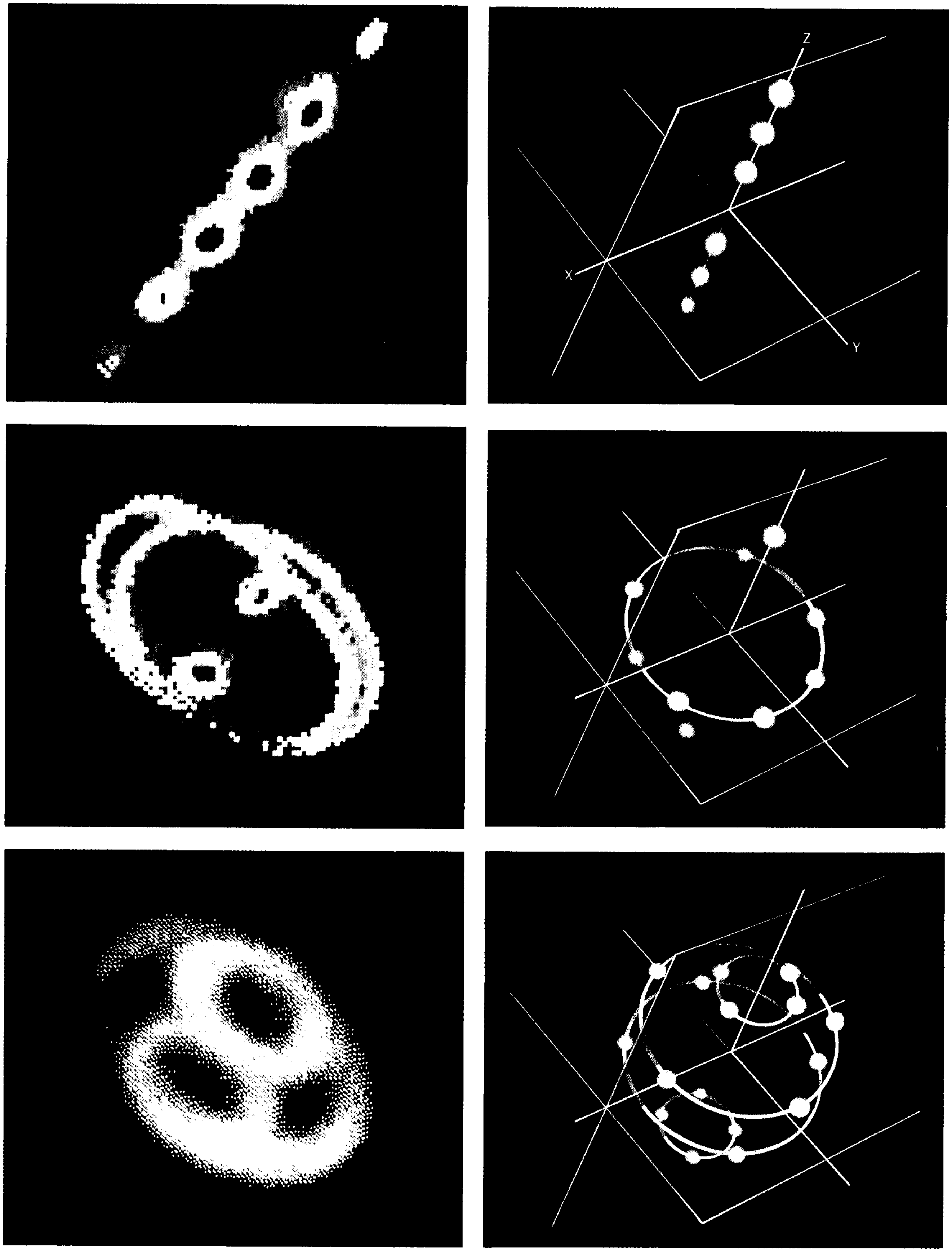
A single dimensionless parameter called the coupling, which can be derived from particle density and temperature, describes the thermodynamic properties of a one-component plasma by providing a measure of how strongly neighboring ions interact. The coupling is defined as the Coulomb potential energy between nearest neighboring ions divided by the kinetic energy of the ions. The Coulomb potential energy depends on both the average distance between the ions (a function of density) and the charge of the ion species. The kinetic energy is simply the temperature multiplied by a physical constant known as the Boltzmann constant.

When the Coulomb potential energy is less than the kinetic energy—that is, when the coupling is less than one—the one-component plasma should have no obvious structure and should behave like a gas. But a one-component plasma whose coupling is greater than one should show some spatial order. In such strongly coupled one-component plasmas, the ions should stay away from each other because the repulsive Coulomb forces are greater than the thermal forces. At couplings of two or more, a plasma should exhibit liquid behavior. At couplings near 180, a one-component plasma should change from a liquid to a solid phase, in which the ions are arranged in a body-centered cubic crystal.

