Physicists Create New State of Matter

By cooling a crowd of atoms to within a hair of absolute zero, researchers have made the crowd behave as one, opening a new arena for physics

> **Special News Report**
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> A special news report on epidemiology begins on page 164. News & Comment and Research News are combined into a single section for this issue.

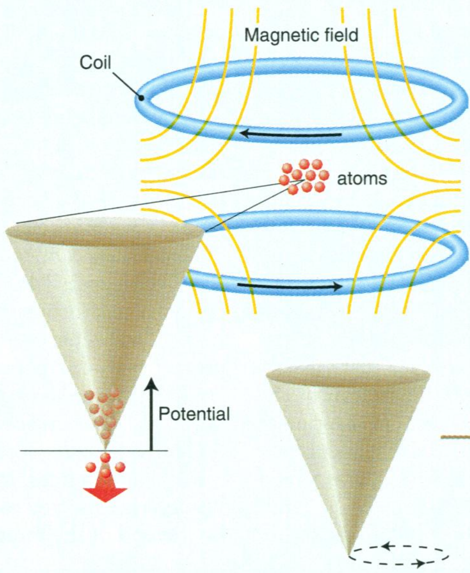
Eric Cornell says that for the first few days after he and his colleagues introduced a new state of matter to this planet, their achievement didn't really sink in. "I really felt kind of numb," says Cornell, a physicist at the National Institute of Standards and Technology in Boulder, Colorado. "It wasn't until my third night afterward that I didn't sleep all night thinking, 'Oh my god, this really happened.' "

What had happened, on the morning of 5 June, was that Cornell and his colleague Carl Wieman, a University of Colorado physicist, had managed to create what is known as a Bose-Einstein condensate (BEC), a gas so dense and so cold—at 180 nanokelvin (billionths of a degree above absolute zero)—that the atoms come to a near standstill. As they slow to a stop, the quantum-mechanical waves that describe each atom spread out and merge, until the entire gas is locked in the same quantum state. In effect, the atoms lose their separate identities and become one. A BEC is to matter what a laser beam is to light: a coherent state in which the usually microscopic laws of quantum mechanics govern the behavior of a macroscopic system.

The prospect of seeing these shadowy laws in action on a large scale had spurred a 15-year quest to create this uncanny material, by snaring and cooling atoms in cages of magnetic force or light. Cornell and Wieman's success, confirmed when they photographed a tiny, durable knot of rubidium atoms at the center of their trap, finally opens the way to realizing that promise.

The achievement, which they report on page 198 of this issue, also puts to rest some nagging doubts. As nature kept foiling ever-more-ingenious schemes for attaining the temperatures and densities of BEC, says Cornell, "people wondered if there was just some reason that Bose condensates were just not meant to be." Even the most promising cooling strategy of recent years, for example, was stymied by a small leak of ultracold atoms from the very center of the trap. By finding a way to plug that leak, Wieman and Cornell, along with Michael Anderson, a postdoc, and graduate students Jason Ensher and Michael Matthews, have put those doubts to rest. "It's a spectacular discovery," says Dan Kleppner, an atomic physicist at the Massachusetts Institute of Technology (MIT) who is a veteran of the quest. "It takes your breath away. This first demonstration is absolutely clear and convincing. It's almost like in a textbook."

The goal was set 70 years ago, when Einstein, building on work by the Indian physicist Satyendra Nath Bose, first predicted this new state of matter. What properties it might have, or even what it would look like, neither Einstein nor any of his successors could say for sure. But the prospect of studying it has been so alluring that ever since the technologies of atom-trapping and -cooling became powerful enough to make BEC seem feasible, a friendly competition has been on to create it (*Science*, 8 July 1994, p. 184).



SOURCE: E. CORNELL ILLUSTRATION: K. SUTLIFF

It's the TOP. In a conventional magnetic trap, the field falls to zero at the center *(left)*, allowing atoms to leak out. The TOP trap rotates the field *(center)*, plugging the leak *(right)*.

Each group has its favored technique and even its favored material—atoms of either hydrogen or so-called alkali metals such as sodium and rubidium—but virtually every experiment has built on the successes of its rivals. And virtually everyone in the field has passed at one time or another through Kleppner's laboratory or that of his former student David Pritchard, also at MIT.

