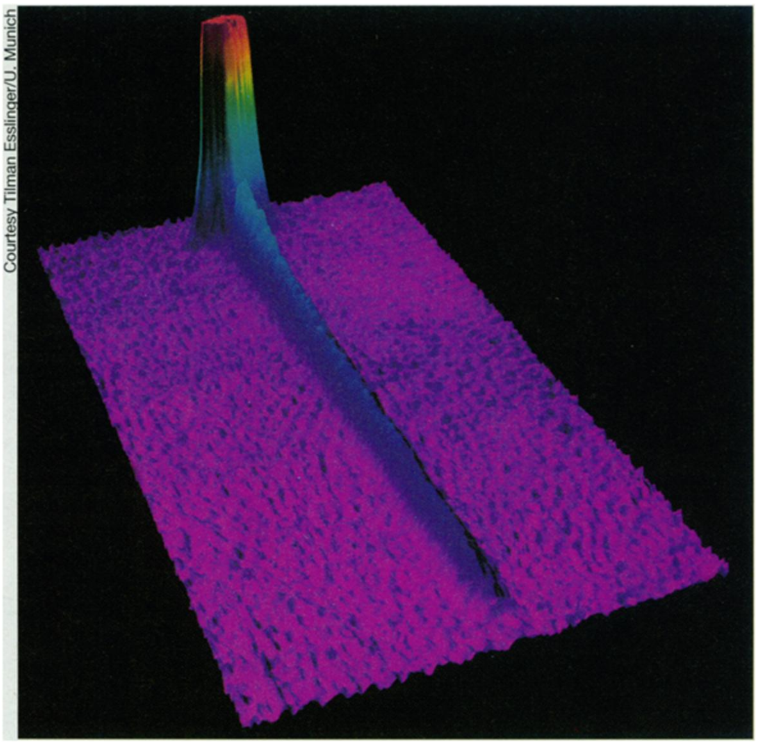
# Ready, Aim, Squirt

## With atom lasers, physicists seek better measurements and new ways to manipulate matter

By PETER WEISS

Summer scorchers are on their way. Laughing children will hop through sprinklers and scurry away from spritzing hoses. At gushing fire hydrants on urban streets, grinning urchins will douse their friends by using empty tin cans to direct arcing torrents of water.

With equal delight, grown physicists in their labs are squirting cold sprays—not of water but of frigid, slow-moving atoms. Working with flows that can be considered laser beams of atoms, rather than photons, researchers are now mastering the rudiments of directing these flows wherever they see fit.



Courtesy Tilman Esslinger/U. Munich

*A continuous atom laser beam (blue ridge) pours out of a rubidium Bose-Einstein condensate (rainbow peak). Tilted up in this false-color image for better viewing, the 2-millimeter-long beam actually drops straight down, propelled only by gravity.*

With these new lasers, the researchers are exploring characteristics of atoms cooled to nearly absolute zero and kept in a vacuum. They are also nudging wider open the doors to a possibly powerful technology known as atom optics. Ultimately, they hope to be able to direct and collect flows of atoms, which behave as waves, much as they control light with conventional optics.

“We're playing with atoms just like we play with photons,” says Ed A. Hinds of the University of Sussex in Brighton, England.

“We can have mirrors, lenses, beam splitters for atoms. We've already made some of that happen,” such as the atom lasers, remarks Daniel Kleppner of the Massachusetts Institute of Technology. “There is a lot of excitement in the field.”

Atom optics may greatly improve the precision of certain types of measuring instruments. Indeed, some laboratory devices, such as interferometers and gravimeters, have already begun to incorporate the new technology (SN: 8/8/98, p. 87). Other developments may include better gyroscopes, nanometer-scale structures built by means of atom beams, and circuitry that uses atoms instead of electrons and would be suited to the creation of exceptionally powerful computers based on quantum mechanics (SN: 4/3/99, p. 220).

The potential applications hinge on a crucial characteristic of lasers: Their waves are linked trough to trough and peak to peak in a fragile uniformity, known as coherence. Two or more coherent beams can interfere with each other, amplifying or reducing each other's intensity. Physicists have long exploited the same phenomenon with light lasers to perform exacting measurements and other tasks.

