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Author(s): Robert Pool
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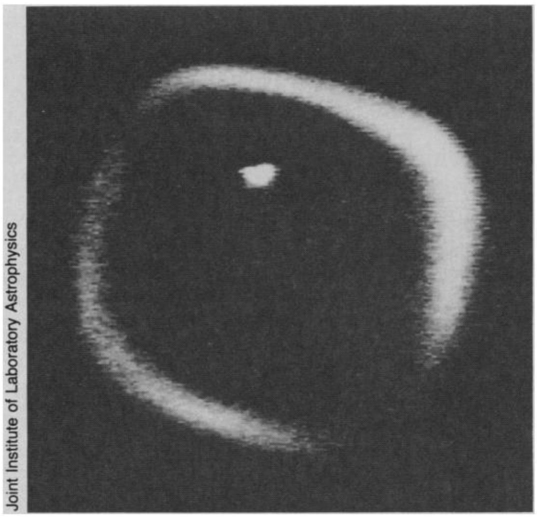
Research News

Making Atoms Jump Through Hoops

With lasers as their whips, a small band of "atom trainers" are teaching atoms a variety of new tricks; the payoff is a better understanding of atomic interactions

WHEN THAD WALKER AND DAVID SESKO looked into their laser trap early last year, they couldn't believe their eyes. "The first thing we did was to make sure it wasn't an optical illusion," Walker recalls. At the center of the trap, the cesium atoms—which normally formed a perfect sphere—had mysteriously aligned themselves into a ringed shape that looked like the planet Saturn. It took Walker and Sesko several months to figure out the cause: a slight misalignment in the lasers combined with a mutual repulsion between the atoms created by the intense laser light in the trap.


Joint Institute of Laboratory Astrophysics

Mysterious ring. *Cesium atoms dance in a laser trap. The ring is about 0.7 centimeters across.*

Walker and Sesko, who work under Carl Wieman at the Joint Institute for Laboratory Astrophysics (JILA) in Boulder, Colorado, are among a small but growing number of physicists who use lasers to control atoms for careful study. Laser traps hold atoms in a small space, usually a few millimeters across or less, and laser cooling techniques slow atoms enough that scientists can get a good close look at them (see box). In the past year, the field has exploded with one new advance after another, as researchers have learned to manipulate atoms in ways that no one had imagined even 5 years ago. Their repertoire now includes atom fountains, atom funnels, and even atom trampolines, as well as the ring-shaped dance seen at JILA.

The goal is more than simply making atoms jump through hoops, however. By controlling atoms' position and velocity with increasing precision, researchers can study atomic behavior that has never been seen—and sometimes never even predicted. One practical consequence will be the production of more accurate atomic clocks, but most workers in the field don't seem too concerned about practical applications right now. They're having too much fun.

The discovery of the ringed system was definitely fun, Walker remembers. It happened accidentally while the group was studying how cesium atoms behave in a laser trap as more and more atoms are added.

With up to 40,000 atoms in the trap, everything went as expected. The atoms collected into a sphere about 0.2 millimeter in diameter and behaved like an ideal gas—they interacted with each other only through collisions. But past 40,000, something strange happened. As more atoms were injected into the trap, the sphere started to expand, just as if the atoms were repelling each other by some long-range force. And when the number of atoms in the trap hit about 100 million, the sphere suddenly transformed into a small core with a large ring orbiting it at about 100 revolutions per second.

To explain that behavior, the researchers had to understand exactly what was happening in their laser trap. The experimental setup was similar to those used by other workers in the field. Cesium atoms from an atomic beam were slowed down by a carefully tuned laser directed against their motion and then caught in a combination magnetic-optical trap.

Both laser slowing and laser trapping work on the same principle: Photons striking an atom exert a small push on it, and enough photons together can move an atom around. Workers in the field compare it to moving a bowling ball around by throwing ping pong balls at it. The trick is that the lasers must be tuned to certain frequencies, called resonance frequencies, because the atoms absorb light only at those frequencies.

The reason the sphere of cesium atoms grew once it had more than 40,000 atoms was rather simple. Each time an atom absorbs a photon, it emits a second photon a short time later. Most of these emitted photons leave the trap, so that the collection of atoms is visible as a tiny glowing ball. But some of the emitted photons are absorbed by a second atom, pushing it away from the first. This "radiation trapping" creates a repulsive force between the atoms in the trap that becomes stronger as the density of atoms grows. "We knew radiation trapping had to be there," Walker recalls. "But we didn't know how much influence it would have." The surprise was that it was powerful enough to dilate the sphere of atoms so much.