These theoretical predictions for one-component plasmas pertain to "infinite" systems, ones whose macroscopic properties do not change when a large number of ions are added or subtracted. In addition, the predictions are valid as long as the ions in the plasma behave classically, that is, as long as the effects of quantum mechanics can be neglected. Under conditions of high density and low temperature, quantum mechanics can be important, as Eugene P. Wigner first investigated in 1934.

Examples of strongly coupled one-component plasmas can be found in

JOHN J. BOLLINGER and DAVID J. WINELAND are physicists at the National Institute of Standards and Technology in Boulder, Colo. Their work on microplasmas grew out of efforts to develop techniques for high-resolution spectroscopy of stored ions. Bollinger received a B.A. in physics from Cornell University and a Ph.D. from Harvard University in 1981. He enjoys playing volleyball and hiking in the Rocky Mountains. Wineland earned a B.A. in physics from the University of California, Berkeley, and a Ph.D. from Harvard University in 1970. He was a research associate at the University of Washington and joined the Institute in 1975. An avid bicyclist, Wineland "plans to race in the Tour de France in his next life."



MICROPLASMAS composed of six, nine and 16 ions of mercury (*top, middle and bottom, respectively*) are held in a Paul trap. A structural diagram is shown next to each photograph. The diagrams are based on the predictions by Wayne Itano of the National Institute of Standards and Technology. Although the ions keep the same relative positions, they orbit around the *z* axis.

the universe, especially in dense stellar objects. The outer crust of a neutron star (the collapsed remnant of a large star that has exploded as a supernova) is expected to contain from 10^{26} to 10^{29} iron atoms per cubic centimeter—a density at least 1,000 times greater than anything on or within the earth. How does a strongly coupled one-component plasma form in this environment? The tremendous pressure in the star's crust breaks down the iron atoms into iron nuclei and free electrons. The iron nuclei behave classically: one positively charged nucleus simply repels its identical neighbors. On the other hand, the free electrons obey the laws of quantum mechanics, specifically the exclusion principle: every electron must occupy a different energy state. Because of the high density of electrons in a neutron star, the electrons are forced into very high energy states. The electrons are therefore unaffected by the motion of the much lower-energy iron nuclei. Hence, they form a uniform density background of negative charge. The mobile nuclei in the electron background form a one-component plasma whose coupling is estimated to range from 10 to 1,000.

To learn more about such natural plasmas, workers have attempted to generate a strongly coupled one-component plasma in the laboratory. Because the thermodynamic properties of a one-component plasma depend only on the coupling, a one-component plasma that is cool and diffuse can have the same properties as a one-component plasma that is hot and dense. Yet until recently one-component plasmas in the laboratory have not been dense enough or cool enough to become strongly coupled. In the outer crust of a neutron star, for example, the density of iron nuclei is roughly 20 orders of magnitude greater than the typical density of ions in the trap. To create a one-component plasma whose coupling matches that of a neutron star, workers must cool trapped, charged ions to a temperature that is roughly nine orders of magnitude less than that of the star. Attaining a high enough coupling demands temperatures well below one kelvin.

In addition to having a coupling equal to that of the natural system, the laboratory one-component plasma must include enough ions to reveal the behavior that is characteristic of the many ions in the natural system. Physicists have recently taken the first step and are now working on achieving the second.

Both efforts involve the technology of electromagnetic traps. The technology is roughly 30 years old: in 1959 Ralph F. Wuerker, Haywood Shelton and Robert V. Langmuir in the laboratory at Thompson Ramo-Wooldridge, Inc., in California tested an electromagnetic trap that confines charged metallic particles. This beautiful experiment demonstrates the effects caused by the strong coupling of the particles. At about the same time, workers began trapping electrons and ions [see "The Isolated Electron," by Philip Ekstrom and David Wineland; SCIENTIFIC AMERICAN, August, 1980].

In principle an electromagnetic trap can be nothing more than a sphere uniformly filled with negative charge. When a positively charged particle is released within the sphere, it is pulled toward the sphere's center by the uniformly distributed negative charge. Overshooting the center, the positive particle experiences a "restoring" force that is proportional to its distance from the center and eventually pulls it back toward the center again. As long as the particle is free to move through the sphere, it will oscillate about the center. If the positive particle is cooled gradually, however—that is, if its kinetic energy is decreased—it will oscillate over an ever smaller distance until it settles in the center.

