Cooling and Trapping Atoms

Atoms are slowed and cooled by radiation pressure from laser light and then trapped in a bottle whose "walls" are magnetic fields. Cooled atoms are ideal for exploring basic questions of physics

by William D. Phillips and Harold J. Metcalf

A highly fruitful area of scientific research has traditionally been the study of the intrinsic properties of isolated atoms. In the early part of this century such inquiry led to the formulation of quantum mechanics, one of the cornerstones of modern physics. More recently, precise measurements with atoms have also shed light on other fundamental physical theories, including relativity.

The triumphs born from probing atomic systems have depended largely on the ability to make precise measurements. A deeper understanding of the structure of matter at the atomic level requires that measurements be made with even greater precision. Unfortunately the necessary precision cannot be easily achieved: in solids and liquids one cannot isolate individual atoms from the effects of their neighbors, and in gases the random thermal motion of atoms makes highly precise measurements difficult.

The continued need for ever more precise measurements has led to the development of many techniques for overcoming the effects of thermal motion. Simply reducing the effects of thermal motion is not sufficient for the most demanding measurements; ultimately it becomes necessary to reduce the thermal motion itself. Methods developed over the past few years provide the required means. Atoms can now be cooled by shining laser light directly on them. The radiation pressure exerted by the laser light can be exploited to push on the atoms in order to slow them down. Once the atoms have been cooled, they can be trapped, or confined to a limited region of space. In our laboratory we trap atoms in a bottle whose "walls" are electromagnetic fields rather than material substances.

Cooled or trapped atoms are ideal for exploring fundamental questions of physics. Early in 1986, for instance, cooling and trapping were employed to observe for the first time a fundamental quantum-mechanical process: the transition of a single atom from one discrete energy level to another (a quantum jump). In this case the trapping was relatively easy because the atom had been ionized, or stripped of one of its electrons. Recent techniques have made possible the trapping of even electrically neutral atoms.

In the future, laser-cooled atoms will certainly facilitate spectroscopic measurements, perhaps leading to substantial improvements in such areas as atomic clocks and measurements of fundamental constants. Cooling and trapping will enable investigators to look at collisions between atoms in detail and better understand the way chemical bonds are formed. Laser cooling and electromagnetic trapping could also be employed to manipulate atoms made of antimatter. Since antimatter annihilates with ordinary matter on contact, ordinary material walls cannot contain it.

At high enough densities certain atoms might even undergo a fundamental type of transition called a Bose condensation. Such a condensation is predicted by quantum mechanics, which holds that there are two types of fundamental particles called fermions and bosons. Fermions, which include electrons, protons and neutrons, cannot be in the same quantum state; in contrast, bosons, which include some atoms (such as the hydrogen atom), can occupy the same quantum state. In a sufficiently cold and dense collection of bosons a major fraction of the particles will be in the same, lowest-energy quantum state. The eagerly sought observation of Bose condensation could well occur in traps populated by laser-cooled atoms.

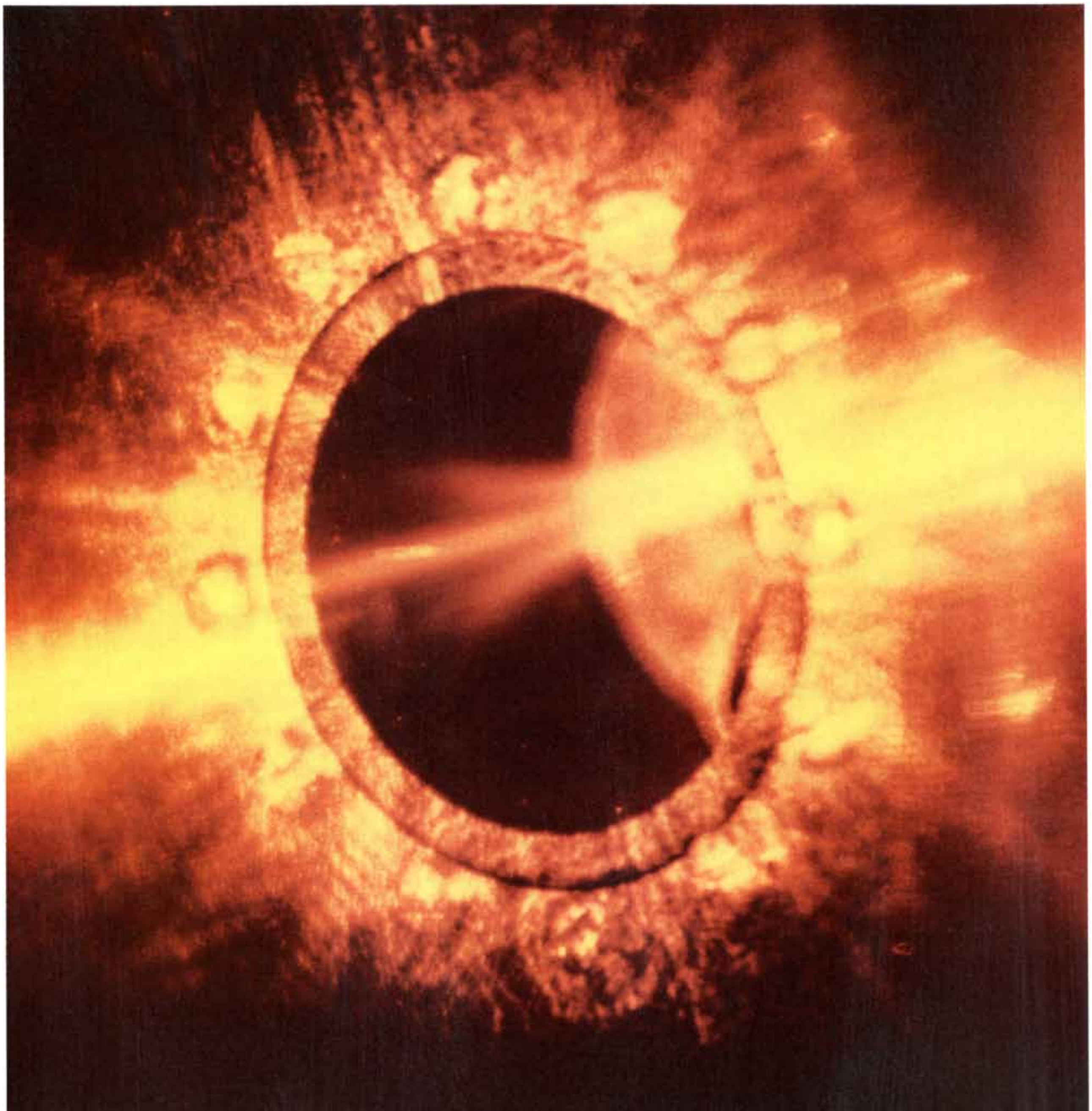
Why are atoms always in motion? The kinetic theory developed during the past century shows that gases are collections of atoms or molecules whose average kinetic energy (which varies directly as the square of the velocity) is proportional to the absolute temperature. Such classical motion can never be eliminated except at the unattainable temperature of absolute zero, or approximately −273 degrees Celsius. At room temperature, for instance, air molecules move at an average speed of about 500 meters per second, or 1,100 miles per hour. Furthermore, the atoms move at various speeds, mostly between zero and twice the average speed.

