

Laser beam focus forms optical trap for neutral atoms

The first color photographs ever to grace the pages of *Physical Review Letters* show us the fluorescent glow from some 500 sodium atoms caught in the first successfully demonstrated optical trap for neutral atoms. The 21 July Letter by Steven Chu, John Bjorkholm, Arthur Ashkin and Alex Cable at Bell Labs, reports¹ that this tiny "optical dipole" trap, formed at the focus of a single laser beam, was able to hold onto an ultracold, high-density accumulation of atoms for several seconds and manipulate them in space. In recent days the group has been able to hold a much larger collection of sodium atoms for a fraction of a minute with a newer optical-trap design.

Last year (PHYSICS TODAY, June 1985, page 17) we told of the first successful neutral-atom trap of any kind—a magnetic trap developed by William Phillips, Harold Metcalf, Alan Migdal and their colleagues at the National Bureau of Standards. The Bell Labs optical atom trap, a lineal descendant of the laser traps in which Ashkin was able to hold tiny glass spheres in 1970, is much smaller—microns rather than centimeters—but it reaches a much lower temperature (300 microkelvin) and far higher density (more than 10^{11} atoms per cm^3) than anything achieved to date with a magnetic trap.

Trapping charged particles—ions, electrons, and very recently even *antiprotons* (see story on page 19) in the electrostatic quadrupole field of a Penning trap is relatively easy. Last year Gerald Gabrielse and his University of Washington colleagues kept a lone electron in suspended bondage for more than ten months (PHYSICS TODAY, May 1985, page 17). But with neutral atoms, lacking the simple Lorentz force acting on a net charge, one has to grasp for a much weaker, second-order handle. The NBS magnetic trap, basically a pair of current coils, avails itself of the atom's magnetic moment. The Bell Labs optical-dipole trap makes use of the electric-dipole force exerted by the intensity gradient of a focused laser beam on the oscillating electric dipole induced in the atom by the same laser field.

Because these trapping potential wells for neutral atoms are extremely shallow—the Bell Labs trap is only 5 millikelvin deep, corresponding to a fraction of a micro-electron-volt—one must first bring almost to a halt the atomic beam that will supply the occupants of the trap. This is accomplished by the radiation pressure from a counterpropagating laser beam, tuned below some prominent absorption resonance of the atoms and aimed directly at the beam. Beam atoms of the correct velocity, perceiving the oncoming photons Doppler blueshifted into resonance, absorb them and thus lose some of their forward momentum. Subsequent reemission being random in direction, the principal net result is a progressive slowing of the beam.

The chief problem here is to maintain the proper relation between the laser wavelength and the beam velocity as the atoms slow down. Phillips and his NBS colleagues do this by slowing the beam with a tapered solenoid, producing a spatially varying Zeeman level shift that just keeps pace with the slowing beam. The Bell Labs group avail themselves of an alternative trick,² perfected by John Hall and coworkers at NBS, Boulder, Colorado. Hall's "chirping" technique sweeps the laser light to higher frequencies in synchrony with the decreasing blueshift seen by the slowing beam.

Optical molasses. When the sodium beam comes to a halt in the Bell Labs setup, the atoms find themselves, first of all, cooled and detained in a "molasses trap" of the kind the Bell Labs group successfully demonstrated³ last year. The optical-molasses trap, formed by the intersection of six unfocused laser beams coming from six different directions, is not really an atomic trap in the full sense; it does not produce a restoring force that could keep the atoms localized indefinitely. Having had their temperature rapidly reduced by a factor of two hundred, the atoms would diffuse away by random walk in about half a second. But this half-second delay is long enough to fill the real atomic trap—the tiny, focused optical-dipole trap lurking at the heart

of the much larger molasses trap, which extends over centimeters.

The idea of the molasses trap, which goes back to a 1975 proposal by Theodor Hänsch and Arthur Schawlow at Stanford, is closely related to that of the initial laser whose radiation pressure brings the incoming atomic beam to rest. The six intersecting laser beams are tuned just a half line width below the prominent D_2 "sodium-yellow" line. Instead of being slowed down in just one direction, with six beams an atom moving thermally in any direction is likely to encounter a photon with just the right Doppler shift for absorption. Thus the stopped beam milling about at 50 millikelvin is rapidly cooled to a few hundred microkelvin. The swarm of photons from all directions, in effect, acts as a sticky molasses, subjecting the atoms to repeated encounters that reduce them to a low-temperature random walk, very much like Brownian motion. The record 240 microkelvin reached by the Bell Labs group a year ago is close to the quantum-limit temperature dictated by the natural width of the sodium D line.