“Most of the power of modern optics lies in the ability of light beams to interfere with one another,” Hinds says. “Most of the exciting power of atomic optics is likely to lie in the interference of atoms.”

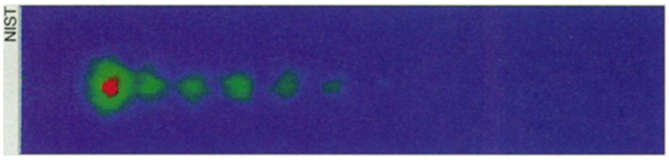
According to quantum mechanics, the wavelength of atoms depends on their momentum. As cooled atoms slow down, their momentum decreases and their wavelengths elongate.

During the past 20 years, researchers have devised increasingly effective means for cooling and trapping atoms at ultralow temperatures. In a 1995 triumph, Eric A. Cornell, Carl Wieman, and their colleagues in Boulder, Colo., at the National Institute of Standards and Technology (NIST) and the University of Colorado created the first example of a long-predicted state of matter called a Bose-Einstein condensate (SN: 7/15/95, p. 36).

By reducing the temperature of rubidium gas to about 2 microkelvins, the researchers caused atomic wavelengths to stretch and overlap until all the waves became coherent—the hallmark of a condensate. When condensate atoms escape the trap but remain coherent, they are considered a laser.

Wolfgang Ketterle at MIT and his colleagues made the first atom laser in 1997 (SN: 2/1/97, p. 71). They created a condensate of sodium atoms held in place by magnetic fields, which act on the atomic property called spin. With pulses of radio waves, the researchers changed the spin orientations of bunches of condensed sodium atoms so that they no longer were susceptible to the magnetic fields. The freed atoms fell out of the trapped condensate as coherent blobs.

Last year, Yale University researchers reported creating similar atom-laser drips from a rubidium condensate suspended briefly by laser light alone. The



*Blobs of coherent atoms fly from a sodium Bose-Einstein condensate (left) during a demonstration of the first atom laser that can spurt in any direction.*

clumps of atoms dribbled out of the condensate more regularly than the MIT laser's droplets did (SN: 11/28/98, p. 342). These first lasers resembled leaky faucets rather than the dazzling beams usually associated with the word laser.

Just as parents need a sprinkler or hose to entertain overheated kids, physicists require jets, not just drips, of atoms to achieve their atom-optics goals. "By and large, when atoms are just falling in empty space, they're not very useful," Hinds says. "You have to be able to control where they go."

In the March 12 SCIENCE, a team led by William D. Phillips of NIST in Gaithersburg, Md., describes the first atom laser that can be aimed. To create it, the group developed a novel way of kicking bunches of condensate atoms out of a magnetic trap. They used a pair of light-laser beams instead of radio waves to tweak the spins of their cooled sodium atoms and make them immune to the trap's magnetic forces.

As condensate atoms absorb and reemit laser photons, they acquire enough momentum to fly from the trap at 6 centimeters per second. Shifting the directions of the light lasers changes the blobs' path, the researchers say. Likewise, changing the light lasers' wavelengths adjusts the initial speed of the blobs, which the researchers believe they can crank up to 36 cm/s or more, says Steven Rolston of the NIST team.

Although it can be aimed, the NIST laser still sends out pulses of atoms. However, scientists need a continuous flow for many envisioned uses of atomic lasers, such as measurements that depend on interference between beams. A German group led by Theodor W. Hänsch at the Max Planck Institute for Quantum Optics in Garching has recently developed the first steadily flowing atom-laser beam.

Like the MIT scientists, the researchers used radio waves to flip the spins, but they employed a trap with an extraordinarily stable magnetic field and transmitted a constant, weak radio wave into it. In the April 12 PHYSICAL REVIEW LETTERS, the group reports that the atoms poured out in a regular stream under the influence of gravity.

Because the new, continuous-flow laser beam is controlled by gravity, it points only down. No atom laser yet offers both uninterrupted flow and the ability to be aimed. Combining those two features should be no problem, Hänsch says. He predicts, for instance, that his group could readily add NIST's light-laser technique for propelling atoms to his own method for trapping them.

