Cornell, Ketterle, and Wieman Share Nobel Prize for Bose–Einstein Condensates

The Royal Swedish Academy of Sciences has selected Eric A. Cornell, Wolfgang Ketterle, and Carl E. Wieman to receive the 2001 Nobel Prize in Physics "for the achievement of Bose–Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates." The three will collect their awards in Stockholm amid more than the usual fanfare, because this year is the centennial of the prize.

Cornell is a staff scientist at NIST in Boulder, Colorado, and adjoint professor of physics at the University of Colorado. Wieman is Distinguished Professor of Physics at the University of Colorado in Boulder. Both he and Cornell are fellows at JILA. Ketterle is the John D. MacArthur Professor of Physics at MIT.

Atoms in lockstep

Atoms in a Bose–Einstein condensate (BEC) have been likened to foot soldiers in a parading battalion, marching in lockstep. All atoms sit in the ground state of center-of-mass motion, and they are collectively described by a single macroscopic wavefunction. Such a state was predicted in 1925 by Albert Einstein, who extended Satyendra Nath Bose's work on blackbody radiation to particles with mass.

Evidence for a BEC has long been seen in superfluids and superconductors, but the constituents of those condensates have strong interactions with one another, so the pristine nature of the BECs is hard to predict and observe. The best hope for clear manifestation of BEC behavior, it seemed, lay with a gas of weakly interacting atoms.

When BECs made their long-awaited debut in a rubidium-87 gas in 1995, they left no doubt about their identity. There, in a textbook plot of atomic density as a function of velocity, was a sharp peak centered at zero. That moment of creation was achieved at JILA by Cornell, Wieman, Michael Anderson, and coworkers.[1] Until then, Wieman now says, "I had guessed we might at first find a tiny condensate on a large background of normal atoms, and we would have to tinker to get a larger signal."

> Macroscopic quantum states of atomic gases, created in 1995, have more than lived up to initial expectations, with journals still bulging with reports of their fascinating behavior.

Four months later, Ketterle and his MIT group[2] formed a sodium-23 condensate, having about a hundred times more atoms. Roughly a year later, with even larger clouds of atoms, they were able to form two condensates, overlap them, and see the resulting interference fringes—clear and beautiful evidence for the coherence of the condensates.

Close on the heels of JILA and MIT was a group led by Rice University's Randall Hulet, who had evidence suggestive of a lithium-7 BEC in 1995, with definitive proof coming in 1996.[3] Although more problematic to work with, ^{7}Li has a lot to offer, because unlike ^{87}Rb and ^{23}Na, ^{7}Li atoms attract rather than repel. A ^{7}Li condensate can only accommodate a small number of atoms before it destabilizes and collectively collapses.

By now BECs have been formed in hydrogen, metastable helium, and, most recently, potassium.[4] Researchers have also produced the fermionic cousin of a BEC, with single atoms filling almost all of the energy states below the Fermi energy.

Today, dozens of groups worldwide are playing in the BEC sandbox, digging up one new feature after another. There have been demonstrations of superfluid properties, breathtaking pictures of triangular lattices of vortices, production and amplification of an "atom laser," studies of Bragg scattering of atoms off a BEC "grating," explorations of nonlinear effects, and manipulation of the interaction between condensate atoms.[5] Theorists are busily exploring the newfound properties. (See the articles by Ketterle and by Keith Burnett, Mark Edwards, and Charles W. Clark in PHYSICS TODAY, December 1999, pages 30 and 37, respectively.)

Possible applications are still on the far horizon. Those that people often mention are ones that exploit the unprecedented control and manipulation of atoms that BECs offer at the quantum level. BECs offer hope of enhanced precision for atomic interferometry, rotation measurements, and atomic clocks. They might find a use in nanofabrication and atom lithography. Or they might play a role in quantum computing.

A challenging race

The race to form a BEC was difficult and, near the end, intense. To make the wavefunctions of individual atoms overlap, the interatomic separation had to be as small as possible—requiring very high densities—and the atomic de Broglie wavelength (which varies inversely with thermal velocity) had to be large—requiring extremely low temperatures. Competitors were helped by techniques developed over the past few decades to trap atoms and to cool them to low temperatures; many of those techniques were recognized by the 1997 Nobel Prize in Physics (see PHYSICS TODAY, December 1997, page 17).

The early entrants in the race, in the mid-1970s, chose spin-polarized hydrogen, whose weak interatomic interactions make it the closest approximation to the gas of identical, noninteracting particles assumed in the work of Bose and Einstein. Unfortunately, these weak interactions also greatly hinder efforts to cool the gas. Two of the pioneers, Daniel Kleppner and Thomas Greytak of MIT, with their coworkers, completed the race three years after the winners.