Why does thermal motion affect precise measurements of atoms? Each atom in the gas acts like a sharply tuned transmitter and receiver of electromagnetic radiation; an atom can efficiently emit and absorb only certain frequencies of radiation. Since different kinds of atoms emit and absorb different frequencies, each set of frequencies, called a spectrum, serves as a "signature" for a particular type of atom. In other words, identical atoms have the same spectrum and share the same signature. The measurement of spectra, called spectroscopy, allows one to draw conclusions about the fundamental structure of atoms.

Unfortunately the observed spectrum of identical atoms in a gas is smeared out at ordinary room temperatures because of the thermal motion of the atoms. When an atom moves with respect to an observer, its characteristic frequencies appear to shift from the intrinsic ones seen when the atom is stationary. The phenomenon is called the Doppler shift, after the 19th-century Austrian physicist Christian Doppler, who explained a similar effect for sound. The basic phenomenon is familiar to anyone who has heard the sudden change in pitch of the horn of a passing train. It is also the Doppler shift that enables a police radar to determine the speed of a car.

The Doppler shift also occurs when an atom moves with respect to a light source. The atom encounters the crests and troughs of the radiation waves at a higher rate, so that the frequency appears to the atom to be shifted up, or higher. Conversely, if the atom moves away from the source, the apparent frequency is shifted down, or lower. Even in the absence of this kind of Doppler shift, as when the atom moves perpendicularly to the line connecting it to the source, there is always another apparent frequency shift owing to special relativity. (The relativistic effect arises from the fact that an observer sees a moving clock run slower than his own identical clock. One consequence of this is the "twin paradox": a twin who travels in a spaceship is found on his return to have aged less than his earthbound sibling.)

Because of the effects of the Doppler shift, a gas of randomly moving atoms—each identical with the others and each having an identical spectrum—appears to be a collection of atoms all of which have slightly shifted spectra. The spreading in frequencies, while it is only a millionth of the optical frequency, has profound consequences. For example, for many years the Doppler broadening of the optical spectrum of hydrogen hid a small but important frequency shift called the Lamb shift. The eventual discovery of the Lamb shift (by nonoptical meth-



LASER COOLING brings atoms moving at speeds exceeding 1,000 meters per second, or 2,200 miles per hour, to a virtual standstill. Here a laser beam shines into a collimated beam of sodium atoms. The sodium atoms enter from the right of the photograph, the laser beam from the left. The atoms slow down from the radiation pressure of the laser light and come to a virtual halt near the center of the circular opening (which is at the end of a solenoid: a long coil). The slowed atoms spread out into a "skirt."

ods) ultimately led to and confirmed the theory of quantum electrodynamics, which is now thought to be a complete description of the interaction of radiation and matter and the paradigm for all modern field theories.

Yet another motional effect that plagues spectroscopy is transit-time broadening. Since atoms are moving, they do not stay in a region where they can be observed for long periods of time. The limited time available for measurement broadens the spectrum. The higher the atomic velocity, the smaller the observation time and the greater the broadening.

Many methods have been developed to overcome the difficulties imposed on spectroscopy by atomic motion. Spectroscopy that is virtually free of Doppler effects can be achieved by a variety of schemes. Still, there are residual effects that arise from imperfections in the apparatus; furthermore, these schemes do not address the problems of transit-time broadening and relativistic shifts, which limit spectroscopy requiring an accuracy of one part in 10^{11} or better.

