How to Get Intimate With Atoms

Tricks of applied optics such as optical molasses and laser trapping allow researchers to inspect and manipulate atoms with a freedom unimaginable a decade ago

Studying atoms can be more than a little trying. The main problem is that the little creatures won't hold still. Try confining them in atomic beams, and they shoot by the measuring equipment; bottle them up in containers, and they stick to the walls; subject them to ordinary electric and magnetic fields, and the atoms, being electrically neutral, blithely ignore them.

But thanks to developments in applied optics, physicists no longer have to put up with such unruly behavior. In the mid-1980s, they learned how to reach into the atomic realm with laser beams that all but stop the infinitesimal bumper cars in their tracks and suspend them in space for leisurely study. Since then, the prospect of controlling atoms has lured researchers of many stripes to the technique, known as laser cooling and trapping. "A little while ago there were only a few of us doing it, and now a few dozen groups have gotten into the game," says Carl Wieman of the University of Colorado, Boulder.

From being a curiosity, laser trapping has evolved into a mini-industry that is yielding a wealth of basic data on atomic and particle physics, such as how tiny variations in an atom's structure or environment affect its ability to absorb or emit photons. Some of these studies promise new insight into the details of an existing theory, quantum mechanics; others may help to take physics beyond the "standard model," the current theoretical description of particles and how they interact. The atom trappers are also exploring applications that should lead to clocks, gravitational field meters, and perhaps other equipment orders of magnitude more precise than current versions. And along the way, they are refining the trapping techniques still further, to the point where atoms can be held practically motionless for minutes at a time, and even confined in geometric arrays.

Laser cooling and trapping begins with cooling—and that means slowing the atoms down. At room temperature, they careen at more than 1000 kilometers per hour; down in the microKelvin regime—millionths of a degree above absolute zero, where today's laser cooling leaders consider that the action begins—atoms loll at about one centimeter per second. The main technique for putting the brakes on was developed in 1985 by Stanford University physicist Steven Chu (then at AT&T Bell Laboratories) and his colleagues. It involves aiming a pair of lasers

Advances in optics continue to add new tools to science's arsenal, as this issue of *Science* makes clear. To complement the perspectives, articles, and reports (see page 1381), this special News report looks at two developments in laser technology that are opening new areas of research: laser trapping of atoms and short-pulse lasers.

at each other (to consider just one dimension), and lowering the frequency of the laser light until the energy of the photons is just below that needed to kick the atom temporarily into an excited state.

A cloud of atoms is then set adrift between these two counter-propagating beams. Any atoms moving in the direction of one of the laser sources will "observe" the light from that laser to have been Doppler-shifted up in frequency, just as the horn on an approaching car sounds higher-pitched. The moving atoms will then start absorbing photons of this higher-frequency light, and like bowling balls being pelted with bbs, the atoms will gradually slow down. Two more pairs of lasers make the effect three-dimensional, so that regardless of which direction an atom moves, it will encounter an opposing force from the laser light in this so-called optical molasses.

Setting a trap

Largely through this trick and variations on it, experimenters have taken a variety of atoms, including sodium, cesium, and hydrogen, to within billionths of a degree of absolute zero. Sluggish as they are, however, the atoms can still wander out of range of the lasers within a second. To stay put, the cooled atoms must then be trapped.

The same laser beams used for cooling can be applied to trapping, provided the light is polarized—that is, made to corkscrew either clockwise or counterclockwise. When a magnetic field is imposed on the cloud of atoms hovering in the polarized beams, a phenomenon known as the Zeeman effect comes into play. The Zeeman effect alters an atom's interaction with polarized light; if the magnetic field's sign and strength vary around the trapping location in just the right way, an atom that starts to wander out of the trap will always interact with the laser beam that pushes it back toward the center of the trap. This technique can keep a cloud of atoms trapped for a few minutes before collisions knock most of them out of trapping range.