These newest strides for atom lasers add to an exhilaration about atomic physics that began with creation of the first Bose-Einstein condensate 4 years ago, remarks Kleppner. "The enthusiasm is, I think, unprecedented in the history of atomic physics," he says.

"It's an atmosphere like after a gold rush," agrees Ketterle.

NIST researchers have used their atom laser to explore whether atom beams can tangle with each other in certain complex interactions that have already been shown for light lasers. In the March 18 NATURE, Phillips and his colleagues demonstrated that blending three atom lasers in space can cause a fourth laser to appear spontaneously.

For example, such interactions cause the frequency of light lasers to double when they pass through certain crystals—a property now being exploited by laser pointer makers to bring green-light pointers to market.

The experiment parallels a landmark 1960s experiment with light lasers that launched the research field known as nonlinear optics.

Despite their exuberance, atom-laser developers are also keenly aware of a major flaw of their devices—the atom lasers rapidly run dry. The longest-lived device, that of Hänsch's group, uses up its supply of atoms in about a tenth of a second.

Last year, after 20 years of trying, Kleppner and his colleagues made a condensate of hydrogen atoms (SN: 7/25/98, p. 54). Because it contains many more atoms than other condensates do, a hydrogen-atom laser—should it be developed—might last longer than others.

Other researchers hope to solve the problem of atom supply by making atom lasers more like light lasers. The latter can stay on indefinitely because new photons are continually produced by atoms boosted to an excited state by a power source. The atoms drop back down in energy as they emit photons that join the laser wave but are quickly restored to the excited state, ready to emit new photons.

In new experiments, Hänsch and his colleagues have shown that it is possible to mimic more closely the generation of a light-laser beam. Ordinarily atom-laser makers form the condensate first and then drain it away. Instead, by turning on their radio wave as the condensate was forming, the Munich researchers found that they could create the coherent cloud at the same time that they released atoms from it. While the laser was on, new condensate formed from the cloud of ultracold but uncondensed atoms present in the trap with the Bose-Einstein condensate.

To make the laser run without limit, the researchers also are trying to devise schemes to replenish that cloud of atoms continually. "There are some tricks that one can pull that should make that possible," Hänsch says.

Even if replenishable condensates should become available, atom lasers will always occupy a different niche from their light-based cousins, physicists say. Atom lasers emit slow, heavy particles whose trajectory droops under the influence of gravity. By contrast, the massless photons in light-laser beams barrel along a billion times more rapidly than the NIST-laser's atoms.

Also, because of their exceedingly low temperatures, atom lasers carry only a smidgen of energy, whereas light lasers can spark nuclear fusion and shoot down missiles.

Moreover, atom-laser beams can't pass through air because their atoms interact readily with other atoms. Photons, on the other hand, which interact far less with other particles, easily propagate through the atmosphere. "The fact that we have to do everything in a vacuum is obviously a big limitation," Phillips says.

Yet the differences between the light beams and matter beams also inspire the dreams of atom-optics researchers. Because the atoms move much more slowly than photons, an atom interferometer of the same dimensions as one based on a light laser has the potential to be 10 billion times more sensitive in measurements of the rotation of Earth or other objects, scientists say. Such measuring devices may push the frontiers of physics by uncovering minuscule, but important, discrepancies between theory and reality.

Ketterle and his colleagues have begun to trap condensates in a way that, they say, may make such precision more attainable. Using a light laser beam to grip the condensate, they eliminate magnetic fields that can disturb atom states and lessen sensitivity.

Atom-laser beams might also focus to as little as a nanometer across, which is roughly a thousandth the diameter of the smallest possible spot of visible light. That sharpness could lead to instruments such as atom-laser–based microscopes that might be able to discern directly the sequence of base pairs in a DNA molecule, Phillips speculates.

Such practical uses will not surface for decades, Ketterle predicts. Besides the tough technological challenges lying ahead, a wealth of new possibilities for basic research will keep physicists occupied for a long time.

By aiming for practical goals prematurely, "I would miss out on the fun," he says.

Like kids with squirt guns, physicists now have atom lasers that really shoot where they aim. The pleasures of finding out what they can hit and what happens to those targets is just beginning. ☐

## Magnets, light steer hyperactive atoms

Atoms rolling around on a tiny table. Atoms following the tracks of minuscule wires. Atoms steering a course determined by patterns of light.