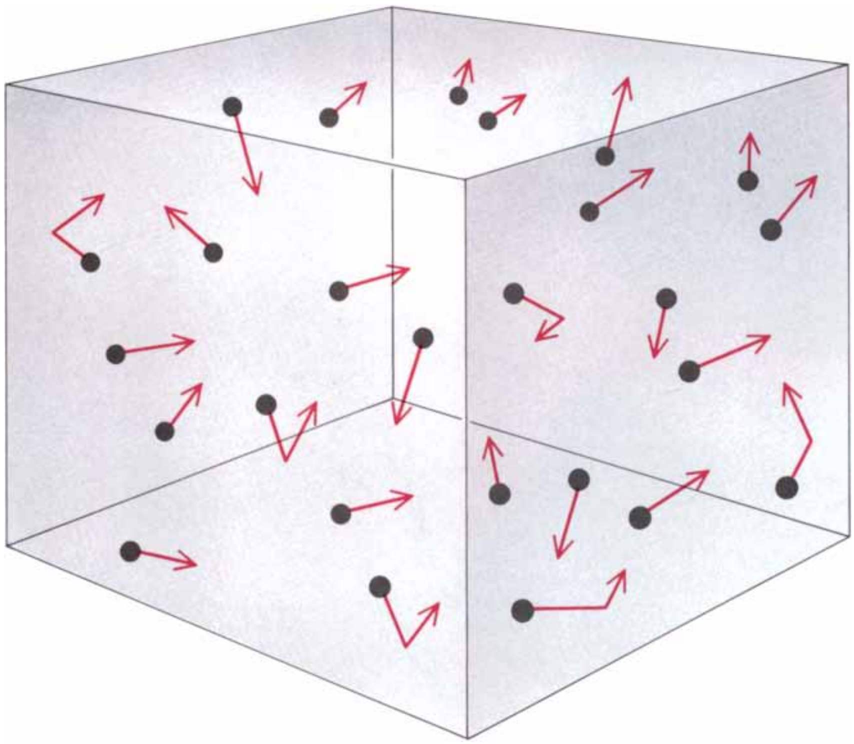
Cooling is the most obvious way to reduce the motion of atoms and minimize such effects, thereby making measurements more precise. One way to accomplish cooling is to have the atoms collide with either the walls of a cold container or another gas of cold atoms. Such cooling works up to a certain point. At low enough temperatures nearly any atom will condense on the container walls or form molecules or clusters with its collision partners. When either happens, the atom is no longer isolated and complicated interactions with its neighbors prohibit accurate measurements.

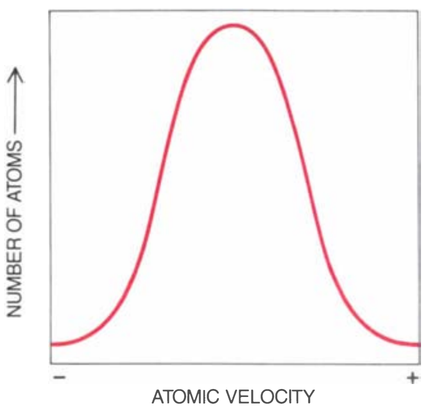
A different kind of cooling—laser cooling—is needed to achieve the low velocities associated with low temperatures without inducing unwanted condensation of atoms. In a sense the highly organized, monochromatic nature of laser light makes the laser a very low temperature system through which atoms can give up heat by their interactions with it. The idea of laser cooling was proposed independently in 1975 by Theodor W. Hänsch and Arthur L. Schawlow of Stanford University for a gas of atoms and by David Wineland and Hans G. Dehmelt of the University of Washington for trapped ions.

Laser light can be exploited to affect atomic motion and cool atoms because it has momentum, and so it pushes against objects that absorb or reflect it. Momentum is a characteristic of motion that can be transferred but not created or destroyed. Matter and light interact and transfer momentum by exchanging discrete packets of light called photons. The number of photons necessary to cool atoms is enormous. In order to bring to rest a single sodium atom traveling 1,000 meters per second, for instance, some 30,000 photons must strike it head on.

To see how laser cooling works, suppose a laser beam shines into a gas of identical atoms at room temperature. Further, suppose the laser beam is tuned to a particular frequency that is lower than one of the intrinsic frequencies at which the atoms emit and absorb radiation. Some of the atoms in their rapid and random motion will therefore have just the right velocity and corresponding Doppler shift to absorb the light strongly, but for the majority of atoms the light will have little effect. In particular, those atoms moving toward the light source "see" it Doppler-shifted closer to their intrinsic frequency, and therefore they absorb light more rapidly. Those atoms will slow down, because the momentum of the light opposes their motion. On the other hand, atoms moving away from the source are less likely to absorb the light, because they "see" the frequency of the laser Doppler-shifted to a still lower value, further away from the frequency they need for absorption. The atoms moving away from the source, which are accelerated when they absorb light, do so much more slowly than the atoms moving toward the source. The net effect is that on the whole the atoms in the gas slow down.

In 1978 workers at the National Bureau of Standards in Boulder and at the University of Heidelberg independently demonstrated laser cooling of trapped positive ions (atoms that have