Once trapped, the atoms can be probed for clues to some very elusive fundamental physics. Wieman's self-proclaimed ambition, for example, is to measure an effect called parity violation. Particle interactions that violate parity behave differently in a mirror-image version of our world, and the effect should be observable as a slight increase in the rate at which a laser beam of a given intensity bumps atoms into certain excited states when a surrounding electric field is reversed. The increase is 100 billion times weaker than the excitational effect of the beam itself, but Wieman believes the lazy cesium atoms he traps are quiet enough to permit the ultrasensitive measurement that would reveal the change. If the magnitude of the effect differs from that predicted by the standard model of particle physics, it could help confirm theorists' belief that the standard model is only an approximation to some more fundamental theory.

And Wieman believes there are hundreds of other measurements of atoms and their constituent particles that may only be practical on cooled and trapped atoms. For example, according to quantum mechanics, particles behave to some extent as waves, and physicists want to get a better picture of atoms' wavelike behavior. Many aspects of such behavior are largely hidden when atoms are shooting around at room temperature, but they start to dominate the picture near absolute zero (see sidebar). The rate at which atoms collide, their ability to jump into higher energy states, their tendency to release or pick up electrons—all these and other properties deviate more and more from classical predictions as the atoms become stiller.

Relatively rare isotopes, created in accelerators, provide some of the best opportunities for testing quantum mechanical predictions, because the slight difference in nuclear structure between isotopes can show up as subtle changes in their excitation rates. Laser cooling, besides aiding the measurements themselves, can also help investigators collect a sample pure enough to study during an isotope's brief half-life, which may last only minutes or hours. The solution developed by Wieman and graduate student Michelle Stephens: boil the isotope atoms off the surface of the metal targets in which they are embedded and capture them in a laser cooling and trapping apparatus that can be set up at the accelerator site. Since the lasers can be tuned to the energy levels of the isotopes, only they and not contaminant atoms are cooled and trapped; the contaminants can then be pumped out, leaving a clean sample. "A lot of accelerator labs have been calling me," notes Wieman. "They see this as a great new way to make use of accelerators."

While Wieman and his colleagues apply laser trapping to understanding the physics of the atom, laser cooling pioneer Steven Chu and his colleagues have been trying to put the cooled atoms to work—in better time standards, for example. Right now, the world standard is set by passing a beam of cesium atoms through a microwave field, then tuning the microwaves until they excite the maximum number of atoms. The time it takes the tuned field to oscillate 9190 times defines an official, standard second. And so far, that interval has been measured precisely enough to set a time standard that varies by no more than a second every 3 million years.

Some scientists want even more accuracy and precision to test such subtle phenomena as the deviations in planetary orbits predicted by general relativity. The limiting factor is the time the atoms spend in the microwave field; the longer the time, the better the opportunity to fine-tune the microwave frequency so that it exactly matches the cesium atoms' energy jumps. "When an atom zips through a field in a thousandth of a second, your measurements can only be so precise," says Chu.

Measurements such as this one can't be made while the atoms are held in the trap, because the trapping lasers and magnetic fields can interfere with the measuring beams and fields. So to get a little more quality time with his atoms, Chu developed a technique known as the atomic fountain, in which cesium atoms are cooled, trapped, and then kicked upward out the top of the trap by shifting the frequencies of the beams so that a stationary atom will interact with, and be pushed by, only the upward-pointing beam. The atoms soar about a foot into a waiting microwave field before being pulled back down by gravity. That little parabolic cruise gives them an entire second in the field, 1000 times longer than in current atomic clocks, raising the possibility of a measurement 1000 times more accurate.

Atoms in free fall

More recently, Chu and graduate student Mark Kasevich have turned the atomic fountain into a device that can detect minute variations in the rate at which the fountaining atoms decelerate under gravity, making it an exceedingly sensitive gauge of gravitational fields. To track these variations, Chu and Kasevich's setup hits the climbing atoms with a series of short laser pulses at a mixture of frequencies. Doppler shifts due to the atoms' velocity determine which pulse can knock an atom into an excited state. By noting which frequencies excite the most atoms, investigators can clock the speed of the atoms, and thus learn how fast they are decelerating under gravity.