Practical devices can approximate this ideal trap. Two types of electromagnetic traps in particular—the Paul trap and the Penning trap—can produce strongly coupled one-component plasmas.

The Paul trap consists of three metallic electrodes: a ring and two end caps [*see illustration on opposite page*]. The ring is wired to a generator whose voltage fluctuates sinusoidally at the so-called driving frequency. The electrodes are supported within a vacuum chamber to ensure that air molecules do not collide with the ions.

How does the Paul trap confine ions? The sinusoidal ring voltage produces a time-varying electric field between the ring and the end caps. The direction of the field alternates: half the time the ion is pushed toward the ring and pulled away from the end caps, and half the time the ion is pulled away from the ring and pushed toward the end caps. The ion wiggles sinusoidally at the driving frequency.

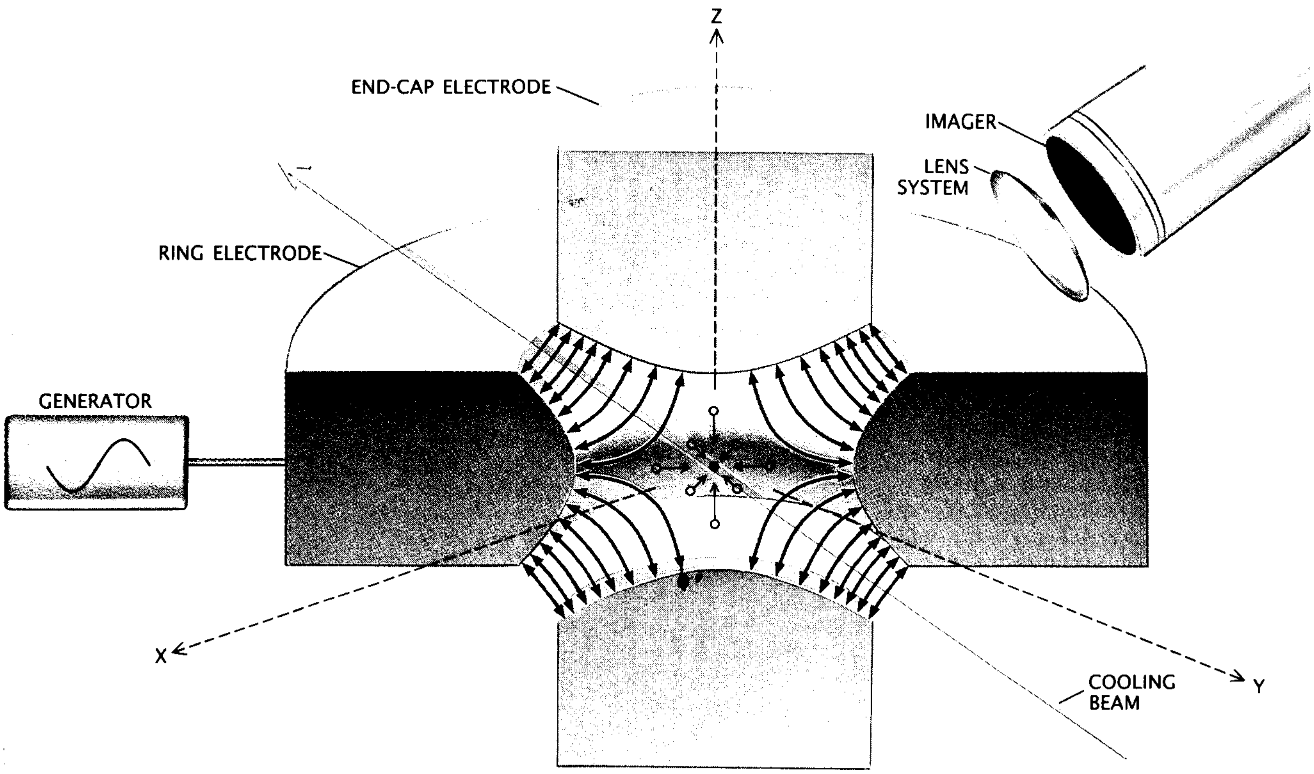
Because the driving force varies sinusoidally over time, one might expect the net force on the ion to be zero. In other words, one might think that the ion would move back and forth under the influence of the oscillating electric field but that the center of its oscillation would remain fixed over time. What, then, drives the ion toward the center of the trap?

The answer stems from the fact that because of the shape of the electrodes, the electric field is weaker at the center of the trap than it is near the electrodes. By considering a special case, one can gain a basic idea of how the spatial variation in the field affects an ion. Suppose that for a time the forced sinusoidal motion of an ion is centered closer to the top end cap than to the bottom end cap. When the ion is at the top of its oscillation, it encounters a strong force toward the center of the trap. When it is at the bottom of its oscillation, the force is toward the top end cap but is somewhat weaker. The ion therefore experiences a net force toward the center of the trap—the so-called ponderomotive force.