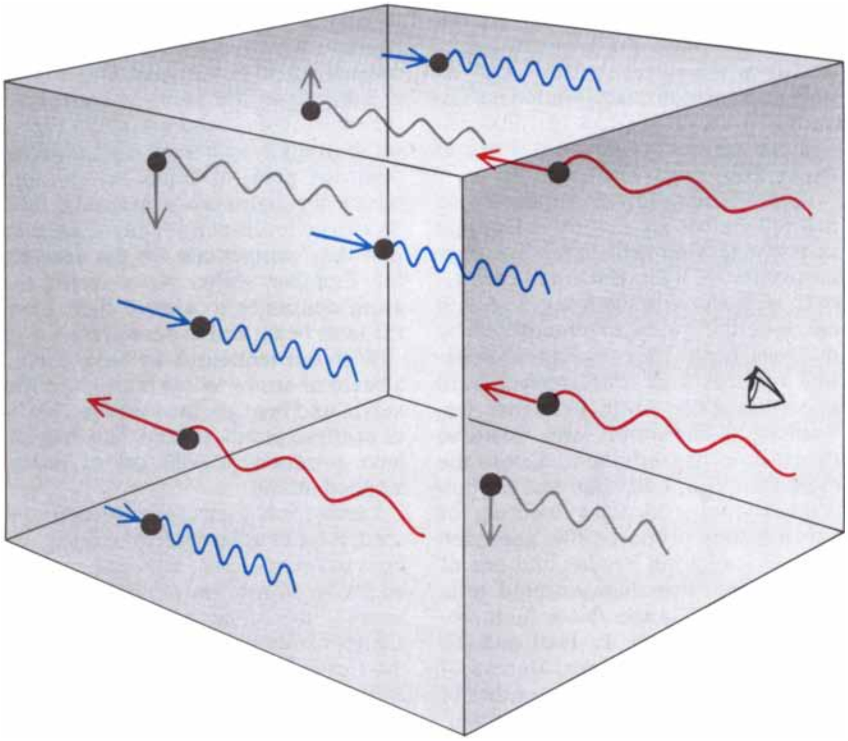
ATOMS in a gas held at room temperature move rapidly, at varying speeds and in different directions (*top*). The atoms collide frequently with one another and, if they are held in a container, with the walls of that container. The distribution of velocities of individual atoms in a gas is given by a bell-shaped curve called a Maxwell-Boltzmann distribution (*left*). The distribution actually shows the number of atoms as a function of the projection of their velocity along a given axis. The higher the temperature of the gas is, the wider the distribution is and the harder it becomes to make precise measurements. One way to avoid such problems is to cool the atoms.

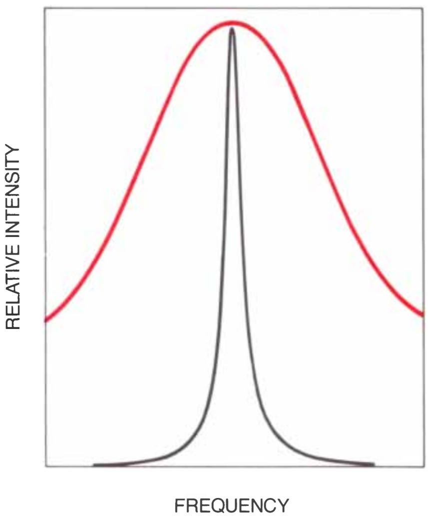
lost one or more electrons and so have a net electric charge). Continued experiments with trapped ions by these and other groups have produced ions cooled to only a few thousandths of a degree above absolute zero, highly accurate atomic clocks and visual observations of single atoms.

We have been working at the National Bureau of Standards in Gaithersburg, Md., to extend the technique of laser cooling to neutral atoms. A key difficulty in cooling neutral atoms is that, unlike electrically charged ions, they are not easily influenced by electric and magnetic fields. Although ions held at room temperature and above are readily trapped in such fields, neutral atoms must first be cooled to temperatures on the order of one degree Kelvin (−272 degrees C.) or below before they can be trapped. Over the past several years our group and other groups at the Institute of Spectroscopy in Moscow, the National Bureau of Standards in Boulder, the AT&T Bell Laboratories, the University of Colorado at Boulder, the University of Bonn, the École Normale Supérieure in Paris, the State University of New York at Stony Brook and the Massachusetts Institute of Technology have successfully developed approaches to cooling neutral atoms with laser beams.

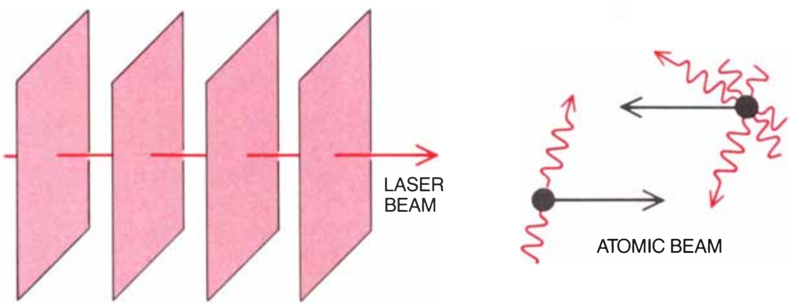
All the approaches begin with freely moving neutral atoms, usually sodium atoms in the form of a beam. We generate the sodium beam by heating an oven containing sodium metal to 450 degrees C. The metal vaporizes, and the atoms come out of the oven through a small pinhole as a diverging beam; we mask off all but a narrow fraction of the beam by positioning another pinhole about 10 centimeters away. In our apparatus a laser shines directly into the sodium beam. In this way each atom can interact with the light for as long as possible.

When an atom absorbs light, it jumps to an excited state. The atom can return to the ground, or unexcited, state by one of two processes, stimulated emission or spontaneous emission. If the emission is stimulated (induced by the laser light), the emitted photon travels in the same direction as the absorbed photon and the atomic momentum does not change. If the emission is spontaneous, however, photons are emitted in random, symmetrically distributed directions. Repeated absorptions followed by spontaneous emissions result in a net deceleration of the atoms in the direction of the laser beam. The maximum deceleration a sodium atom can experience in laser cooling is about a million me-





IDENTICAL ATOMS moving with different velocities in a room-temperature gas appear different to an observer because of a phenomenon known as the Doppler shift (*top*). The basic effect is familiar to anyone who has heard the sudden change in pitch of the horn of a passing train. If the atoms were stationary, they would absorb and emit radiation of almost the same frequency. Atoms moving toward the observer appear to radiate at slightly higher frequencies (*blue*), because the crests and troughs of their radiation waves reach the observer at a higher rate. Atoms moving away from the observer appear to radiate at slightly lower frequencies (*red*). The effect of the Doppler shift is to smear out what would otherwise be a sharply defined spectrum, or distribution of frequencies (*left*). The smeared-out spectrum has the same shape as the Maxwell-Boltzmann distribution in the illustration on the opposite page.