Chu's gravimeter is already capable of detecting the tiny weakening of gravity that results when the device is raised a mere 3 centimeters farther from the surface of the earth. That's already better than the best existing devices, and with further refinement, the laser gravimeter should exceed them by a factor of 1 million. Chu is also talking to oil companies about a rugged, portable version that could replace the cumbersome and less accurate mechanical devices used to detect the gravitational anomalies that can indicate oil deposits. "That's 10 years in the future and will take serious money," he says. "But then again, the oil companies *have* serious money."

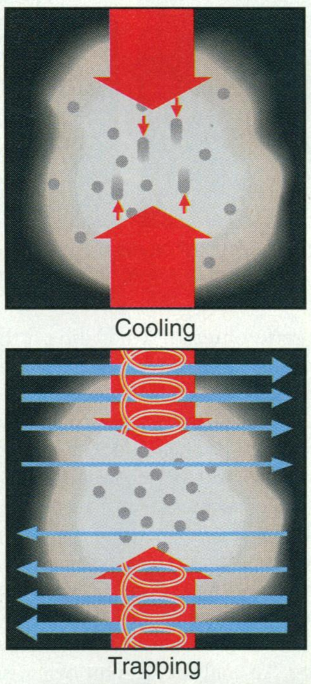
While Chu and his colleagues are measuring gravity, Claude Cohen-Tannoudji and his associates at the Ecole Normale Supérieure in Paris are trying to get rid of it, so that cooled atoms will stay put when the trapping lasers are turned off—opening the way, for example, to time-keeping measurements of unprecedented accuracy. As a first step, Christophe Salomon and others in Cohen-Tannoudji's lab have constructed a cooling and trapping setup designed to be mounted on the floor of an airplane. By climbing, arcing over, and diving along a parabolic path, the plane can briefly simulate close to zero gravity. In a series of 90 flights, about 10% of Salomon's atoms hung around for at least 0.2 seconds after the lasers were turned off, far longer than they do under normal gravity. In true zero gravity, the atoms should loiter for perhaps 25 times longer still, a possibility the workers now aim to test with a setup adapted to fly in a satellite. Asks Cohen-Tannoudji, "Can you imagine having a full 5 seconds to measure these atoms?"

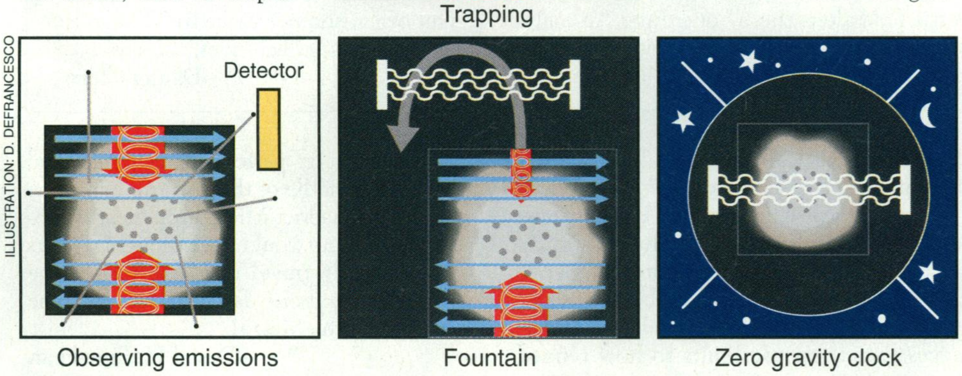
The Paris group, including Alain Aspect, is pushing the limits of trapping in another direction as well, by enlisting a new technique known as "dark states" that gets atoms even colder than optical molasses can. In optical molasses, even a stationary atom absorbs and emits an occasional photon, imparting to it a minimum velocity, because the laser is tuned to a frequency very close to one that stationary atoms can absorb. In dark states, in contrast, a near-stationary atom never absorbs or emits any photons because the laser light is tuned to a frequency with which the atom simply can't interact.