Despite their reputation as the stolid building blocks of matter, atoms are increasingly particles on the go.

In atom-optics labs around the world, researchers are creating mirrors, lenses, waveguides, beam splitters, and a raft of other components to handle the beams from atom lasers. "We're now at the period of trying to develop the basic tools, like people in the 17th century were trying to do for light," says Ed A. Hinds of the University of Sussex in Brighton, England.

"People are just learning how to do things," agrees Jörg Schmiedmayer of the University of Innsbruck in Austria. A few intriguing recent results offer a glimpse at the wide range of strategies being pursued.

Hinds and his colleagues have been creating mirrors for atoms. The team transforms pieces of commercial videotape into atom-repellent surfaces, or mirrors, by recording magnetic field patterns onto them (SN: 9/9/95, p. 175).

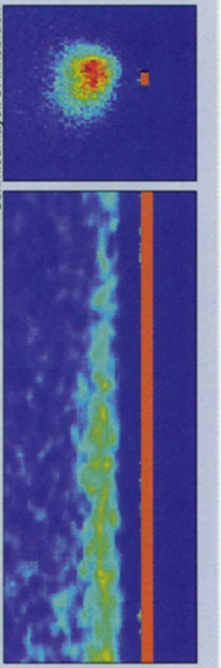
The group's larger goal is a "table" on which atoms could be manipulated. "Atoms fall down under gravity, so we need an antigravity machine," Hinds explains. By refining one of its mirror designs described in the Jan. 18 Physical Review Letters, the Sussex group has recently produced "a very smooth table for atoms to roll around on," Hinds says. Magnetic forces levitate the atoms at a slight distance off the surface, thus keeping the particles from sticking.

Meanwhile, a team under Schmiedmayer has been hustling atoms along narrow paths. In the March 8 Physical Review Letters, the Innsbruck group describes guiding cold lithium atoms by means of a suspended wire carrying electric current. The wire's current-induced magnetic field combines with an external magnetic field to form a trough of low field strength within a millimeter of the wire. Atoms collect and move along in the trough. The same technique works with wires that fork, subsequent research has shown. Experiments demonstrate that a branching wire can serve as a beam splitter or a switch, Schmiedmayer says.

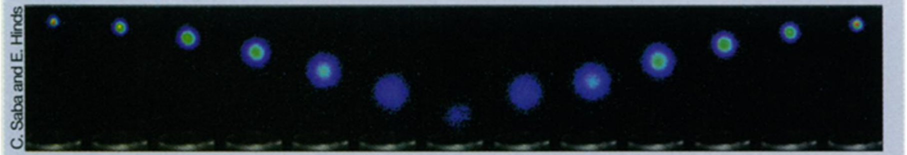
This approach to controlling atoms has practical appeal because it lends itself to miniaturization in which wires would be laid on or in a surface by using standard microchip-fabrication methods. The Innsbruck group has already developed some simple designs for devices with surface wires. "We're making the first integrated circuits," Schmiedmayer says.

In a reversal of the usual roles of light and matter, some recent atom-optics experiments employ light waves as mirrors, filters, and other optical components to influence atoms' behavior. Mara Prentiss of Harvard University and her colleagues, for instance, used a standing light wave, its undulations fixed in space, to control where excited atoms deposit their energy onto a reactive film. Their experiment suggests that atom beams may someday be used like light beams to project integrated circuit patterns onto semiconductors.

The technique, reported last year, depends on manipulations of internal quantum mechanical states, which are far more abundant in atoms than in photons. "We aren't just trying to re-live photon optics," Prentiss says. "Atoms have something more to offer." —P.W.


Schmiedmayer/U. Innsbruck

*Lithium atoms (left) move along in a trough of low magnetic field that parallels a current-carrying wire (right). Atom cloud and wire are shown on end (top) and from the side (bottom).*


C. Saba and E. Hinds

*A small cloud of ultracold rubidium atoms bounces off a curved, magnetic mirror. As the cloud falls, it spreads out due to the atoms' kinetic energy, but after hitting the mirror, it becomes refocused into a tight ball.*