LASER COOLING of a gas takes place when atoms "see" more "head wind" than "tail wind." Such conditions are realized by tuning a laser beam to a frequency lower than the frequency strongly emitted and absorbed by the atoms. Some of the atoms moving toward the laser beam will then have the appropriate Doppler shift to absorb and reradiate the light, and they will slow down. Atoms moving with the laser beam, on the other hand, see the frequency of the light shifted still lower, and they are less likely to absorb the light: they will be speeded up very little. Consequently on the whole the atoms slow down.

ters per second squared, which is close to 100,000 times the acceleration of gravity at the surface of the earth. At such an enormous deceleration a sodium atom with a velocity of 1,000 meters per second would be stopped in one millisecond over 50 centimeters.

As the atoms slow down, even by a few meters per second, their Doppler shift changes enough to inhibit their absorption of light. Eventually the atoms will stop decelerating and will continue their journey unimpeded by the laser beam. One way to compensate for this undesirable effect is to sweep the laser beam to higher frequencies as the atoms slow down so that the atoms continue to absorb the radiation. V. S. Letokhov and his colleagues at the Moscow Institute of Spectroscopy proposed this approach in 1976, and John Prodan and one of us (Phillips) first demonstrated it in 1983 in our Gaithersburg laboratory. Since then John L. Hall and his co-workers at the National Bureau of Standards in Boulder and a number of other groups have successfully employed the approach.

Throughout most of our work, however, we have exploited a different technique to overcome the complication caused by the changing Doppler shifts. We hold the frequency of the laser beam constant and manipulate the energy levels of the atoms so that the atoms continue to absorb the beam. We do this by sending the atoms through a magnetic field whose strength varies along the path traveled by the atoms. The energy levels of an atom change in a well-determined way when the atom is placed in a magnetic field, a phenomenon known as the Zeeman effect. We have tailored the magnetic field in our apparatus so that it is strong at the point where the atoms first enter it and gradually tapers off in strength with increasing distance from the point of entry. As an atom passes through such a magnetic field its energy levels continually change so that they compensate for the decreasing Doppler shifts. As a result the atom continues to absorb light from the laser beam and to decelerate.

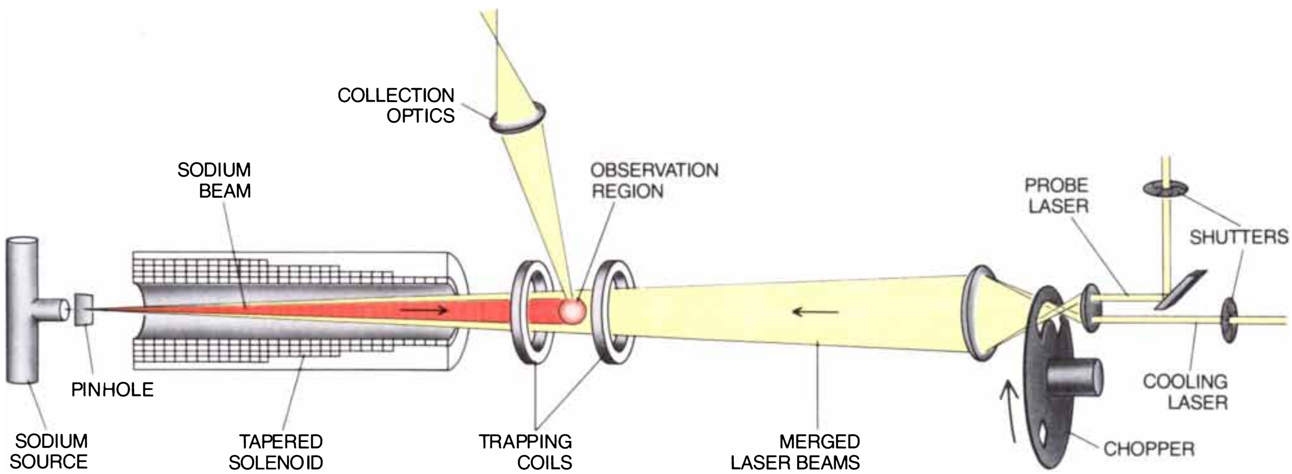
With our technique we have cooled a beam of atoms to less than 100 millikelvin and brought the average velocity of these atoms to zero. In effect we have produced a cold gas of nearly stopped atoms.

Laser-cooling a gas of atoms, in contrast, is quite different from laser-cooling a beam of atoms. The reason is that all atoms in a beam move in approximately the same direction, so that a single laser beam suffices to oppose their motion. On the other hand, free atoms in a gas move in all directions and therefore require several laser beams to cool them. At the AT&T Bell Laboratories, Steven Chu and his colleagues, having laser-cooled a beam of atoms, employed multiple laser beams to further cool the sample to less than a millikelvin. Atoms at the intersection of the multiple beams experience a retarding force in any direction in which they move and are therefore said to be in an "optical molasses."

One of the exciting consequences of stopping neutral atoms is that they can then be held in atom traps: bottles for atoms whose "walls" are electromagnetic fields rather than material substances. It has long been possible to trap electrons, ions and other charged particles, because strong electric and magnetic fields can greatly affect their motion [see "The Isolated Electron," by Philip Ekstrom and David Wineland; SCIENTIFIC AMERICAN, August, 1980]. The same electric and magnetic fields have little effect on a neutral atom, however, since it carries no net charge.