A moving atom can still absorb the laser photons, but not merely because of a Doppler shift. Instead the scheme takes advantage of a subtle quantum-mechanical effect: The momentum of the moving atom makes a second state available to it. This new state interacts with laser light—until, by luck, the bombardment of photons knocks the atom into a near-zero velocity. The atom will then be locked into a "dark" state that no longer interacts with the light. Eventually, many atoms become "velocity-trapped" in this fashion.

Cohen-Tannoudji's group recently employed the technique to chill helium atoms to 200 nanoKelvin in one dimension—that is, the atoms' motion was only slowed along that one dimension—and he says it will be a simple matter to extend the results to three dimensions. He notes that at these temperatures the atoms' behavior becomes so wavelike that it could provide a rare example of how, for example, collisional rates differ at quantum-mechanical extremes.

Besides refining simple cooling, Cohen-





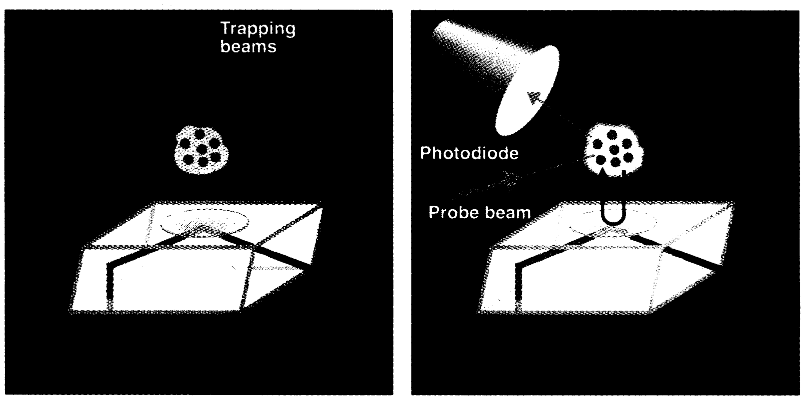
Taking liberties with atoms. Once cooled and trapped, atoms can be watched for photon emissions *(left)*, kicked out of the trap so their frequency response can be studied away from light and magnetic fields *(center)*, or suspended in zero gravity for even more precise measurements *(right)*.

Playing Ball With Laser-Cooled Atoms

Once you have tamed an atom by cooling and trapping it with lasers (see main text), you can make it do all kinds of tricks. You can make it resonate with a beam of microwaves to set an accurate frequency standard for time, or force it to rise and fall in an atomic fountain. And when trapping is combined with an ingenious atomic mirror, a group in Claude Cohen-Tannoudji's laboratory at the Ecole Normale Supérieure in Paris has shown, you can even bounce an atom over and over again like a minute rubber ball.

For now, says Jean Dalibard, the leader of the Paris team, the group is just practicing the trick. But once they have polished it, they hope to exploit the fact that when atoms move slowly enough—and the bouncing atoms are, by the standards of most atomic physics, glacially slow—their quantum-mechanical wave nature emerges. The bouncing atoms should resemble reflected light, and, like reflected light, they should interfere with themselves. And just as devices based on optical interference can serve as fine measuring tools, an interferometer based on atoms could serve as the basis for an exquisitely sensitive gauge of acceleration or gravity.

The kind of optical device, known as a Fabry-Perot interferometer, that Dalibard's group hopes to mimic requires a pair of mirrors, which create an optical "cavity" in which light is reflected back and forth. If the mirrors are separated by an exact multiple of half the wavelength of the light, the light overlaps with itself to create an apparently stationary interference pattern, or standing wave, that is extremely sensitive to anything that affects the propagation of the light. To build the atomic analogue of such a device, the Ecole Normale group realized, they would only have to reflect the atoms at one end; providing the device was vertical, gravity would take care of the other, as the atoms rose and fell.