Optical dipole trapping. In 1970, while he was studying the ability of radiation pressure from focused laser beams to push micron-size glass (and other dielectric) spheres around in liquids, Ashkin noticed that there was another force at work when a particle was off axis, tending to pull it into the most intense region of the laser light. Whereas the ordinary radiation pressure comes from the symmetric scattering and absorption of the beam, this second force, Ashkin concluded, is due to the transverse momentum transferred from light asymmetrically refracted through the glass sphere acting as a lens.

Alternatively, one can talk in terms of the dipole force of the gradient of the nonuniform laser intensity acting on the oscillating electric polarization induced in the dielectric material by the light. Thus one refers to this second force, as distinguished from the ordinary radiation pressure, as the optical-dipole force, pushing the particle toward the region of highest light intensi-

ty. If the laser light is focused to something like a point, one has the beginnings of a trap for small, transparent dielectric particles.

Soon thereafter, Ashkin pointed out that one might be able to do much the same thing with neutral atoms as well as glass beads. Vladilen Letokhov, at the Institute of Spectroscopy in Moscow, had made a similar suggestion in 1968. In the case of glass, visible wavelengths are always well below the absorptive resonances one finds in the ultraviolet. That's why glass is transparent. More generally, however, the dipole force changes sign as the laser frequency goes through an absorptive resonance. Below resonance, the oscillating laser field and the oscillating electric dipole it induces in the atom are in phase, so that one gets a "restoring" dipole force, pushing the atom in the direction of the light-intensity gradient, toward the point of highest intensity; the atom acts as a weak positive lens. Above resonance the phase difference goes to 180° , reversing the sign of the atom's polarizability, so that one gets an expulsive force, pushing the atom away from the light.

One reaches the same conclusion by thinking of the optical dipole force as the consequence of an ac Stark effect. If the laser frequency is below resonance, it Stark shifts the ground level to lower energy, and the excited level to higher energy. Thus if one tunes the laser far enough below resonance, so that most atoms are in the ground state, the atoms will seek to minimize their energy by going to the region of highest light intensity.

One of the first specific designs for an optical-dipole atom trap, proposed by Ashkin in 1978, involved two counter-propagating laser beams focused almost at a common point. This two-beam design was intended to balance the unwanted radiation pressure produced by a single beam. Ashkin soon realized, however, that this two-beam configuration would be particularly susceptible to "dipole heating," caused by quantum fluctuations in the dipole force. If you put atoms in such a trap 5 mK deep—even at zero temperature—they would be boiled out by dipole heating in much less than a millisecond. In their classic 1980 analysis of dipole heating, Ashkin and James Gordon concluded that a single-laser-beam dipole trap—an alternative design Ashkin had put forward in 1978—would suffer much less from this malady. Ashkin had pointed out that the dipole trapping force could overcome the unbalanced radiation pressure of a single laser beam, if the beam were focused strongly enough and tuned sufficiently far below resonance.

Why then did it take until 1986 before the Bell Labs group finally



About 500 optically trapped sodium atoms produce the tiny yellow spot barely visible near the top of the fluorescent orange cloud at the stopped end (right) of a beam of neutral sodium atoms at Bell Labs. The cloud is a much larger collection of sodium atoms milling around in the "optical molasses" created by the intersection of six laser beams. The tiny optical trap lurking in the midst of this molasses is formed by the sharp focus of a seventh laser beam, whose optical-dipole gradient force holds the trapped atoms in place for several seconds. The optical molasses has cooled the stopped atomic beam to 300 μ K. The optical-dipole confining volume is a minuscule 10^{-9} cm^3 , so that the 500 captured atoms represent an extraordinary density of 5×10^{11} cm^{-3} . The atomic beam was brought to a halt in the molasses by the radiation pressure of yet another laser beam, shining directly into the oncoming atomic beam. In this vacuum environment, the laser beams are not directly visible.