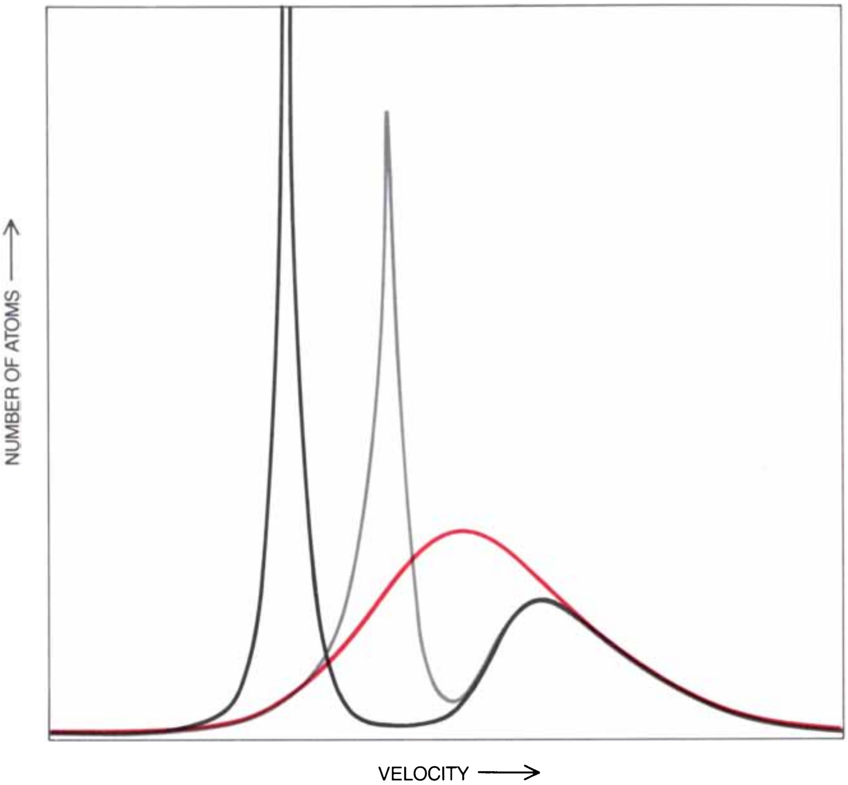
A number of different traps for neutral atoms have been proposed over the past 25 or 30 years. In the 1950's Wolfgang Paul of the University of Bonn suggested that, in principle, magnetic traps could be employed. Another alternative, laser traps, was proposed in about 1970 independently by Letokhov and by Arthur Ashkin of Bell Laboratories. In 1978 Paul and his colleagues succeeded in trapping neutrons in a magnetic storage ring. Their experiment was a landmark one, because it was the first time that neutral particles had been confined electromagnetically. Their work enabled them to make new measurements of the average lifetime of the neutron. (After about 15 minutes an isolated neutron decays into a proton, an electron and a particle called a neutrino.)

Our trap for neutral atoms exploits the same physical principles used in Paul's neutron storage ring. Even though a neutral atom has no net electric charge, it can still have a small magnetic dipole: the atom can behave as if it were a tiny bar magnet. Now, if a bar magnet is immersed in an inhomogeneous magnetic field, the strength of the field at one pole differs



AUTHORS' APPARATUS for cooling an atomic beam and magnetically trapping neutral atoms is shown schematically. The investigators slow a beam of sodium atoms traveling through a solenoid by shining a laser beam on the atomic beam. Measurement of the velocity distribution of the atoms and the laser-induced changes to it is done by collecting and detecting the fluorescence from atoms excited by a second, very weak probe laser propagating nearly parallel to the atomic beam. The absorption and hence the intensity of this fluorescence will depend on the atomic velocity because of the Doppler shift of the probe beam. The dependence of the fluorescence on the probe-laser frequency reflects the velocity distribution of the atoms. Very slow atoms can be trapped in the magnetic field generated by the pair of "trapping coils." The trapped atoms move as if they had a temperature of 10 millikelvin, slightly above absolute zero. The chopper and shutters are used to turn the laser beams on and off at appropriate times.

from the strength at the other pole, and a force will be exerted on the magnet. If the bar magnet happens to be an atom, the force will be quite small, but it is nonetheless an observable quantity. The effects of an inhomogeneous magnetic field on a neutral atom were first demonstrated in 1924 by Otto Stern and Walther Gerlach. The Stern-Gerlach experiment showed that a silver atom can be thought of as a bar magnet whose axis can have only two possible orientations with respect to the magnetic field. (An ordinary bar magnet, of course, can have a continuous range of orientations.)



EFFECTS OF LASER COOLING on the distribution of velocities in a beam of atoms are pronounced. Without laser cooling the velocity distribution is wide (*colored curve*). When the atomic beam is opposed by a laser beam and travels down a long solenoid that produces a uniform magnetic field, the velocity distribution is changed: some atoms near the center of the distribution are slowed and concentrated into a fairly narrow peak where all atoms have roughly the same velocity (*gray curve*). By tailoring the magnetic field so that it is strong at the point where the atoms first enter it and gradually tapers off in strength with increasing distance from the entry point, many more atoms are slowed to a much lower velocity and concentrated into a sharper velocity distribution (*black curve*). It is important to distinguish between deceleration, the reduction of velocity, and cooling, the reduction of velocity spread. The authors' method achieves both.