In the same way, the ion will experience a ponderomotive force that tends to drive it toward the center of the trap if it oscillates below the center or to either side. In the vertical direction the ponderomotive force is called the axial force; in the lateral direction it is called the radial force.

At all times, then, an ion in the trap experiences a driving force and a ponderomotive force. It turns out that the axial ponderomotive force is greater than the radial ponderomotive force. An ion therefore oscillates with three characteristic frequencies: driving, radial and axial. The trap is usually designed so that the radial and axial ponderomotive frequencies are about 10 times lower than the driving frequency. Hence, the motion caused by the driving force is a small, fast wiggle superposed on a large, slow oscillation about the center of the trap that is caused by the ponderomotive force.

If one disregards the smaller, faster oscillation caused by the driving force, an ion in the Paul trap moves in the same way it would inside a negatively charged sphere. Because the ponderomotive force differs in the axial direction, however, it is more appropriate to think of the Paul trap as a spheroid that is oblate (pancake-shaped) or prolate (cigar-shaped). To control the shape of the spheroid and the combined forces on the ions, one can apply an additional constant voltage between the ring and the end caps. When the overall radial force is greater than the axial force, the trap acts as a prolate spheroid. Conversely, when the radial force is less than the axial force, then the trap acts as an oblate spher-



PAUL TRAP creates a time-varying electric field (*red lines*) between the electrodes. As a generator applies a changing voltage to the ring, the electric field changes strength and direction, but its shape stays constant. The resulting ponderomotive forces (*black arrows*) confine charged particles. A laser beam directed at the trap's center cools and probes the ions.

oid. Thus, the Paul trap can both confine the ions in the center and orient the collection in the axial or radial direction.

In 1987, working at the National Institute of Standards and Technology with James C. Bergquist, Wayne M. Itano and Charles H. Manney, we used a Paul trap to observe strongly coupled microplasmas of mercury ions. At the same time, groups led by Herbert Walther and Frank Diedrich of the Max Planck Institute for Quantum Optics in Garching, by Peter E. Toschek of the University of Hamburg and by Richard G. Brewer of the IBM Almaden Research Center in San Jose, Calif., were conducting similar experiments on various ion species.

At the start of our experiment, a small amount of mercury vapor was allowed to leak into the vacuum system containing the Paul trap. As the mercury atoms passed through the trap, they were bombarded with a beam of electrons. The electrons in the beam had just enough energy to knock a single electron out of any mercury atom they struck, thereby ionizing the atom.

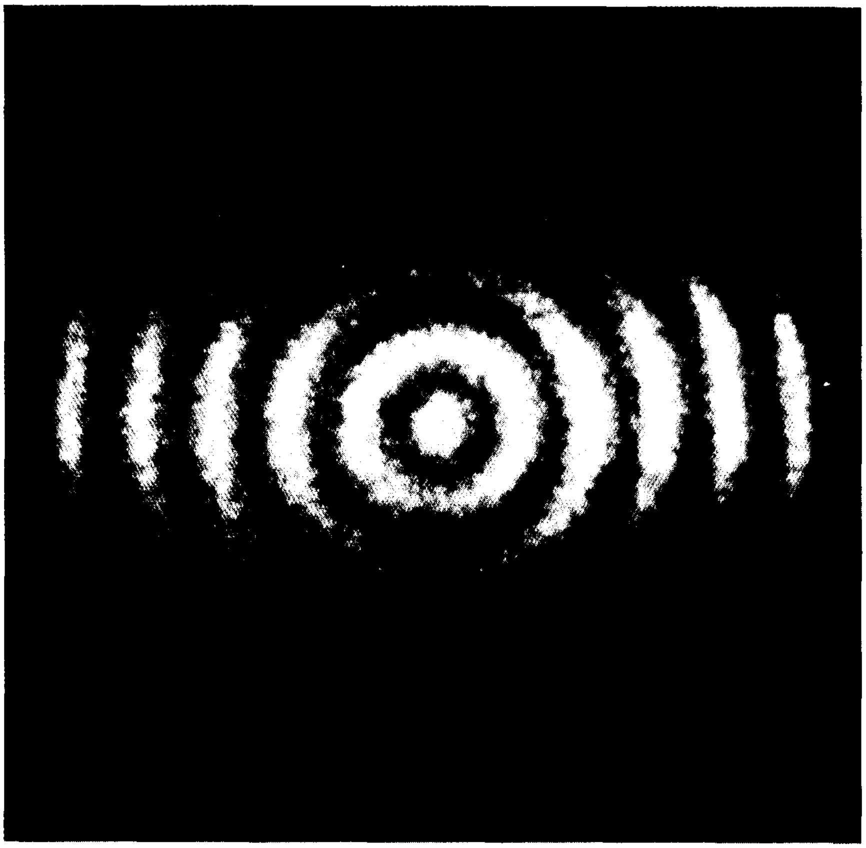
To cool the ions, we relied on the technique of laser cooling [see "Cooling and Trapping Atoms," by William D. Phillips and Harold J. Metcalf; SCIENTIFIC AMERICAN, March, 1987]. We generated a laser beam at a frequency slightly below a frequency that the ions could easily absorb. The ions traveling toward the laser source, however, "saw" the frequency as being slightly increased because of the Doppler effect. These ions absorbed the light strongly and slowed down. The ions traveling away from the source encountered the light at a lowered frequency; as a result, they absorbed the light weakly and did not speed up much. Overall the average motion of the ions was reduced: the ions were cooled.

