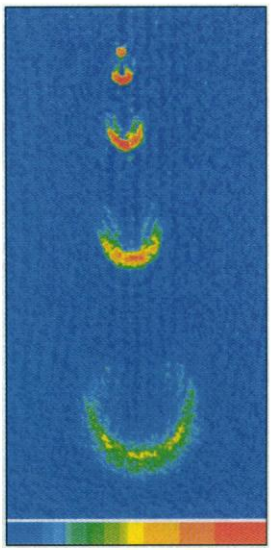
PHYSICS

First Atom Laser Shoots Pulses of Coherent Matter

To the uninitiated, a laser is a pin-thin beam of brightly colored light that you'd be wise not to shine in your eyes. To connoisseurs, it is a coherent beam of photons locked in identical quantum states, meaning they all have exactly the same wavelength and travel precisely in step, crest to crest, trough to trough. Now, the word laser has taken on yet another meaning: a beam of atoms marching in quantum lockstep, like the photons of a light laser.

Such a laser could aid everything from atomic clocks to chipmaking. Two years ago, physicists achieved the crucial starting point when they created an exotic state of matter known as a Bose-Einstein condensate. Now, a group at the Massachusetts Institute of Technology (MIT) led by Wolfgang Ketterle reports on page 637 that they have shaped this novel material into pulses of atoms that have the hallmarks of a laser beam. "The experiments are gorgeous," says Oxford University physicist Keith Burnett, and the demonstration that this is really a laser is "the most beautiful clear evidence."

A Bose-Einstein condensate is a dense cloud of atoms cooled in a magnetic trap to within an iota of absolute zero, where their quantum-mechanical waves merge. The formerly disparate atoms take on the characteristics of a single particle, in which the microscopic laws of quantum physics are writ large. Simply making a condensate is "bloody difficult," says Burnett, let alone turning it into a laser. Since Eric Cornell, Carl Wieman, and their colleagues at the National Institute of Standards and Technology and the University of Colorado made the first one in 1995 (*Science*, 14 July 1995, p. 198), only Ketterle's group and a team at Rice University led by Randy Hulet have been able to follow suit. Now, the MIT group has found a way to extract pulses of atoms from a condensate and has shown, by allowing two pulses to interfere with each other, that each constitutes the single coherent wave required of a laser.



M. R. ANDREWS *ET AL.*

Line of fire. An atom laser emits millimeter-scale pulses of atoms, all propagating as a single wave, at intervals of 5 milliseconds.

The first step, creating what laser physicists call an output coupler to extract the atoms from the trap, was relatively easy—"peanuts," says Ketterle. In a conventional laser, the output coupler simply taps light from the lasing cavity, where it is bouncing back and forth between mirrors. "Laser light is like a big wave," Ketterle explains, sloshing back and forth between the mirrors. "You want to take a little bit out for the beam, and then the big wave is amplified again and regenerated." An ordinary laser relies on leaky mirrors to allow perhaps 10% of the light to escape and form a beam.

For the atom laser, says Ketterle, the MIT team opened a leak in the trap confining their sodium atoms. The trap, he says, "can be described loosely as like atoms bouncing back and forth between magnetic walls." The walls, however, only retain atoms whose spin axis is pointing up. Flip those spins, and "the restoring forces become expelling or repulsive forces." So the MIT researchers simply apply another magnetic field to the atoms, which tilts their spins to any desired angle. "We varied the angle between 0 and 180 degrees, and at 0 degrees the magnetic mirror was still reflective, so nothing was coupled out; and at 180 degrees, everything was coupled out." By controlling the angle, the researchers could then "pulse out" portions of the condensate, the way a laser pulses out dollops of coherent light.

That was the peanuts part, which Ketterle's group reported at a conference in Sydney, Australia, last July and in the 27 January *Physical Review Letters*. What's reported in this issue of *Science* is the challenging part: showing that these dollops of condensate are coherent, which means the quantum-mechanical wave functions of the particles are all oscillating up and down in phase. To show that, says Ketterle, "you have to overlap matter waves from two different sources, [just as] you can prove light is a wave by passing it through two slits and looking at the interference pattern."