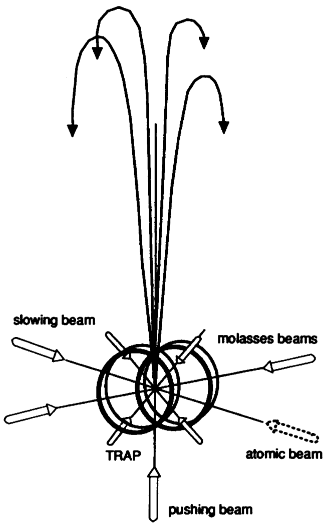
Explaining why the atoms in the trap should spontaneously form a ringed system was harder. The JILA team figured out that once the trap has about 100 million atoms in it, the repelling forces between the atoms nearly cancel out the forces holding them at the center of the trap, and the system becomes unstable. If the lasers of the trap are misaligned slightly in a particular way, it creates an off-center force that pushes many of the atoms into a ring circling the inner core. The discovery is unlikely to have any practical applications, but it is fascinating to physicists because it reveals a complicated, unexpected behavior that arises in a relatively simple system.

Meanwhile at Stanford University, Steven Chu and colleagues are using a combination of lasers and magnetic fields to put atoms through a variety of maneuvers. The most striking is an "atomic fountain," first produced last summer. In those experiments, the Stanford workers caught sodium atoms in a magnetic-optical trap, turned off the trap, and slowed them down—thereby cooling them—with a six-laser configuration called "optical molasses" (see box). After the atoms were chilled to 50 μK, the researchers shut off the molasses and fired laser pulses at the atoms from below. Like water in a fountain, the atoms shot up gently until the force of gravity pulled them back down.

Such an atomic fountain could play a role in making atomic clocks more accurate, Chu says. These clocks work by measuring the resonance frequency of a particular atom, such as cesium, and the precision of the measurement depends in part on the length of time over which it is taken. By pushing the atoms up in a fountain, the researchers had a full 0.25 second to study them outside the perturbing effects of electric or magnetic fields. The result was a measurement of the atoms' transition frequency to within 2 hertz, as compared to the 26-hertz precision of the present U.S. time standard.

This April, the Stanford group reported an "atom funnel" that produces a concentrated stream of atoms much as a normal funnel gives a concentrated stream of liquid. With a combination of lasers and magnets, they siphoned off some of the sodium atoms in an atomic beam and focused them into a narrow stream of atoms all moving at about the same velocity. The atoms in the funnel were slowed down to about 270 centimeters per second, compared to 2000 centimeters per second in the original beam. Atomic physicists can use such low-velocity, high-flux atomic beams for a variety of experiments, including precision spectroscopy and electric dipole moment measurements.

Recently Chu has "bounced atoms off a surface of light." To create the surface of light, a laser beam is bounced around inside a prism so that the light never leaks out. Although the light does not make it through the sides of the prism, quantum effects create an intense electromagnetic field running over the prism surface. An atom that comes very close to the prism can feel this field. This "surface of light" is not strong enough to stop atoms moving at normal velocities, but slow-moving atoms will bounce off it. Chu says he has dropped cooled atoms onto such a surface and watched them bounce up, fall back down, and bounce up again—an



Falling atoms. *A laser pushes the atoms up out of the trap, creating a "fountain."*

Laser Cooling Hits New Low

In the past few weeks, two research teams have cooled gases of cesium atoms down to a few millionths of a degree above absolute zero, or about one-tenth the previous record low of 30 μK. The work illustrates how quickly the field of laser cooling and trapping is moving: Just 2 years ago, it was generally accepted that such a sample could not be cooled to below 120 μK, and now at least one worker is predicting he can beat today's lowest temperature by a factor of a million.

That record is now held by Alain Aspect, Christophe Salomon, Jean Dalibard, and Claude Cohen-Tannoudji of the Ecole Normale Supérieure in Paris, who have cooled a sample of cesium atoms to a chilly 2.5 μK. Independently, Carl Wieman and co-workers at the Joint Institute for Laboratory Astrophysics (JILA) in Boulder, Colorado, have reached 5 μK. Both groups used a laser technique called "optical molasses" to slow down the movements of the cesium atoms. Since the temperature of a material is directly related to the average speed of the atoms in the material, reducing the atoms' velocities means cooling the sample.