To observe the individual mercury ions and their spatial structures, we illuminated them with ultraviolet light, which mercury ions scatter strongly. An ultraviolet video camera recorded up to 100,000 photons of ultraviolet light per second and thereby generated a motion picture of the trapped ions. The camera could resolve details as small as one micron (one millionth of a meter).

At first we worked with only one mercury ion in the trap and cooled it to millikelvin temperatures. The ponderomotive force confined the ion to the center of the trap. When we allowed two ions into the trap, we discovered two possible configurations. If the radial ponderomotive force was stronger than the axial force, the two ions lined up in the axial direction, so that they were equidistant from the trap center. Conversely, if the radial ponderomotive force was weaker than the axial force, the ions lined up in the radial plane equidistant from the trap center. As we added more ions to the trap, our intuition about the locations of the ions became questionable. But, with the assistance of a computer to keep track of the many forces and ions, Itano simulated various conditions in the trap and accurately predicted the resulting configurations of ions.

By confining ions, we confirmed that a Paul trap could support a one-component plasma. Although the ions were strongly coupled, as the observed spatial structures demonstrated, we needed to calculate the coupling from measurements of density and temperature. We could easily determine the density of the ions from images, but we had to measure temperature indirectly. We observed (as have many other groups in other experiments) that the motion of the ions modified the absorption spectrum associated with the ions. (The absorption spectrum of an atom or molecule reveals the frequencies of radiation absorbed most strongly by the atom or molecule.)

A collection of absolutely stationary ions would have a very sharp absorption spectrum, indicating absorption only at well-defined frequencies. On the other hand, if the ions moved around to some degree, the absorption spectrum would be blurred. The blurring results from the motion of the ions toward or away from the radiation source. From the perspective of the ions, however, it is the source that is moving toward or away from them, and so the frequency of the light is shifted by the Doppler effect. Thus, ions moving toward the source will be able to absorb radiation of slightly lower frequencies more effectively than motionless ions can, and ions moving away from the source will be able to absorb radiation of slightly higher frequencies. The combination of many ions moving in many directions has the effect of "smearing out" the spectrum, and the amount of smearing discloses the temperature of the ions. This technique proved that the temperature of the ions in our trap approached 10 millikelvins. The couplings, then, were as large as 500.



These measurements of the couplings, which indicated that the Paul trap could support a strongly coupled one-component plasma, were done with fewer than about 25 ions in the trap. We found it difficult to create similar solid states with more ions. The difficulty arose from the effects of the oscillation induced in the ions by the driving force. As an ion oscillates at the driving frequency, the repulsion between the ion and its neighbors enables it to influence the oscillations of the other ions. This additional perturbation can cause a plasma's structure to heat to a breaking point under certain operating conditions of the trap. The effect is known as radio-frequency heating, because the driving frequency for atomic ions is about the same as the frequency of radio waves. Radio-frequency heating was first observed in the experiments of Wuerker, Shelton and Langmuir.