achieved successful trapping with the single-beam design? It turns out that even the reduced dipole heating in a single-beam optical trap would boil the atoms out in a few milliseconds. Furthermore, it was not until last year that the two NBS groups perfected the beam-stopping techniques that are indispensable with these very shallow potential wells. In addition to dipole heating and the shallowness of the dipole potential, one is confronted by the small dimensions to which a laser-focus trap is limited. Even if the group could achieve a density of 10^6 atoms/ cm^3 —a thousand times the density Phillips and company had reached with their much larger magnetic trap—they would still have trapped only about $1/10$ of one atom in their minuscule 10^{-7} cm^3 optical trap. "Not a very interesting experiment," comments Chu.

The successful attainment of the optical-molasses "trap" last year presented the group with a simultaneous solution to all the remaining problems: One could now precool the stopped atomic beam to less than 300 μ K, so that even a 5-mK well would look very deep. Secondly, if the laser-focus dipole trap is located in the middle of the molasses, the randomly walking cold atoms would hang around long enough in the neighborhood for a significant number to fall in, despite the tiny trap volume. Finally, the optical molasses counteracts the dipole heating by continuing to cool the atoms that have already fallen into the dipole trap.

This last remedy is not as straightforward as it sounds. The molasses effect depends upon tuning the six cooling laser beams just a half line width below

the sodium resonance. The focused trapping laser, on the other hand, is tuned much farther below the D line. Near the focal point, its strong inhomogeneity produces large Stark level shifts that vary with position. Thus the two effects—dipole trapping and molasses cooling—are apparently incompatible; you can't do them both at the same place and time.

In 1983 Jean Delabard, Serge Reynaud and Claude Cohen-Tannoudji (École Normale Supérieure), in a paper that revitalized the quest for optical trapping, pointed out that you could do both, alternately, if you switched back and forth fast enough. And that is indeed how the Bell Labs group finally succeeded, chopping the two laser systems at a cycling rate of about a megahertz—alternately cooling, trapping, and cooling again. The minimum cycle speed is dictated by the harmonic oscillation frequency of an atom in the dipole trap. "If you chop that fast, the atoms effectively see the molasses and the dipole trap simultaneously," explains Chu.

The successful trapping, in March, began with a pulsed sodium beam, produced by vaporizing the surface of a sodium pellet with a pulsed laser burst. The beam was then slowed to a halt by the radiation pressure from a single counterpropagating chirped laser beam, landing finally in the six-beam molasses trap, at the center of which lurked the tiny focused dipole laser trap, tuned 650 GHz below the yellow D_2 line of sodium.

A video camera monitored the fluorescence from the trapped atoms. Analyzing the video images yielded an

estimate of about 500 atoms trapped in a 10^{-9} cm³ well at the dipole laser focus, with a density of 5×10^{11} cm⁻³ and a temperature of about 300 μ K. The trapping lifetime, limited by residual background gas at 2×10^{-9} torr and room temperature, was about two seconds, considerably larger than the holding time of the surrounding molasses. "These results all agree remarkably well with the theory; and the trap is easily reproducible," Chu told us.

One really wants to trap the atoms for much longer than two seconds—perhaps for as long as a minute. But even in a vacuum of 2×10^{-9} torr there are enough residual room-temperature atoms around to knock the atoms out of the trap in relatively short order. "The gentlest glancing blow from a 300-K gas atom will make short work of an atom in a 5-mK potential well," explains Chu. Having recently improved their vacuum, enlarged the trapping volume and made other design changes not yet published, the Bell Labs group has now achieved trapping lifetimes on the order of ten seconds.

Uses. A trapped gas of atoms at these remarkably low temperatures and high densities holds out the promise of observing spectacular quantum effects. The de Broglie wavelength of a 240- μ K sodium atom is about 300 Å, only one order of magnitude shorter than the nearest-neighbor distance at the trapping density already reported. The Bell Labs group is working toward lower temperatures (by exploiting laser cooling transitions with lower quantum limits) and higher densities. But can one attain the holy grail of Bose condensation with an optical-dipole trap?