Kleppner and Greytak's work on spin-polarized hydrogen was a major inspiration to the whole field. A key contribution was the technique of evaporative cooling, conceived in 1986 by their postdoctoral assistant Harald Hess (now at KLA Tencor in San Diego). In evaporative cooling, the most energetic atoms are allowed to escape from their magnetic trap, lowering the average temperature of the remaining atoms. David Pritchard of MIT later suggested applying radiofrequency radiation that can evaporate atoms above a selected energy.

By 1990, Cornell, Ketterle, and Wieman were starting the work that

New laureates, Eric Cornell and Carl Wieman addressing well-wishers in Colorado.

would lead them to a BEC. Wieman had an established laboratory at JILA, where he had begun to work on laser cooling a few years earlier. Cornell, with a fresh PhD from MIT in hand, had arrived as a postdoc in Wieman's lab. Ketterle, having decided after a year of work on combustion diagnostics that he would prefer to do basic research, had accepted a postdoc in Pritchard's laboratory to learn the business of atom trapping and cooling.

Around 1990, Wieman and his group started to view alkali atoms as a better bet than hydrogen for achieving a BEC. Unlike hydrogen, alkali atoms lent themselves to laser cooling, a technique in which photons impart momentum kicks that essentially slow the atoms. Furthermore, alkalis were expected to have higher rates of elastic scattering, which are essential for evaporative cooling.

At first, no one had good measurements of the collision rates for the various alkali atoms, so that choosing a particular atomic species to cool was a gamble. All three of this year's physics laureates admit to some luck in their choices. Wieman and Cornell began with cesium-133, but when Cornell set up a second lab at JILA, he picked rubidium, which has two isotopes. "That way," he said, "I got two rolls of the dice."

The road from JILA

In the mid 1980s, Wieman was studying parity nonconservation in atomic physics by doing laser spectroscopy on ^{133}Cs. As an economy measure, he adapted cheap diode lasers rather than the conventional, but expensive, stable dye lasers. In parallel with the parity experiments, Wieman tried using his diode lasers to cool atoms. In 1986, he worked with Pritchard to design an optical trap based on spontaneous light forces, but readily admits that Pritchard had a much better idea the following year when he and collaborators from MIT and Bell Labs developed a magneto-optic trap (MOT) based on the ideas of Jean Dalibard at the Ecole Normale Supérieure in Paris.

Shortly thereafter, Wieman used diode lasers to create an inexpensive vapor-cell MOT that could capture and cool atoms out of a vapor cloud (as opposed to an atomic beam, as in the MOT built by the MIT–Bell Labs team). In studying processes that limited the temperatures and densities achievable in the trap, Wieman and his team found that the laser light scattered from trapped atoms was pushing other atoms out of the trap. To reach a BEC, he concluded, one would have to use laser cooling only to a point and then get rid of the lasers and transfer the atoms to a purely magnetic trap for evaporative cooling. Wieman admits that his ideas then were very vague.

About this time, Cornell arrived in Colorado. On an interview trip to NIST in 1990, he had been hooked by the small scale of the experiments he saw in Wieman's lab. "I was so impressed that you could do laser cooling with that level of money, equipment and effort, that I thought maybe you could make a BEC with it," he says. When his postdoc was up, he secured a permanent position at NIST and his own lab, but he and Wieman remain close collaborators.

Wieman gives credit to Cornell, along with Christopher Monroe (now at the University of Michigan), for working out the details of evaporative cooling in their experiment. At first, they thought the big problem would be inelastic collisions that kick atoms out of the magnetic trap. For evaporative cooling to work, the rate of "good" (elastic) collisions had to be about 100 times greater than the rate of "bad" (inelastic) collisions. Fortunately, the alkali atoms they were using turned out to have such a favorable ratio.

The challenges then, said Cornell, were to assure efficient loading of atoms out of the MOT and into the magnetic trap, and to attain a really good vacuum to keep atoms trapped long enough for evaporative cooling to work. In designing a method to transfer from one trap to another, Wieman, Cornell, and company had to reconcile the con-

Wolfgang Ketterle acknowledges congratulatory applause as MIT colleagues (from left) Thomas Greytak, David Pritchard, and Daniel Kleppner look on.

flicting vapor pressure requirements of the two kinds of traps. They compromised at an intermediate pressure. Today, they use two MOTs, one at a higher pressure than the other.

The final problem was that the quadrupole magnetic trap has a "hole" in it: a region in the center where the magnetic field is zero. Atoms there can be spin-flipped and lost from the trap. Cornell solved the problem by applying a rotating field, which moved this null-field point around the trap in such a way that the field was never zero where the trapped atoms resided. With that hurdle overcome, the team soon achieved a BEC.