The sodium atoms in our experiments have two classes of orientations: one class in which the atoms are attracted to strong magnetic fields and one in which they are repelled by strong magnetic fields. In our process of laser cooling we optically pump all the atoms into the orientation repelled by strong magnetic fields. To trap the atoms we therefore constructed a pair of current-carrying coils arranged so that their magnetic fields oppose each other. There is zero magnetic field at the midpoint between them, from which the strength increases in any direction, and so the atoms are pushed toward the midpoint. This kind of trap was one of several early proposals made by Paul; similar traps have been proposed for the confinement of ultracold neutrons [see "Ultracold Neutrons," by R. Golub, W. Mampe, J. M. Pendlebury and P. Ageron; SCIENTIFIC AMERICAN, June, 1979].

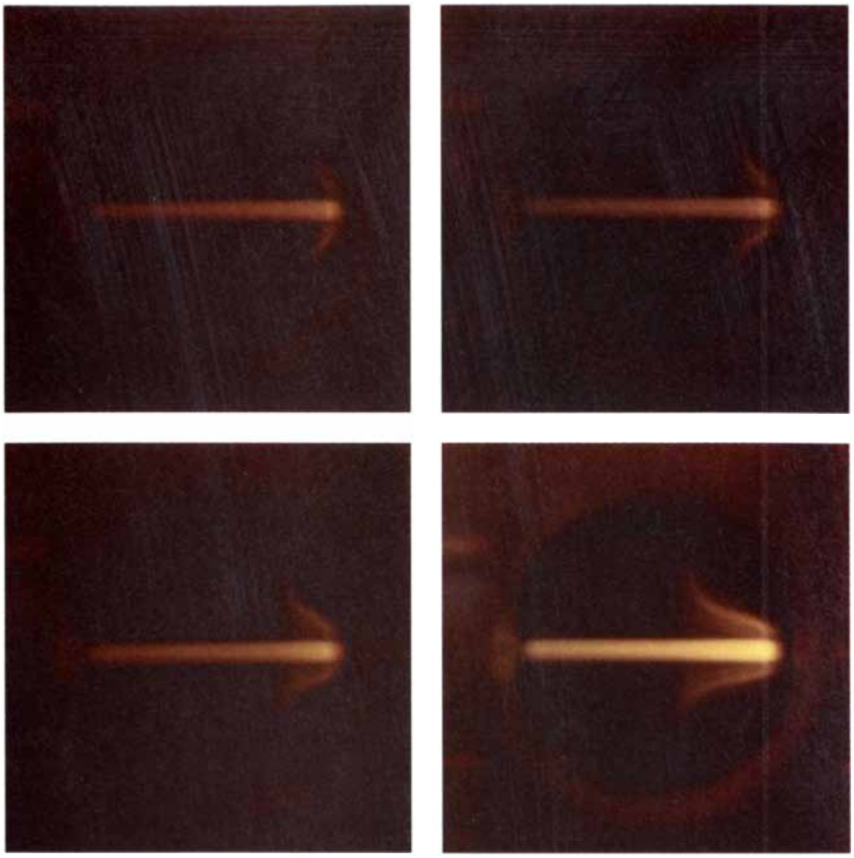
In our trapping experiments we decelerate atoms to low velocities by laser-cooling them. We then let the atoms drift into the space between the two current-carrying coils and bring the atoms to rest with a short pulse of light, a technique we developed in our laboratory with Prodan, Alan Migdall, Jean Dalibard and Ivan So. The residual motion of the atoms in the sample is so small—the atoms travel at speeds of only a few meters per second or so—that once the atoms have entered the region between the coils there is ample enough time to turn on the electric current that energizes the magnetic trap.

Our trap has proved successful in catching and confining some of the atoms in the sample, as experiments we have done with Thomas H. Bergeman of Stony Brook and the above collaborators have shown. The major loss of atoms from the trap is due to random collisions with background gas molecules. Since the magnetic force that holds the atoms in place is so very small, the trap is said to be "shallow." An atom held in the trap is a "sitting duck" if it is struck by a room-temperature molecule. Even though the apparatus is placed in a vacuum, there are still enough stray atoms moving around to cause destructive collisions and impart enough energy to eject atoms from the shallow trap.

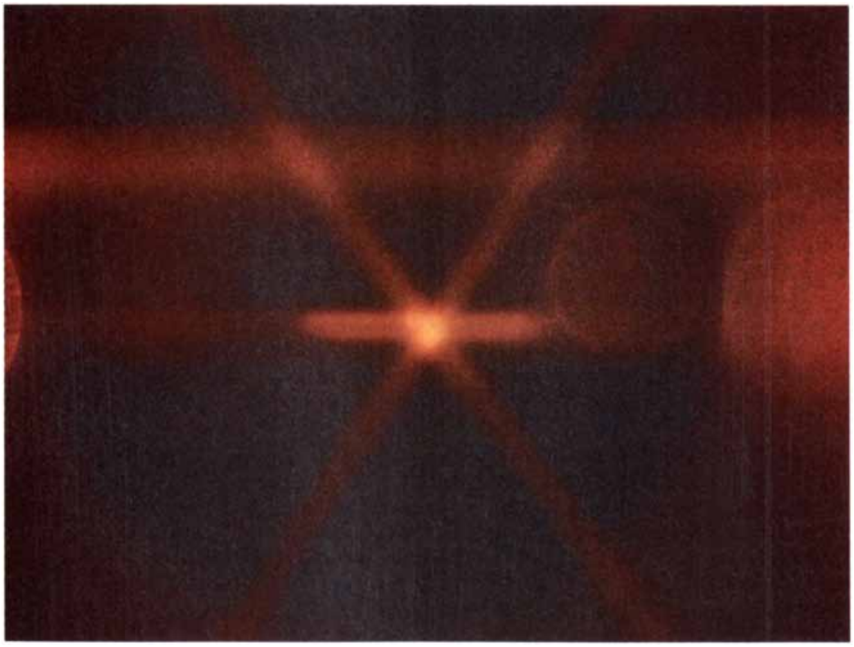
The maximum speed a sodium atom can have and still be held in our trap is 3.5 meters per second, which corresponds to an energy in temperature units of about 17 millikelvin. We have trapped tens of thousands of atoms with this energy and less for periods longer than one second in a volume of about 20 cubic centimeters, which is roughly the volume of a golf ball. The limitation on the trapping time is due entirely to collisions with any stray atoms left in the vacuum. In a perfect vacuum the ultimate limitation on trapping time would be the rate at which an atom makes a quantum transition from a state that is repelled by strong magnetic fields to a state that is repelled by weak magnetic fields. Calculations show that most atoms would remain trapped for many hours.