The Bell Labs optical trapping technique appears to be limited to alkali atoms—although helium is a possibility. To get to Bose condensation one needs to prevent the formation of molecules or a frozen solid as temperature is reduced and density increased. This is hard enough to do with spin-polarized atomic hydrogen (PHYSICS TODAY, June 1980, page 18), not to mention alkali atoms, which are far more reactive. The NBS magnetic trap, on the other hand, can in principle trap hydrogen, although its density and temperature results to date are still far behind those obtained in the first optical-trap results.

The magnetic trap also has the advantage that it doesn't heat the trapped atoms. Once cold they stay cold, with no further cooling required. On the other hand, it's difficult to get the magnetically trapped atoms very cold in the first place, because the inductance of the magnet coils prevents one from turning them off and on rapidly to permit laser cooling. Furthermore, the large volume of the magnetic traps may

prove an impediment to laser cooling at high density, because the trapped aggregate will become optically thick and thus impenetrable to laser light.

On the other hand, the continual cooling required by optical traps has an unfortunate "mixmaster" effect, Chu told us, disturbing the interesting quantum statistical effects one wants to observe. Lithium-6 and lithium-7, the lightest of the alkalis, for example, are chemically identical. But at the quantum extremes of temperature and density, the Fermi gas (Li⁶) should behave very differently from the Bose gas (Li⁷). One cannot now foresee which trapping technique will prevail. "There are lots of tradeoffs," says Chu. He points to the possibility of hybrid systems in which one might first trap and cool the atoms in an optical trap, and then move them to the more benign environment of a magnetic trap. "It's very easy to manipulate atoms in an optical trap. You just have to move the laser light around."

Bose condensation is by no means the only interesting physics to be sought in a trapped gas at low temperature and high density. Very little is known about the interactions of such atoms with one another and with surfaces. David Lee and his Cornell colleagues, for example, have observed nuclear spin waves in very cold, spin-polarized atomic hydrogen at densities still far

below what's needed for Bose condensation (PHYSICS TODAY, June 1984, page 19).

The various techniques developed in the last few years "give us awesome control over the atoms," says Chu. "It's all so new. We have a list of a dozen experiments we want to do; and the list grows daily. Daniel Kleppner (MIT) calls the new developments "breath-taking. It opens the way to observe with great clarity how atoms interact, and how [these interactions] evolve. . . . This is a new ball park, and the whole history of physics shows that when you move into areas that are different by orders of magnitude, there are always surprises."

Summarizing 16 years of work on optical trapping, Ashkin points out that "we can now make simple single-beam traps that work over a size range of 10^5 —from atoms, to submicron Rayleigh particles, up through 10-micron Mie-size particles."

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Now they're even trapping antiprotons

The University of Washington group that made its reputation by doing measurements of exquisite precision on single protons, electrons and positrons held for astonishingly long times in a Penning trap (PHYSICS TODAY, May 1985, page 17) has finally succeeded in trapping antiprotons. They accomplished this feat¹ in July at the LEAR low-energy antiproton ring at CERN, where they had been granted one day's running to do a feasibility test for precision antiproton measurements they hope to carry out next year.

The difficulty is obvious: Antiprotons are produced at GeV energies. LEAR decelerates them to 21 MeV. Ordinarily the quadrupole electrostatic field of a Penning trap is called upon to hold onto charged particles no more energetic than a few eV. For this makeshift test, the Washington group, led by Gerald Gabrielse, degraded the $\bar{p}$ energies coming out of LEAR to 1 keV by passing the beam through a thick degrader. They then trapped a small fraction of these still very energetic antiprotons on the wing by rapidly applying kilovolt potentials to the electrodes of a crude Penning trap built for the occasion.

In this first one-day feasibility run, Gabrielse and his colleagues achieved trapping times as long as ten minutes. With improved vacuum, they expect eventually to attain much longer trapping times. Because of their very high annihilation cross sections with ordinary matter, low-energy antiprotons require a particularly good vacuum environment.

With longer trapping times, the group expects to measure the equality of the inertial masses of the proton and the antiproton with ten thousand times the precision thus far achieved—an important test of CPT invariance. Furthermore, they hope to find a way to observe, for the first time, the gravitational fall of antimatter. If they can accomplish this with neutral anti-hydrogen atoms—positrons bound to antiprotons—rather than lone antiprotons, the test would be much less sensitive to stray electric fields.

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