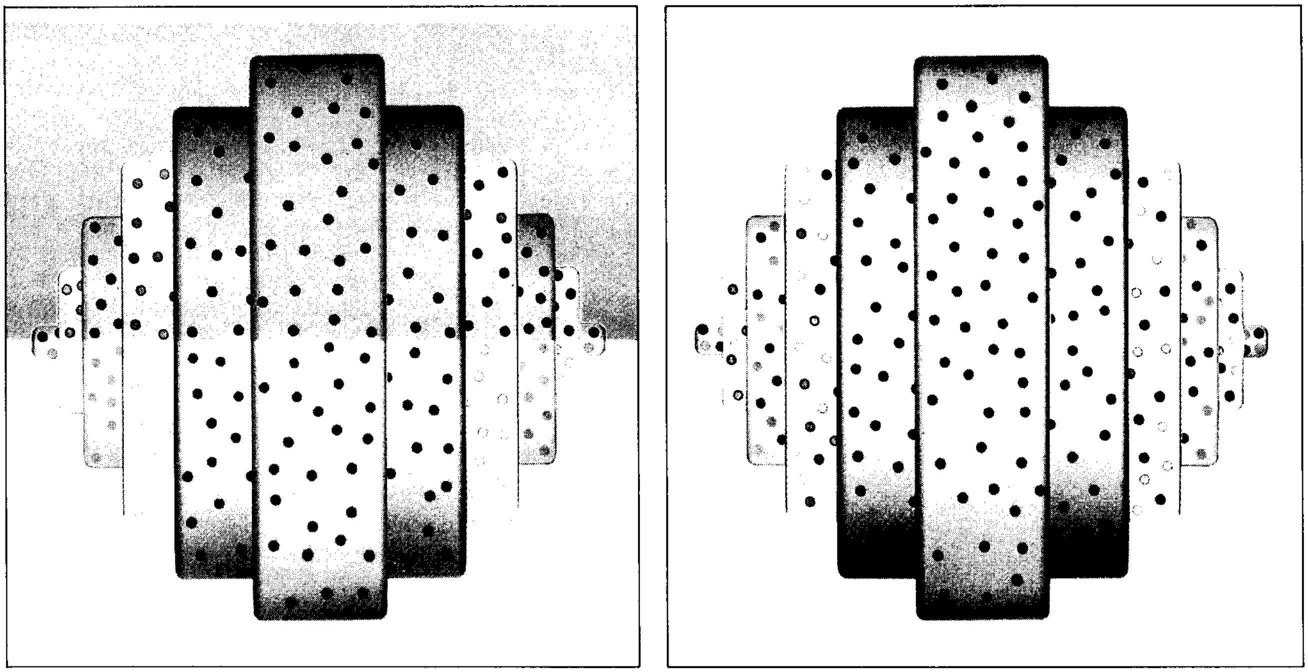
More recently Reinhold Blümel and co-workers at the Max Planck Institute and John A. Hoffnagle and colleagues at the IBM Almaden Center have studied radio-frequency heating of atomic ions in great detail. These studies show that a small change in the system parameters of the Paul trap can cause a sudden transition between cold, crystalline states and hot, gaseous states. For example, the rate at which the ions are cooled is very sensitive to the frequency of the laser light employed for cooling. If the laser is tuned far below the optimal cooling frequency, radio-frequency heating transforms the ion plasma into a hot, disordered state. If the laser frequency is increased, the rate of laser cooling increases, until at a critical frequency the laser cools the ion plasma quickly enough, so that some order starts to appear. At that point the radio-frequency heating diminishes drastically, and the ion plasma suddenly freezes into an ordered state. This frozen state is quite stable and will persist even if the laser frequency is again decreased somewhat. The irregular nature of radio-frequency heating makes it difficult to study the liquid-to-solid phase transitions predicted for one-component plasmas.

The problem of radio-frequency heating grows as the number of ions in the trap increases. When many ions are in the trap, some are pushed toward the electrodes, where the driving force is stronger. Those ions then oscillate at the driving frequency with a large amplitude and thereby increase the effects of radio-frequency heating. These considerations have limited the number of ions that can be cooled at one time in a Paul trap to about 200. If the difficulties associated with radio-frequency heating can be overcome, the Paul trap should allow workers to study the liquid-to-solid phase transition as well as other properties of the "infinite" one-component plasma.

At present the Penning trap provides a more hospitable environment for experimenting with large strongly coupled one-component plasmas than the Paul trap does. Unlike the time-varying electric fields of the Paul trap, the electric and magnetic fields that confine charged particles in the Penning trap are static. In 1988, with Sarah L. Gilbert, we constructed a Penning trap to confine beryllium ions. Malmberg and colleagues have also employed a Penning-type trap to confine strongly coupled plasmas of electrons.

Our trap consisted of four cylindrical electrodes arranged end to end along a common axis [*see illustration on page 130*]. A positive voltage was applied to the two outer cylindrical electrodes. This voltage generated an electric field between each inner electrode and the adjacent outer electrode. These fields trapped the ions in the axial direction, near a plane between the inner electrodes.

