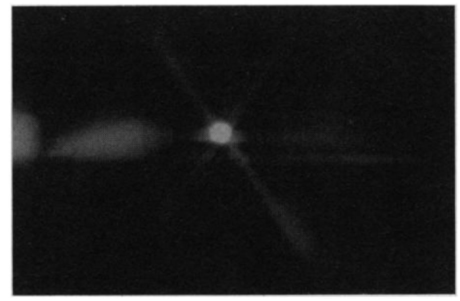
Laser-Cooled Atoms Hit Record Low Temperatures

Carefully tuned lasers now chill atoms to a few millionths of a degree, allowing precise measurements of atomic properties



Six laser beams meet, *creating a region of "optical molasses" that holds atoms of sodium gas.*

LIKE ENERGETIC CHILDREN racing about a schoolyard at recess, atoms bouncing around in a gas are hard to get a good, close look at. Both the children and the atoms move quickly, randomly, and with constant changes of direction. With children, however, one needs only ring the recess bell and march them back to their classroom seats to get them to slow down, if not stop moving completely. With atoms, it is a bit more complicated.

One way scientists have found to slow down atoms is to use the light pressure of a laser beam to push against the normal motion of the atoms, thus decreasing their momentum. Scientists have studied this laser-cooling method since the 1970s, and in the past few months the technique has boomed. Several groups recently have cooled atoms to record low temperatures and, in one case, researchers chilled an atomic gas to a temperature five times lower than had been thought possible. By slowing down atoms this much, scientists say they will be able to perform much better measurements on atoms—either single atoms or groups—and this in turn could lead to such practical benefits as more accurate atomic clocks.

Atoms in a gas move around almost randomly, changing directions after bouncing off other atoms or the walls of a container, or after absorbing or emitting photons of light, and this motion causes various problems for scientists studying the properties of atoms. In spectroscopic studies, for instance, the motions of the atoms affect the frequency of the light that they absorb and emit. (If the atom is moving toward the light, the atom perceives an absorbed photon as having a slightly higher frequency than it really does, and if the atom is moving away, the light seems to have a lower frequency. This so-called Doppler shift is the same phenomenon that causes a train whistle to seem higher pitched when the train is moving toward you and lower when it is moving away.) Cooler atoms make a difference when scientists study collisions of atoms. The warmer a gas is, the higher is the average velocity of its atoms and also the larger is the spread of velocities—the difference in speeds between the most energetic atoms and the least. A scientist studying collisions of atoms wants to know with reasonable accuracy what the energies of the atoms were before a collision, and cooling the gas will improve the accuracy because it decreases the spread of energies.

To combat these problems, researchers try to slow down atoms as much as possible and to hold them in one place long enough to get a good look at them. The average speed of the atoms in a gas is measured by the temperature of the gas, so the lower the temperature, the easier it is to study various properties of the atoms. Recently, researchers at the National Bureau of Standards (NBS) in Gaithersburg, Maryland, cooled a gas of sodium atoms to 43 μK (0.000043 degree above absolute zero), which was less than one-fifth of what theory predicted would be the lowest temperature possible—240 μK.

The technique the NBS team used to achieve this surprisingly low temperature is representative of many of the laser-cooling experiments now being done. It starts with a beam of sodium atoms that first are brought to relatively low speeds with a laser aimed directly against the beam. As individual photons in the laser light strike sodium atoms, each transfers a small amount of momentum to an atom. "It's like slowing down a bowling ball by throwing ping-pong balls at it," said team member Paul Lett.

Once the sodium atoms are moving slowly enough—about 20 meters per second—they are caught in what is known as "optical molasses." This is a region bathed in light from six lasers, each aimed directly at the center of the molasses. Whether an atom tries to move right or left, up or down, forward or back, a laser beam is pushing against it, slowing it down.

The key to the molasses is the way the lasers are tuned. They are adjusted to a frequency slightly lower than a resonance of the sodium atoms. (Atoms absorb and emit light only at certain frequencies, known as resonances.) In this way, when an atom starts to move toward a particular laser, the Doppler shift causes the atom to see the laser light as being at a slightly higher frequency. This brings the light into resonance with the moving sodium atom so that the atom absorbs more photons, and these photons slow down its movement. Any atom that tries to move away from the center of the region feels as if it were walking in molasses.

This experimental setup at NBS was not much different from one done at AT&T Bell Labs 3 years earlier for a similar experiment, but the NBS results were dramatically different. Standard theory predicts that the sodium atoms could be cooled no more than to about 240 μK, and this is precisely what the Bell Labs group found. Naturally, the Bell Labs group believed they had reached the cooling limit.

The NBS group repeated the Bell Labs experiment about a year ago and saw the same thing, Lett said. "But the more we studied the molasses, the more things didn't look right," he said. "A whole lot of things didn't agree with what the theory said." The break came when the team decided to look at cooling as a function of the laser detuning, or how far below the resonance the laser was tuned. Whereas theory predicted that maximum cooling would come when the frequency of the laser was about 5 megahertz below the resonance frequency, the NBS researchers found the cooling increased as they moved farther away from resonance. With the laser set at 20 megahertz below resonance, they found the sodium gas had cooled to 43 μK, one-fifth the predicted minimum.

Since the publication of those results, the NBS group has lowered its record temperature even more. Lett said that by being careful to get rid of the background magnetic field, the team cooled a sodium gas to "significantly less than 40 μK," but measurement uncertainties kept him from being more specific. The group is getting closer to the 3 μK photon recoil limit—a more fundamental limit on the temperature of the gas equal to the energy transferred when a stationary atom absorbs or emits a single photon.