A New Recipe for Atom Condensates

While researchers at the Massachusetts Institute of Technology have concentrated on turning a Bose-Einstein condensate into an atom laser (see main text), a group at the University of Colorado and the National Institute of Standards and Technology (NIST) in Boulder has found a new recipe for these exotic assemblages of atoms. They serendipitously created two of them coexisting in the same magnetic trap, "a little bit like a big blob of oil next to a big blob of vinegar," says NIST's Eric Cornell.

In a paper in the 27 January *Physical Review Letters*, Cornell, Carl Wieman, and their colleagues—who created the first Bose-Einstein condensate in 1995—report that they cooled a single cloud containing rubidium atoms in two subtly different quantum states. The states are distinguished by whether the electrons and nucleus of each atom have spins that are oriented in the same or opposite directions. Because the mechanism used to cool the atoms into a Bose-Einstein condensate works on only a single state, the researchers normally "take care to put all the atoms in the same internal state," says Cornell. "But on this particular day, the apparatus was not working very well, and almost by accident we got two internal states" in the trap. The system promptly cooled the atoms in one state, but the other atoms cooled "sympathetically," says Cornell, by losing heat to the adjacent, already-cooled cloud.

The end result was two distinct clouds, says Cornell: "They're all exactly the same isotope of rubidium, but you have one rather distinct cloud in one internal state and another distinct cloud in another internal state. They do overlap a little bit, but they find each other repulsive."

To Wieman, "That is the most remarkable thing about the experiment." He adds that the interaction holds "a lot of interesting physics." The sympathetic cooling process should also expand the repertory of condensates, he says. "There are all kinds of other atoms one can now stick in the trap and turn into Bose-Einstein condensate by sympathetic cooling. It's like a refrigerator where you only know how to cool Freon directly, but you can get anything cold by sticking it in thermal contact with the Freon." The condensate chefs now have a new tool. –G.T.

It took months of hard work to do this. "It only looked easy after it was finished," says Ketterle. First, he and his colleagues created two condensates by beaming a laser up through the middle of their magnetic trap. The laser light repelled the atoms and split the condensate into two distinct halves. For this test, there was no need to pulse the condensates out of the trap; instead, the group just turned off the trap and let them free fall. As the condensates fell, they expanded into the surrounding vacuum until they overlapped and interfered, demonstrating the atomic version of the bright and dark fringes in an interference pattern.

"The density of the overlapping region is modulated," says Ketterle. "Every 15 microns, we have matter, no matter, matter, no matter. Now, we just shine some light onto the pattern and see this shadow with black-and-white stripes." Says Burnett, "It's not just a little crappy demonstration but a big, juicy interference pattern."

Having proved the condensate is coherent, Ketterle and his colleagues can use the output coupler to extract the condensate in pulses, which makes the setup effectively the first primitive atom laser and raises the question of where they go next. So far, they have been able to get eight pulses out of a condensate before they have to reload, which takes 20 to 30 seconds. One of their first goals is to figure out a way to restock the condensate as they go along to create the atomic version of a continuous wave laser. "Remember, these things are a few weeks old," Ketterle says, "and we need a major improvement in output power, a major reduction in complexity, and also improvement in shaping the pulses."

At that point, any field that relies on beams of atoms might benefit from the brighter and better controlled beams of an atom laser. Atomic clocks, which are based on the vibrations of atoms drifting through a cavity, are one candidate. Another is nanolithography, the technique by which circuit designers lay out minuscule features. It now depends on a mask or stencil to control where atoms or light land on a surface, but an atom laser—which could be focused and directed like a light laser—might provide a way of writing the patterns directly, says University of Texas physicist Dan Heinzen.

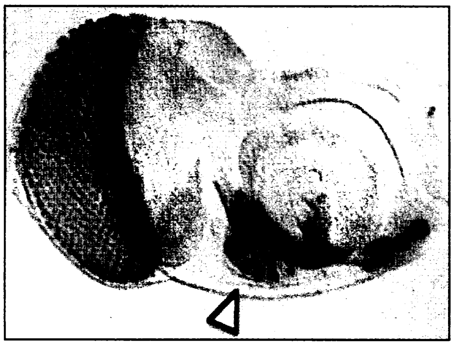
The technology does seem to come with a handicap: Unlike light, an atomic laser beam can't propagate freely through the atmosphere. But Burnett says it's too early to focus on limits. After all, at the birth of the light laser, "people talking about applications really didn't imagine them being in every supermarket check-out counter."