Wieman, for instance, had worked with Kleppner for 2 years as an undergraduate at MIT before going off to Stanford University and then joining the University of Colorado in 1984. Kleppner's own strategy for approaching BEC is to refrigerate hydrogen atoms, then trap them in a magnetic field and let the hotter ones fly out of the trap, leaving colder ones behind—a technique known as evaporative cooling. As early as last year this strategy seemed to have put Kleppner, working with his MIT colleague Tom Greytak, in the lead in the race to achieve BEC.

In Colorado, however, Wieman took up a competitive technique, known as laser cooling, which works best with alkali atoms. Far cheaper and simpler than Kleppner's refrigeration apparatus, laser cooling works by bombarding atoms with photons. The laser is tuned to a frequency slightly too low for the atoms to absorb when they are at a standstill. But when the atoms are moving toward the laser, the frequency of the light as seen by the atoms is Doppler-shifted upward and the photons hit home, slowing the atoms and hence cooling them.

But although laser cooling can chill atoms to less than a millionth of a degree above absolute zero, a temperature even colder than Kleppner and Greytak had achieved for hydrogen, it could not match the densities they had reached. Manyfold colder temperatures or higher densities—or both—would be needed for BEC. Wieman, however, hit on a possible solution: If he could laser-cool rubidium atoms first and then evaporatively cool them as Kleppner and Greytak had done with hydrogen, he might reach the threshold. When Cornell—a former Pritchard student—joined him in 1990, they set out to make it happen.

To pull off this marriage of techniques, they transferred atoms that had already been laser-cooled to within a few tens of millionths of a kelvin to a magnetic trap. Providing the magnetic axes of the atoms are all lined up in the same direction, the trap can snare them within a "quadrupole" magnetic field, which is strong at the edges of the trap but falls to a spot of zero field at the very center. The hottest, fastest atoms are allowed to escape, leaving colder atoms behind. The strategy cools the atoms by another factor of 5; at the same time, it boosts their density as they cluster at the center.

That was the good news. At a meeting in Anaheim, California, a year ago, however, the Colorado group and others pursuing the hybrid strategy—which also included an MIT group led by Wolfgang Ketterle—faced the bad news: the spot of zero field at the center of the trap. The coldest atoms do indeed cluster at the center as predicted, but because there's no magnetic field there to keep them aligned, they leak out, leaving the researchers four orders of magnitude short of the density-temperature threshold of BEC.

Ketterle proposed one fix: Aim a laser beam at the zero point to repel any atoms that approached it. Ketterle's laser-plugged trap worked, but not as well, or at least not as quickly, as the idea Cornell came up with, which even Ketterle calls "a real gem."

Cornell simply added a second magnetic field to his existing trap, one that would swing the zero point around in a circle—which is one reason why he and Wieman call the result a TOP trap. "The TOP trap," says Wieman, "simply takes this zero field point and moves it away from the center and spins it around. Now what you've got is this orbit of death. As long as the atoms are cold enough to stay in the center and not get out to the orbit of death, they stay there forever and you can keep cooling them down."

By the end of May, the researchers were confident they could achieve the temperature and density needed to create a BEC, but they hadn't figured out how to see it if they did. The Bose condensate would consist of a few thousand atoms in a ball 10 microns across, too small to allow them to see whether the atoms' velocities had dropped to the levels of BEC—"All we'd see is a little smudge," says Wieman.

The solution was what they called ballistic expansion: They would open up the trap, leaving the atoms free to fly apart. Says Cornell: "We wait for a while, and the cloud gets a lot bigger, and then we take a picture of the cloud" using a laser. The structure of this expanding cloud, he says, reveals the velocity distribution in the original cloud before the trap was opened. Hotter atoms should have spread out, but at the center, the density of the atoms should rise steeply. These, he says, are the relic of the BEC that existed until the trap was opened.

That was the theory, anyway. On 5 June, the predicted density peak appeared on the experimenters' video screens. "It was so close to what we have been telling people that it ought to look like that we were initially kind of suspicious," says Cornell. Now his doubts have vanished. Asked whether he and his colleagues could be wrong, Cornell says simply, "I hope not," which he quickly amends to "No. The data are pretty clean. We're not averaging data for 300 hours, getting a [weak] effect, and just happy-talking ourselves into seeing what we want to see."