A powerful magnet placed around the electrodes created a uniform mag-



SHELL STRUCTURE of a microplasma consisting of about 1,000 beryllium ions is revealed in a photograph (*left*) made by shining a laser beam through the microplasma and recording the resulting fluorescence. The illustrations depict the complete shell structure as well as the diffusion of the beryllium ions from one moment (*center*) to the next (*right*). The microplasma behaves like both a solid and a liquid: the ions (*colored dots*) travel around within the shells but not between the shells.

netic field directed along the axis of the cylinders. The magnetic field prevented the ions from leaving the trap in the radial direction. The radial force of the electric field near the center of the trap is directed away from the trap center. This force combines with the axial magnetic field to cause the ions to orbit about the trap axis. As the orbiting ions pass through the magnetic field, they experience a Lorentz force that is directed radially inward. The Lorentz force is what confines the ions radially.

Except for this uniform rotation of the microplasma, the confining forces of the Penning trap are equivalent to the confining forces in the uniformly charged spheroid. Hence, even though ions in a Penning trap rotate, they behave like ions in a one-component plasma—in particular, they have the same thermodynamic properties.

To begin the experiment, we produced beryllium ions by a method similar to that described for making mercury ions in the Paul trap. The ions were cooled by two intersecting laser beams. A third laser beam, called the probe, was employed to measure the temperature of the ions. The light scattered by the ions was collected to make an absorption spectrum. As in the mercury-ion experiment, the temperature of the ions could be deduced from the blurring of certain features of the spectrum. This technique revealed that the ions had been cooled to below 10 millikelvins.

The rotation frequency of the beryllium microplasma could also be deduced from the spectrum. Beryllium ions circulated inside the trap at a rate of from 20,000 to 200,000 rotations per second. Because the rotation frequency is directly related to the radial electric fields, which are in turn related to the ion density, we were able to calculate that the ion density ranged from 50 to 300 million ions per cubic centimeter. From ultraviolet images of the plasmas we could determine the volume occupied by the trapped ions and therefore the number of trapped ions. The temperature and density measurements yielded couplings as large as 200 to 400 for less than about 15,000 ions in the trap.

We expect a phase transition from a liquidlike to a solidlike state to occur at a coupling of 180 for a one-component plasma with an infinite number of ions. Our measured values for the coupling indicate that the trapped ions should form a crystalline ion solid, if the trap contains enough ions. Should a system of 15,000 trapped ions, though, behave like an infinite system?

Recently some computer simulations have elucidated this question. The late Aneesur Rahman of the University of Minnesota at Minneapolis, John P. Schiffer of the Argonne National Laboratory, Hiroo Totsuji of Okayama University and Daniel H. E. Dubin and O'Neil of the University of California at San Diego have created simulations of a trapped plasma containing as many as several thousand ions. The simulations reveal several remarkable features. When the couplings exceed one, the ions are concentrated in concentric shells, which are spaced evenly. For couplings around 10, the shells are in a liquid state characterized by short-range order and diffusion in all directions. As the coupling increases, the shells become more clearly defined; the ions diffuse quickly within the shells and slowly between the shells. For high couplings (above 200), the diffusion of the ions within a shell slows down and the ions form a solidlike state. Instead of showing a sharp phase transition, the plasma evolves gradually from a liquidlike to a solidlike state.