In France, meanwhile, a group of researchers from the Ecole Normale Supérieure in Paris reports it has found a way to sidestep even the photon recoil limit, albeit in a limited way. The scientists took a beam of helium atoms and used two lasers facing each other across the beam to slow down the random motions of the atoms in the direction along the line between the lasers. The one-dimensional temperature of the beam dropped to 2 μK in the direction between the lasers, which is below the photon recoil limit of 4 μK for the helium gas. (The one-dimensional temperature can be defined in terms of the average velocity in that direction.)

In a third type of cooling experiment, a group at NBS in Boulder, Colorado, slowed down a single positively charged mercury atom to near absolute zero. The ion, which was held and cooled in an electromagnetic trap, was slowed down to the point that it was in its ground state 95% of the time. (This ground state is the quantum-mechanical configuration in which the ion has its minimum kinetic energy. An atom or ion in its ground state is as close to absolute zero as one can get.) David Wineland, a member of the NBS team, said the ion's temperature was about 47 μK, and it could be dropped even further by modifying the experimental setup to keep the ion in its ground state an even larger percentage of the time.

For scientists, the cooling of atoms and ions to such low temperatures means they will be able to observe these particles much more closely. For instance, they can measure an atomic spectrum to greater accuracy if the atom is nearly motionless, because this removes much of the Doppler shift's shifting and smearing of the spectrum. Researchers also expect to see interesting effects in the interactions between two slow-moving atoms.

Probably the most immediate and the most practical benefit will be in improving the accuracy of atomic clocks. Atomic clocks depend on the measurement of one type of atomic frequency or another, such as the resonance frequency of an atomic transition. The limit to the accuracy of an atomic clock is how accurately such a frequency can be measured, and because of the Doppler shift, the accuracy of the frequency measurement is limited by the motion of the atoms or ions. With laser cooling, Wineland said, researchers hope to improve the accuracy of the best atomic clocks from the current 2 parts in 10^{14} to 1 part in 10^{18}.

■ ROBERT POOL

ADDITIONAL READING

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Trapping with Optical Tweezers

Lasers can cut, burn, destroy. They cut metal in factories; they burn off cataracts in eye surgery; they have even been nominated to destroy intercontinental ballistic missiles as part of a space defense system.

But there is a gentler side to lasers. Like a tiny, delicate pair of tweezers, a laser can be used to grasp and manipulate objects too small to be seen with the naked eye. For years, scientists have used lasers to trap microscopic particles, molecules, and even single atoms so that they could be studied in detail. Now researchers are using laser traps to study living microorganisms. With the development of lasers that are delicate enough to hold single-cell organisms without harm and even grab onto interior parts of these creatures and move them around, scientists have a new tool for the study of tiny living organisms.

Although laser trapping of various types of atoms and particles has been going on for more than a decade, it has only been in the past 2 years that researchers have begun to use lasers to catch biological particles, such as viruses, bacteria, and single cells of plants and animals. Scientists at AT&T Bells Labs have developed what they call "optical tweezers" that use focused laser light to hold onto biological particles and even reach inside them to manipulate their internal structures.

The idea behind the optical tweezers is relatively simple, although at first it may seem somewhat opposed to common sense. A lens is used to focus a laser beam to a very small point, much like a much like a Boy Scout might use a magnifying glass to focus sunlight onto a piece of paper to start a fire. Surprisingly, when an object such as an amoeba is brought into the focus point of the laser light, the intense light pressure does not push the object out of the focus but instead keeps it trapped inside. The precise reason this works is somewhat complicated, but it has to do with the way the laser light refracts through transparent objects so that there is always more light pressure pushing an object toward the focus point than away from it.

Arthur Ashkin, leader of the AT&T group that developed optical trapping of biological particles, said the group first trapped viruses, such as the tobacco mosaic virus. Eventually, he said, they noticed that bacteria that had gotten into the sample would stay alive for a while inside the laser trap. However, just as with the Boy Scout's focused sunlight, the bright laser light could do some damage. "If the power got too high, the bacteria would just explode," Ashkin recalled. His group called it "optocution," and they looked for a way to hold onto bacteria and other biological objects without harming them.

The key turned out to be using an infrared laser instead of one that used visible light. With an infrared laser trap, the damage done to the organisms decreased by one or two orders of magnitude and Ashkin found he could keep bacteria alive in the trap for hours at a time. With a microscope aimed at the trap, he could watch as the bacteria multiplied until the trap held several generations.

Next Ashkin's group went to larger organisms such as yeast cells, which are much bigger than the optical trap itself. Because the focused point of laser light was smaller than the yeast cells, the cells could not be held inside the trap (as the bacteria were), but it still worked out. What happened was that the focused beam became trapped inside the cell for a reason very similar to why bacteria were trapped in the beam—once the focus approached the outside layer of the cell, the same refraction effect would take over, and the beam would catch onto the outside layer. The result was that once the beam was focused inside a cell, Ashkin could drag the cell around by moving the beam; the focus point would move freely through the inside of the cell, but it would not cross the edge. It would catch when it hit the edge and pull the cell with it, just like a pair of "optical tweezers." In video movies of this action, the cells look as if they are being pulled by a physical, tangible object instead of a beam of light.

The AT&T group went further and found they could reach into a biological object with the laser beam and grasp a substructure inside it. One set of photographs shows a tiny organelle inside a protozoan being dragged from one end of the creature to the other.

The ability to safely hold cells and single-cell organisms and even manipulate small organs inside them without cutting into the cells will open up a world of new analytical techniques for biologists, Ashkin predicted. He said he has already heard from a number of scientists interested in learning to use his optical tweezers. ■ **R.P.**