Indeed, the very first images seem to have cleared up some of the theoretical speculation about what a BEC might be like. For starters, says Wieman, "it takes a couple seconds for it to form, and there's some interesting physics behind that." But one of the most intriguing questions about BEC remains to be answered: What does it look like? Light waves should interact very differently with atoms whose own wave functions have merged than with ordinary matter, but theorists' predictions about the result have been all over the map, with some opting for transparency, some for inky blackness, and some for a silvery sheen. "We have finessed that whole issue by letting the stuff expand out before we ever look at it," says Wieman. But now, he says, it will be very easy to shine a laser on it before it expands and see what happens.

And that's just the beginning of the scrutiny they plan for their prize, he adds. "A thousand atoms [of BEC] is a big chunk, and we'll be able to make a lot more." Then "we will have a whole bunch of [other] knobs we can turn" to probe the new material.

Cornell and Wieman won't be the only researchers doing so. Perhaps half a dozen experiments are still on the verge of creating a BEC, and other groups are likely to join them, inspired by the Colorado group's success—and by the low price of admission. Costing perhaps $50,000 for hardware, plus several months of labor, Wieman and Cornell's apparatus was breathtakingly cheap by modern physics standards. "We worked hard to pursue this using techniques that were cheap and simple," says Wieman, "so if it actually worked it would be opening up the field."

–Gary Taubes

PLASMA PHYSICS

Go Back to Basics, Says NRC Panel

The hottest spot on Earth is the interior of a huge, donut-shaped vessel at the Princeton Plasma Physics Laboratory. The device, called a tokamak, uses a spiraling magnetic field to trap million-degree plasma, or ionized gas, allowing some of the plasma's ions to fuse—a process that could someday be a practical source of energy. In the field of plasma physics, though, the hottest thing right now is an assessment of the field released this week by the National Research Council (NRC) suggesting that an exclusive focus on applications like tokamak fusion may actually pose a threat to the field as a whole.

Even as Princeton's tokamak sets record after record for power output (*Science*, 2 December 1994, p. 1471), the report* concludes that the basic plasma research that made this achievement possible has become all but extinct in the United States. If the situation doesn't change, says the NRC, "a dangerous gap will develop" in the knowledge needed to continue the fusion program itself. The panel's prescription to fill this gap: Shift $15 million from fusion and other applied research into basic plasma science.

At a time when fusion research (*Science*, 23 June, p. 1691) and science in general are under siege in Congress, these measures were "not lightly recommended," says John Ahearne of Sigma Xi, a science and policy research society in Raleigh-Durham, North Carolina, co-chair of the NRC panel on opportunities in plasma science and technology. But he says that after "very difficult" discussions, even fusion researchers on the panel finally agreed on the need for a return to basic research. One of those panelists—Ronald Davidson, director of the Princeton Plasma Physics Laboratory—argues that the NRC's diagnosis doesn't hold true at his own lab, where "the component of basic plasma-science research is very, very strong." But he agrees that the fusion program as a whole may need a new infusion of basic research.

The report aims to remedy a situation dating back at least to the 1950s, when physicists realized that the nuclei of hot, confined plasmas would fuse, emitting enough energetic particles to drive large power plants. The result, says Ravi Sudan of Cornell University, chair of NRC's plasma science committee, a contributor to the report, was that "plasma physics got a little distorted in its development because it was driven by applications."

Plasma physics research came to focus on large plasma-confinement devices at government-run labs. As a consequence, says Sudan, the discipline "didn't sink its roots" into university curricula. Still, many plasma physicists say that funding agencies such as the Department of Energy (DOE) did keep basic science afloat until the 1980s. Then, says John Cary, a plasma physicist at the University of Colorado, Boulder, "it seemed we got into a situation where [DOE] said, 'We're not going to support any more basic stuff. We understand enough to build bigger tokamaks.' " Basic research funding dried up across the board, falling to less than 10% of the $370 million a year that now goes to fusion.

Although fusion is by far the largest consumer of funding in plasma science, it isn't the only reason the field is "suffering from

* "Plasma Science: From Fundamental Research to Technological Applications"