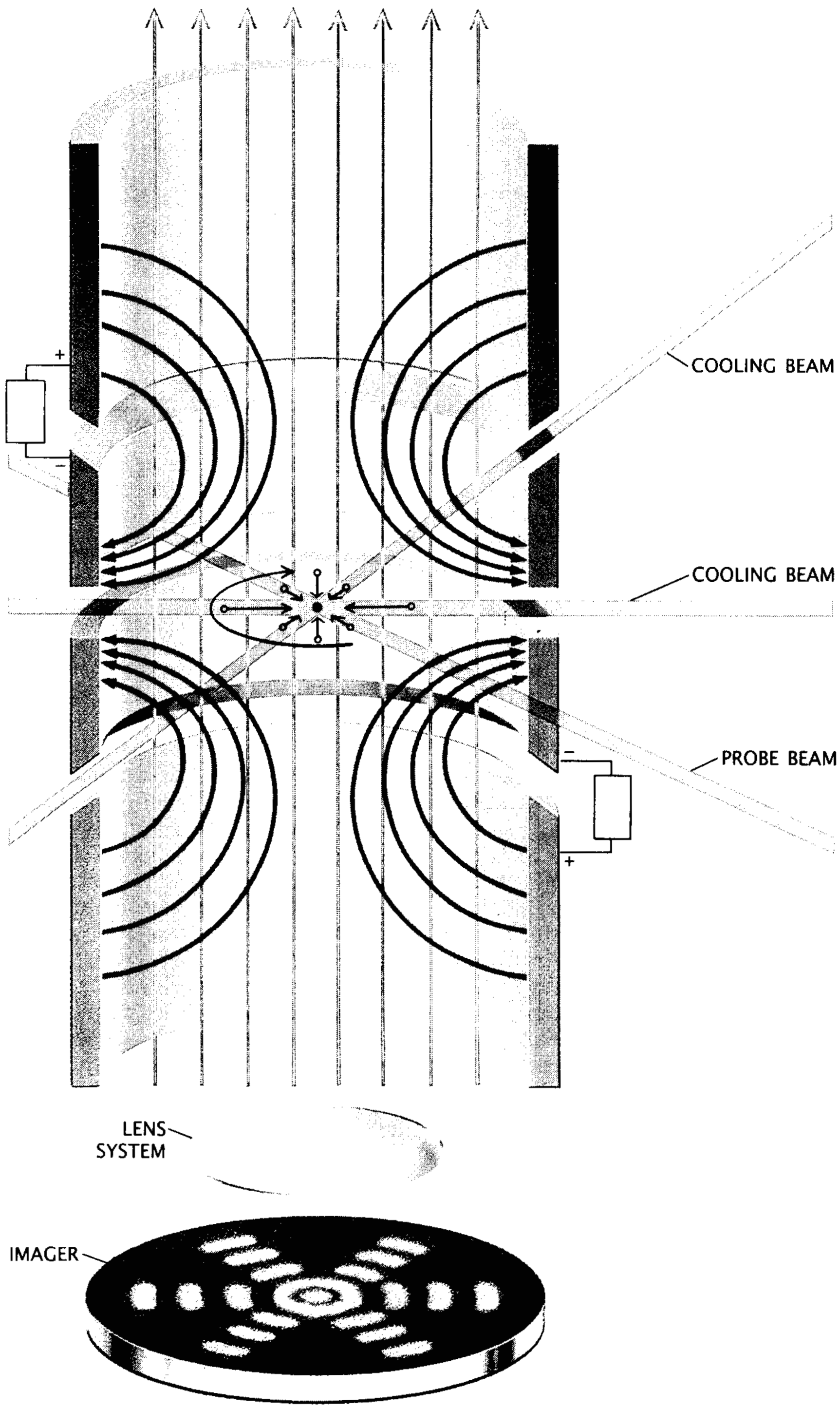
Experiments have confirmed these predictions. Even though the plasma of beryllium ions rotates around the axis of the Penning trap, the shell structure is preserved in the radial direction. The scattered light from a laser beam cutting across the plasma shows alternating bright and dark bands corresponding to the shells. We looked for shell structure in plasmas that contained as few as 20 ions and as many as 15,000 ions. In a plasma of 20 ions, a single shell was clearly observed. In a plasma of 15,000 ions, we could distinguish 16 shells. So far we have not detected any distinct structure within a shell because of the rotation of the plasma in the trap.

We were able to test predictions that for couplings around 100, the plasma will act like a liquid within a shell but like a solid between the shells. In particular, the ions should diffuse faster within shells than between shells. To demonstrate the effect, we optically "tagged" the ions by tuning the probe laser to a specific frequency. The probe laser suppresses the emission of light from the ions it strikes by placing them in a "dark" energy state in which they do not scatter light from the cooling laser beams.

First we darkened an outer shell of the plasma and measured the time required for the dark ions in the outer shell to move to the inner shells. Then we darkened part of the plasma across several shells and measured the time required for dark ions in one part of a shell to move to other parts of the same shell. These measurements verified that for moderate couplings the diffusion of ions between shells is more than 10 times slower than the diffusion of ions within a shell.

Many questions about microplasmas are still unresolved. At what point will the behavior that is characteristic of an infinite system start to appear? How many ions are required for the system to exhibit a sharp phase transition? At what stage will the solid state become a body-centered cubic lattice rather than a collection of shells?

At present these questions are difficult to answer even in theory. Dubin predicts, however, that perhaps as many as 50 to 60 shells may be required before a body-centered cubic lattice would become an energetically favorable configuration. That would require about a million ions, more than 50 times the number of ions in the largest, strongly coupled microplasmas created so far. Current technology should be able to confine cold plasmas of this size. If couplings of 200 or more can be maintained for a plasma of a million ions, we may be able to visit the surface of a neutron star in a laboratory on the earth.



PENNING TRAP generates electric fields (*red lines*) and magnetic fields (*green lines*) to produce forces (*black arrows*) that confine charged particles. The electric and magnetic fields also cause the microplasma to rotate. Two laser beams cool the particles; a third serves as a probe for various experiments. The magnetic field arises from an electric current flowing through a solenoid (not shown) that encircles the trap.

FURTHER READING

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