Caught on the rebound. A cloud of atoms, released from a laser trap *(left)*, bounces off an atomic mirror and is detected by probe laser *(right)*.

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The starting point is a laser trap that holds about 10^7 chilled cesium atoms. To bounce the atoms, the researchers turn off the trapping lasers and let the atoms fall the 3 millimeters onto a concave depression cut in the top of a block of glass. Since atoms falling onto an ordinary glass mirror would simply stick to it, the researchers had to enlist a technique for reflecting atoms with light, first suggested by other researchers in the early 1980s.

Another laser beam passes through a channel in the block and is reflected off the inside surface of the curved mirror. This light beam creates an alternating electric field outside the glass, just above the surface of the mirror, known as an evanescent wave. The laser beam, and hence the evanescent wave, is tuned to a frequency to which cesium atoms are particularly sensitive. As an atom falls into the evanescent wave, the electric field alters the spacing of the atom's quantum-mechanical energy levels, raising its potential energy. Like a ball rolling uphill, the falling atom experiences a force that pushes it away from the steadily increasing field. If the force is strong enough, the atom never touches the glass but bounces out of the field. Eventually gravity takes over, the atom drops back into the field, and then bounces out once again.

To detect the bouncing atoms, the researchers shine a probe laser beam above the mirror. This beam is tuned to a frequency at which the atoms fluoresce. The stronger the fluorescence, presumably, the more atoms have bounced up from the mirror. Because the probe beam knocks all the atoms off course, the researchers have to repeat the experiment, probing for cesium atoms at different times. The result: After the atoms were dropped, the area above the mirror was first empty, then full of atoms, then empty again, at intervals of 50 milliseconds—the time for one bounce. As the group reported in the 8 November *Physical Review Letters*, they have managed to sustain up to 10 bounces so far.

These bouncing atoms are not quite ready to serve as a Fabry-Perot interferometer, says Dalibard. Even though the atoms are cooled close to absolute zero before being dropped, they still have some residual velocity. An atomic interferometer needs all the atoms at the same velocity so that their wavelengths are identical and in step. That will take more work, Dalibard says. In the meantime he and his colleagues are refining their technique: "Thirty to 40 bounces is not hard on paper," he says.

Further in the future there is an even more tantalizing possibility. A resonating optical cavity is the basis of a laser, which produces coherent light. An atomic cavity could, in theory, produce a coherent beam of atoms, which could probe material surfaces. But a few details still need to be worked out, Dalibard concedes. For one thing, "atom laser" is a bit of a misnomer, since the "l" stands for light. "We're still looking for the right acronym," he says.

–Daniel Clery

Tannoudji's group, including Gilbert Grynberg, has been arranging multiple "microtraps" in a three-dimensional array, which may eventually allow them to study how atoms interact over long distances. They build the array by arranging four laser beams in a pyramid-like configuration to interfere with one another, creating a three-dimensional array of regions in which the electric field is alternately strengthened and weakened. This effect tends to trap atoms in what Cohen-Tannoudji calls an optical lattice. "By varying the size of the lattice," says Cohen-Tannoudji, "we can hope to observe how effects [such as quantum-mechanical interactions between neighboring atoms] change as a function of distance."

But even Cohen-Tannoudji acknowledges that there are limits to how refined laser cooling and trapping can get. Cohen-Tannoudji's ultra-chilled atoms, for instance, are so easily disturbed that the group has had to start performing experimental runs in the middle of the night to avoid the stray electromagnetic fields from nearby subway trains. Who would have thought objects that ordinarily travel nearly as fast as the Concorde could one day be so still as to be disturbed by the Metro?

–David H. Freedman

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