SURFboard

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Light Beams Trap Heavy Atoms

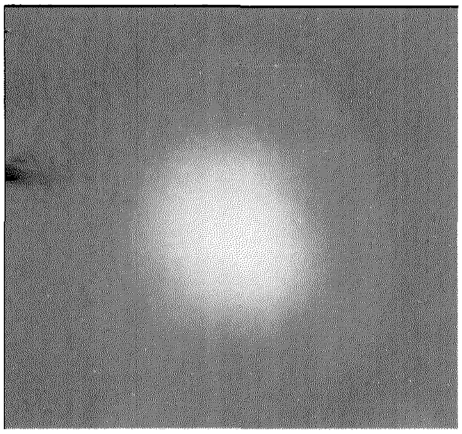
Just as Ping-Pong balls can hover in a jet of compressed air, atoms can float in a beam of light. And if keeping the balls in midair is tricky, the atomic equivalent is more so. It takes six laser beams, pressing in from above and below, left and right, and fore and aft, to hold the atoms in place.

Many laser-based atomic traps have been built over the last four or five years—elaborate, expensive contraptions that require a small army of graduate students and postdocs to run them, because of the ancillary apparatus needed to coax the atoms into the one-cubic-millimeter region where the lasers intersect. Atoms in a vapor at room temperature rip along at average velocities of hundreds of meters per second. Short of slamming the atoms into a brick wall (impractical), there's really no way to bring them to a dead halt within the span of a few millimeters. Instead, the atoms must be slowed—"cooled"—over a distance of a meter or so by head-on collisions with another laser beam to eventually yield "molasses"—a cloud of atoms stuck in a viscous sea of photons. These atoms are traveling at a leisurely half-meter per second, slow enough to catch. This speed is equivalent to a temperature of a few hundred microkelvin, or millionths of a degree above absolute zero.

But the "hot" room-temperature vapor really doesn't have to be elaborately cooled to yield a low-temperature cloud of atoms. The laws of statistics permit some atoms in the vapor to be much cooler than average to begin with. Trapping the few already-cold atoms cuts the tail off the distribution curve, as it were. Allowing the remaining atoms to rerandomize their motions regenerates the curve's tail, which can be cut off again ad infinitum, quickly filling the trap with cold atoms. A handful of traps have recently been built using this scheme, developed by Carl Weiman of the University of Colorado, and others.

And now Professor of Physics H. Jeff Kimble's group has got one, built this past summer by SURF (Summer Undergraduate Research Fellowship) student Robert Lee, a junior in applied physics, grad student Guangqing Chen, and postdoc José Tabosa. Kimble, who spent July lecturing at a summer session on quantum optics at Les Houches, France, offered what guidance he could via transatlantic telephone as Lee, Chen, and Tabosa built the vacuum system—"They did a superb job, basically unassisted," says Kimble. Cesium, their atomic quarry, burns spontaneously in air and is thus shipped in glass ampules filled with argon. The quartz-glass sample cell had to be mated to an intact ampule, which then had to be broken open from within the vacuum system without cracking the rest of the glassware—a problem eventually solved by using a small magnet, sealed into the system, as a drop hammer. The resulting vacuum system achieves a base pressure of less than 10^{-9} Torr, or one-trillionth of atmospheric pressure.

The trap uses a titanium-sapphire laser whose near-infrared beam passes through a maze of mirrors, beam splitters, and other optical components mounted on stalks so closely spaced that the entire setup resembles an unkempt asparagus patch growing on a four-by-ten-foot optical table. As the laser beam wends its way along, it is subdivided sixfold and its components refocused head-to-head to create the trap. The laser is tuned to a frequency slightly below one that cesium absorbs, so that an atom moving toward the beam will see the frequency shifted up, by the Doppler effect, to the absorbed one. Successively absorbed photons transfer their momentum to the atom, canceling out its forward motion, cooling it, and confining it within the trap. (Cesium,



A cloud of a million cesium atoms, formed into a one-millimeter-diameter sphere by the pressure of laser light.

The tiny ball of trapped atoms takes a visible hit, recoiling along the direction of the probe beam like a prizefighter who has just taken one on the chin.

despite its drawbacks as a chemical, has a comparatively simple absorption spectrum that makes it easy to trap.) Coils of wire above and below the trap carry current in opposite directions to create a strong "spherical quadrupole" magnetic field, whose influence on the cesium atoms' electrons is akin to the role of gravity in binding the planets in their orbits. That is, the magnetic field and the photons in concert create a "potential well" that holds the cold atoms.

The trap has been up and running since August 18. It holds about a million atoms in its current configuration. Any given atom stays in the trap for about a second before slithering out, but another atom immediately takes its place, making the trap stable for as long as the laser is on. At about 300 microkelvin, the atoms are so cold that the mechanical effect of absorbing or emitting photons is obvious. When atoms absorb photons, from a second (probe) laser for example, the tiny ball of trapped atoms takes a visible hit, recoiling along the direction of the probe beam like a prizefighter who has just taken one on the chin.

Kimble's group is pursuing nonlinear spectroscopic studies of the trapped atoms. Spectroscopy measures the interaction between atoms and photons. The interaction is generally linear—varying in proportion to the number of photons bombarding the atoms. But under certain circumstances—when the atoms are trapped in strong electromagnetic fields, for instance—the interaction is no longer linear, and the complex way that the interaction varies provides information about the status of the atoms and their coupling to the external field. "It's similar to the difference between observing a free-swinging pendulum and a system of two pendulums connected by a spring," says Kimble. Once the trap was running, Lee spent the second half of the summer firing a very weak (less than one microwatt) probe laser into the trapped atoms and observing their absorption spectrum. (If the beam is any stronger, it just drills a tunnel through the cloud of atoms.) He has already discovered one odd peak not visible in usual linear spectroscopy, and he, Chen, and Tabosa are trying to interpret it theoretically.

The trap has many potential uses beyond spectroscopy. Kimble and Associate Professor of Astrophysics Kenneth Libbrecht (a recent convert to optical physics) plan to build an atomic-beam source based on the trap. Once the atoms have been cooled, they can be collectively laser-accelerated to higher velocities and still remain "cold"—that is, they will have a small velocity dispersion even though they're moving in bulk at a large velocity. This beam of cold atoms will be used for experiments in "cavity quantum electrodynamics," which investigates the fundamental coupling of atoms in an optical resonator—from the atomic point of view, not unlike being trapped in a funhouse's hall of mirrors—to the electromagnetic field.

Stranger uses are also possible. Matter can behave as a wave under some conditions, just as light sometimes acts like a wave and sometimes like a particle. An atom's deBroglie wavelength is inversely proportional to its momentum. At normal temperatures, an atom's wavelength is infinitesimal compared to its diameter, but an atom cooled to a few microkelvin would have a wavelength of about one millionth of a meter—large enough to give the atom a wavelike character that can be diffracted by millimeter-scale obstacles. This leads to the possibility of atomic interferometry. A single atom, traveling as a wave, could be split into two waves by a slit. The waves could travel independently for quite a distance before being recombined to make an interference pattern. In effect, the atom "splits" and follows both spatially separated paths at once. Although this experiment won't help a harried mother who needs to be in two places at once, it will allow physicists access to an entirely new range of phenomena. □—*DS*