Progress at MIT

When Ketterle arrived at MIT in 1990, he wasn't focused on achieving a BEC: The phase-space densities for trapped alkali atoms were then more than six orders of magnitude away from those required for a BEC, whereas the hydrogen gases cooled by Kleppner, Greytak, and company were within a factor of ten. Still, he says, he was intrigued by the possibility of combining laser cooling and evaporative cooling, being influenced by his mentor, Pritchard, and his office neighbor, Kleppner, both of whom had done pioneering work on these techniques.

Under Pritchard's direction, Ketterle attacked the challenge of creating a much denser cloud of atoms than had yet been achieved. The two devised a simple technique to circumvent several problems caused when excited atoms interact with the trapping light in the MOT. Pritchard and Ketterle blocked the repumping light in the center of the MOT, allowing already trapped atoms to spend most of their time in a hyperfine quantum state that did not absorb the trapping light. With such a "dark-spot MOT," they cooled an unprecedented number of atoms to high densities. The JILA experimenters also used the dark-spot idea, although its effect in their vapor cell MOT was to increase the number, and not the density, of the atoms.

Before his work on the dark-spot MOT, Ketterle told us, he thought that laser cooling could not get atoms dense enough for evaporative cooling to be effective. But in 1992, he and Pritchard concluded that the dark-spot MOT could provide a bridge between laser and evaporative cooling. At that moment, said Ketterle, "we set full sail for BEC and dropped everything else."

In 1993, Pritchard stepped aside in a remarkably magnanimous gesture. Ketterle was then a candidate for an MIT professorship, and wanted to continue working toward a BEC. To save Ketterle from having to compete in the shadow of his mentor, Pritchard bowed out of the BEC project and turned his laboratory over to Ketterle so that the former postdoc could continue the quest. Pritchard told Ketterle at the time, "I'm giving you the keys to the family car because I know you can drive faster than I can."

By 1994, Ketterle's group saw the onset of evaporation, and within the next year, they reduced the phase space by six orders of magnitude. They plugged the hole in the magnetic quadrupole trap by shining a laser beam through the center, and arrived at their destination with about 500 000 atoms in their condensate.

In retrospect, Ketterle realizes that the dark spot MOT was unnecessary; his group could simply have built a very quiet magnetic trap and waited for evaporative cooling to work. "We created overkill because we never thought it would work so easily," he says, "but that overkill was responsible for the dramatic progress of the field."

Biographies

Cornell earned a BS in physics from Stanford University in 1985 before going to MIT for his PhD. Although Pritchard was his adviser, Cornell did his thesis on single ion mass spectrometry rather than on laser cooling.

Wieman earned a BS in physics from MIT in 1973, doing undergraduate research there with Kleppner. For his PhD, earned in 1977, he worked under Theodor Hänsch at Stanford doing two-photon spectroscopy of hydrogen. He spent two years at Michigan before going to Colorado.

Ketterle earned his master's diploma in 1982 from the Technical University of Munich, writing his thesis in theoretical physics. He turned to experimental work—spectroscopy—to earn his PhD in 1986 under Herbert Walther at the Ludwig Maximilians University of Munich and the Max Planck Institute for Quantum Optics in Garching. After a first postdoc at Garching and a second one in chemical physics at the University of Heidelberg, Ketterle took his third at MIT.

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5. See links to PHYSICS TODAY coverage of BEC-related discoveries at http://www.physicstoday.org.

Isotopic Analysis of Pristine Microshells Resolves a Troubling Paradox of Paleoclimatology

In 1947, Harold Urey pointed out that the oxygen-isotope composition of fossil seashells could serve as a paleothermometer. The more ^{18}O a shell incorporated, he showed, the colder was the water in which it was formed. For decades now, the concentration of the heavy isotope ^{18}O in the microshells of foraminifera—single-celled marine animals—has been widely used to reconstruct the temperature profiles of ancient seas.

> If fossil isotopic data tell us that the tropical ocean was much cooler 50 million years ago than it is now, then either the data are flawed or we understand very little about global warming.

Since the mid-1980s, however, models of CO_2 greenhouse warming have confronted ^{18}O data from fossil planktonic (floating) foraminifera with the so-called "cool-tropics paradox." In stark defiance of the global climate models,[1] the planktonic ^{18}O data seemed to suggest that 50 million years ago, a time when the CO_2 level was almost certainly much higher than it is today and the Arctic was balmy enough for crocodiles and giant monitor lizards, tropical ocean surfaces were about 10°C *cooler* than they are now.

A new analysis of planktonic foraminifera from the late Cretaceous to the late Eocene (67–35 million years ago), by Paul Pearson (University of Bristol) and coworkers, does much to lay the troubling cool-tropics