–Gary Taubes

DEVELOPMENTAL BIOLOGY

A "Master Control" Gene for Fly Eyes Shares Its Power

In a startling experiment reported 2 years ago, Swiss biologists caused surplus eyes to sprout on fruit flies' wings, legs, and antennae—all by manipulating a single gene called *eyeless* (*ey*). Grotesque as this spectacle was, researchers hailed it at the time: Besides shedding light on eye development, it also supported the seductive idea of "master control genes" that can single-handedly order up complex organs by turning on other genes. But now it seems that *ey* has a partner—perhaps even two—and the all-powerful master controller may be merely a member of a committee instead.


SHEN AND MARDON, 1997

Eyes up. Expressing the *dac* gene in the wrong place in flies causes eyes to sprout (arrow) where antennae normally grow.

New work reported in the January issue of the journal *Development* shows that a fly gene called *dachshund* (*dac*) can, like *ey*, give rise to ersatz eyes when turned on in out-of-the-way places such as a developing leg or antenna. And the researchers also discovered that *ey* can't build these so-called ectopic eyes in flies missing *dac*—an indication that the two genes normally work together. "It's really an oversimplification to say that any one gene is the master-control gene for eye development," concludes developmental geneticist Graeme Mardon of Baylor College of Medicine in Houston, who authored the study with technician Weiping Shen.

The Baylor team's result "is a very interesting discovery," agrees Nancy Bonini, a *Drosophila* geneticist at the University of Pennsylvania. "If *dac* had been found before *ey*, you might say that *dac* is 'the' master regulatory gene in eye development. So, maybe we should think differently about these terms." But Walter Gehring, the Swiss geneticist who led the original dramatic *ey* study—and whose lab recently discovered yet another eye-forming fly gene, christened *twin-of-eyeless* (*toy*)—says *eyeless* is still the master switch. "I don't think this [label] has to be revised," he says.

The eye-popping powers of *dac* were discovered by accident. The gene got its name several years ago, when Yale University biologist Iain Dawson came across a mutation in the fruit fly *Drosophila melanogaster* that resulted in short, stubby legs—and also affected the arrangement of the 800-some individual eyes (called ommatidia) in each of the flies' compound eyes. Mardon, then a postdoc in the lab of geneticist Gerald Rubin at the University of California, Berkeley, found the gene independently. He went on to clone it and discovered that the protein it encodes resides in the cell nucleus, suggesting that *dac* helps regulate the expression of other genes.

But Mardon couldn't find which genes those might be. Then, in 1995, Gehring and colleagues Georg Halder and Patrick Callaerts at the University of Basel in Switzerland published their study on *ey*. To trick the gene into becoming active where it should be dormant, they used genetically engineered fly larvae that produced a gene-activating protein called GAL4 in many different body parts, such as wings, legs, and antennae. Then, they mated these flies to others in which *ey* was connected to a control switch activated by GAL4. The result was a brood of flies with eyes in unorthodox places (*Science*, 24 March 1995, pp. 1766 and 1788).

Mardon, eager "to see what *dac* might be doing," borrowed the technique, linking not *ey* but *dac* to the GAL4-activated control switch. He and Shen found that 20% of the resulting flies developed clusters of fully formed ommatidia in odd locations. That's a much lower fraction than the Gehring team's 100%—perhaps, Mardon speculates, because making eyes in certain places in the body would require genes that *dac* does not activate, but *ey* does. Intriguingly, the Baylor team also found that ectopic expression of *ey* induces *dac* expression in the same places, and that *dac* can also turn on *ey* in a subset of these cells. And when Gehring's experiment is repeated in flies lacking *dac*, no ectopic eyes form. All this suggests to Mardon that the two genes evolved as partners, reinforcing each other's eye-building signals in a positive feedback loop.

So, which is the true master-control gene for the fly eye? Neither, says Mardon. Both, suggests Ulrike Heberlein, a *Drosophila* geneticist at the University of California, San Francisco. "Maybe we need to talk about a hierarchy of master regulators," she says. But Gehring maintains that between *ey* and *dac*, *ey* is still the