The "molasses" is actually a region of intense laser light formed by aiming six lasers at a single spot. If an atom inside that region tries to move in any direction—up, down, right, left, forward, or back—it is opposed by the light from one of the lasers, which pushes against it and slows it down. The laser light has the same effect on the atom as a pool of molasses has on a trapped marble—no matter what direction the marble tries to roll, the molasses holds it back.

The lasers are tuned to a frequency slightly below the atom's resonance frequency, and when an atom moves toward a laser, the Doppler effect causes the light from that laser to appear at a slightly higher frequency to the atom. This upward shift in frequency brings the laser close to the resonance frequency of the atom, which makes the atom absorb more photons from that laser, slowing the atom back down.

Researchers at AT&T Bell Labs first developed this technique in 1985, cooling sodium atoms to 240 μK. At the time, they believed this was the best that could be done. Each time an atom in the molasses absorbs a photon of laser light, it emits a second photon rather quickly, giving a small random push to the atom. The motion thus created works against the molasses effect. Theorists calculated that this would limit the cooling of sodium atoms to 240 μK, and of cesium atoms to 120 μK.

In 1988, however, researchers at the National Institute of Standards and Technology in Gaithersburg, Maryland, announced that they had cooled a gas of sodium atoms to 43 μK (*Science*, 26 August 1988, p. 1041). It took several months for theorists to figure out how this could be. In late 1988, Steven Chu at Stanford University and, independently, Dalibard and Cohen-Tannoudji in Paris showed that the cooling could be explained by several subtle effects involving the polarization of the lasers and "optical pumping," where lasers force atoms into particular quantum states.

Following this theoretical lead, the groups in Paris and Colorado were both able to cool cesium atoms almost to the "recoil limit"—the velocity produced by the emission of a single photon. And the Colorado group took the process one step further. Until now, there has always been a trade-off between trapping and cooling. The atoms in laser traps cannot be cooled lower than about 300 μK, and atoms in optical molasses leak out of it quite quickly—within a fraction of a second. Wieman gets around this by first cooling the atoms to a few microkelvin in the molasses, then turning off the molasses and catching the atoms in a magnetic trap that does not heat them. "We can study them at our leisure," Wieman says.

One practical application of cooling atoms could be increased accuracy for atomic clocks. Such clocks are based on the frequency of light absorbed by cesium atoms. If the atoms are moving, the Doppler effect shifts the frequency of the absorbed light to various degrees, depending on the atoms' velocities. This limits the accuracy of the measurement. The colder the atoms, the less they move, and the more accurately the resonance frequency can be measured.

How cold can atoms go? "There is no limit," Chu says. He is now working toward creating a packet of atoms with almost identical velocities. For all practical purposes this is equivalent to cooling a sample to near absolute zero, because there is no real physical difference between a collection of atoms moving together at the same velocity and a collection of atoms all sitting still. His goal is to get a velocity spread of 1 picokelvin, or a trillionth of a degree. Now that's cold. ■ R.P.

atomic trampoline.

The ultimate goal of all these shenanigans is to better understand how atoms interact—with each other, with light, and with the rest of the world. One area in which researchers have already seen some new physics is in slow collisions.

At room temperature, atoms in a gas move at several hundred meters per second. When two atoms collide at these speeds, they bounce off one another like billiard balls. But near absolute zero, the atoms are moving at about 10 centimeters per second and collisions proceed much more slowly, which allows quantum effects to appear. For example, Wieman and colleagues at JILA have studied collisions between cesium atoms held in a laser trap at around 250 μK. At this temperature, a collision between two cesium atoms stretches over about 30 nanoseconds, which is approximately the same amount of time it takes a cesium atom to reemit a photon that it has absorbed.

"The collisions that we've observed are quite novel," says Walker. They are slow enough that if one of the atoms is in an excited state, it can emit a photon in the middle of bouncing off the other atom. These quantum effects not only modify the way two atoms collide but actually affect the probability of a collision occurring. Theorists Alan Gallagher of JILA and David Pritchard of the Massachusetts Institute of Technology have a rough model that is "probably close to correct," Walker says, but the fine points of the collisions are still not understood.

One reason more labs aren't doing laser trapping and cooling experiments is their traditional dependence on bulky and expensive lasers and atomic beams, but work at Wieman's lab seems likely to change that. Wieman says he has cooled atoms to much less than 1 mK with a system that costs about $1,000, as compared to about $250,000 for a standard setup.