Another method of trapping neutral atoms relies entirely on laser beams and the forces they exert. In one version of such a trap the forces do not come from the simple transfer of momentum that occurs when an atom absorbs a photon and spontaneously emits another photon, as in the laser-cooling process itself. Rather, they come from a subtler and potentially stronger process. The laser beam, which consists in part of an oscillating electric field, induces dynamic changes in the atom that result in a force if the laser field is nonuniform (just as in the case of a magnetic moment in a nonuniform magnetic field). By convention such a force is called a dipole, or gradient, force.

The dipole force can be used to confine atoms, as Letokhov suggested in 1968. In 1978 Ashkin proposed a particularly simple and elegant form of



LASER-COOLED BEAM of sodium atoms is shown as it emerges from the solenoid in the authors' apparatus. The atomic beam travels from right to left; the laser beam moves from left to right. As the frequency of the laser is decreased, the position at which the sodium atoms stop moves to the left and more of the skirt comes into view (*left to right, top to bottom*). The beam is viewed through a circular port in the side of the apparatus.



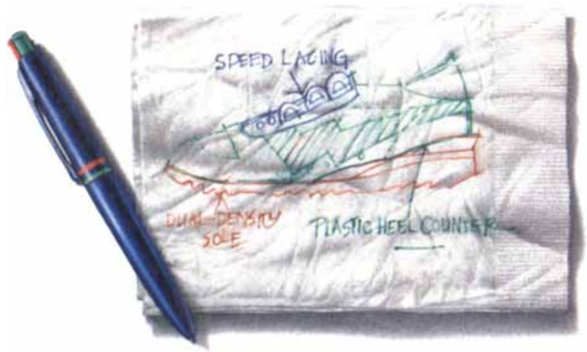
OPTICAL MOLASSES produced in the authors' laboratory by Phillip Gould and Paul Lett is seen as a bright spot at the intersection of six laser beams. The six laser beams strongly oppose and quickly damp any atomic motion in the intersection region, as if the atoms were in molasses. Laser-cooled sodium atoms enter the molasses from the left and get stuck. A cooling laser beam illuminates some of the atoms (*top horizontal streak*).

laser trap, which has just recently been demonstrated. In Ashkin's design a single laser beam is focused to a small spot. The focusing produces a laser field that is strongest at the center of the focus; the field decreases with increasing distance in all directions away from the focus. When the laser frequency is tuned below a frequency at which the atoms absorb strongly, the dipole force pulls the atoms into the strongest part of the field. Of course, the ordinary radiation pressure resulting from momentum transfer tends to push the atoms along the direction in which the laser beam travels, but the dipole force can overcome the unwanted effect if the laser beam is tightly focused, is intense enough and is tuned far enough away from the absorbing frequency of the atoms. Still, the depth of a laser trap is very small, and Ashkin's design had to wait, along with the magnetic trap, for the success of laser-cooling techniques before it could be implemented.

An additional complication of laser traps is that, in contrast to magnetic traps, the trapping field itself tends to heat the atoms so that they "boil" out of the trap. The solution to the problem is to continue to laser-cool the atoms while they are in the trap. The precise scheme for doing this, which involves switching rapidly between cooling and trapping by turning various laser beams on and off, was proposed by Dalibard, Serge Reynaud and Claude Cohen-Tannoudji of the École Normale Supérieure. All these techniques were recently combined, along with three-dimensional cooling in optical molasses, by Chu and his colleagues to make a tiny laser trap for sodium atoms in which a few hundred atoms are held in a volume of 10^{-7} cubic centimeter at a temperature below a millikelvin.

Even more recently a group of investigators in Cohen-Tannoudji's laboratory demonstrated that an atomic beam can be cooled by means of dipole forces. Their method shows great promise, because the strength of the dipole force allows the cooling to proceed much faster than it can with ordinary laser cooling.

Although the future of laser cooling and trapping of neutral atoms and ions is hard to predict, it is clear they are solidly established as major areas of research. Thermal motion, which has long bedeviled investigators, is in rapid retreat. Atomic beams and gases that have millikelvin temperatures are now easily generated; microkelvin temperatures and below may soon be possible. A new era in atomic measurement is at hand.



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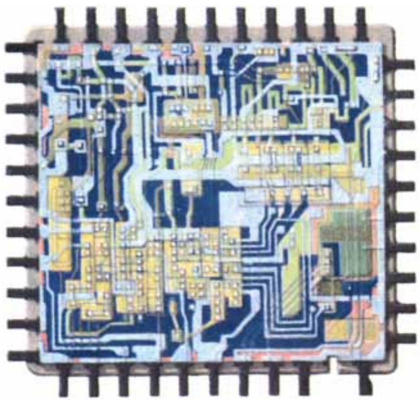

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