Instead of using an atomic beam to supply the atoms, the researchers found they could use a small glass bulb that contains a dilute vapor of cesium atoms. And in place of the normal laboratory lasers, the Colorado lab's system uses two tiny and inexpensive diode lasers that are each split into three beams, with all six focused on a spot in the center of the bulb. As the atoms move around the bulb, they are caught in the focus of the laser trap and held there. Although the whole trap takes up only "half a desktop," it is powerful enough to hold tens of millions of cesium atoms at a time. It is cheap enough and simple enough to be used in an undergraduate physics laboratory, Wieman says, and it's way ahead of the state-of-the-art equipment of just 3½ years ago. It could introduce a whole new generation of researchers to the joys of making atoms jump through hoops. ■ Robert Pool

A Reliable Animal Model for AIDS

Much of what is known about how human immunodeficiency virus (HIV) causes AIDS has been inferred from studying its effects on cells growing in the laboratory. Researchers have had little alternative: HIV only infects humans and chimpanzees and it doesn't make chimpanzees sick, so there have been no good models to work with. Now, however, that is changing.

On page 1109 of this issue, Ronald C. Desrosier and his colleagues at the New England Regional Primate Center in Southborough, Massachusetts, report that they have identified and cloned a simian immunodeficiency virus (SIV) that will reliably cause AIDS-like symptoms—and ultimately death—in rhesus monkeys. SIV has already been shown to cause a simian form of AIDS, but the infectivity and pathogenicity of wild strains of the virus is variable. The significance of Desrosier's work is that it starts with a thoroughly characterized virus—not a wild virus grown in culture but a clone with a known sequence that consistently causes disease.

HIV and SIV are closely related, both genetically and biologically, and simian AIDS closely parallels the human disease. By using this new cloned virus, scientists can design experiments that will help reveal just how this retrovirus causes disease.

"It's some of the most exciting stuff that I've heard," enthuses Dani Bolognesi, an AIDS researcher from Duke University School of Madison. "With this clone and mutants of it he has a handle on resolving issues of pathogenesis."

And that's just for starters.

In studies conducted both at the New England Regional Primate Center and the California Regional Primate Center, Davis all 11 monkeys inoculated with the SIV clone became infected and half died within 1 year. Murray Gardner, an AIDS researcher at the University of California in Davis, says Desrosier's animal model is "the gold standard." "Using this model you can do the systematic, grunt science—the step by step things that have to be done to work out the best vaccine and the best treatment," says Gardner.

Desrosier has already launched on three separate lines of research. First, he is studying how the virus changes in its host over time and how those changes correlate with the progression of disease. "We have an experimental system derived from a single DNA molecule, whose sequence we know, and we've been able to precisely measure the rate at which the envelope gene mutates as a function of infection of the animal," says Desrosier. "This is really the first time that anyone has ever been able to quantitate the rate of genetic change in an infection of animals."

A second direction is to study the so-called nonessential genes in the SIV genome. Like HIV, SIV has several genes—including *rev*, *vip*, *vpr*, and *nef*—that are thought to regulate the virus's growth, but they are called nonessential because the virus will still grow in tissue culture even after they have been removed. Desrosier believes it may be a different story in vivo. "Some of [the nonessential genes] might play a role in getting the virus into certain secretions, like vaginal fluid or semen," he says. "Now we have the capability to look at each of these 'nonessential' genes and ask if they're essential for the pathogenic potential of the virus. If so, they would become targets for drug development."

Finally, Desrosier is studying how the virus's affinity for different types of cells changes during the course of an infection. For example, Desrosier's SIV clone does not grow in macrophages in the laboratory. But virus recovered from one monkey just before it died did grow in those cells. Intriguingly, this was the only monkey that exhibited granulomatous encephalitis, rash, and giant cell pneumonia. Could these particular symptoms be related to a change in the virus that makes it target macrophages?

Gardner points to one other crucial issue that is resolved by Desrosier's work. All by itself, the SIV clone causes disease in otherwise healthy animals. "This is what virologists and others want to have as the ultimate proof that a virus is the etiologic agent," says Gardner. "This is the sine qua non. This nails it down." And if SIV infection is all that is needed to cause simian AIDS, that's one more indication that HIV is all that is needed to cause human AIDS. ■ Joseph Palca