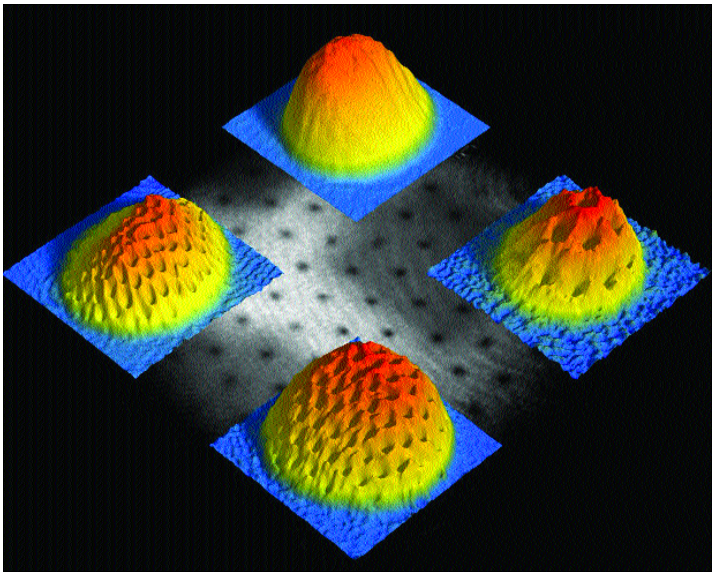
by Eric J. Lerner

A Sensor for Underground Tunnels?

In 1995, 35 years after lasers first produced coherent photons, physicists Eric A. Cornell and colleague Carl E. Wieman, and Wolfgang Ketterle, working independently, got atoms to do the same trick—"to march in lockstep," as Ketterle puts it. The new state of matter, a Bose-Einstein condensate (BEC), which does not exist in nature, consists of supercooled atoms all in the same quantum-mechanical state, with their wavefunctions in phase. For their achievement, Cornell of the National Institute of Standards and Technology (Boulder, CO), Wieman of the University of Colorado at Boulder, and Ketterle of the Massachusetts Institute of Technology (MIT) received the 2001 Nobel Prize in Physics (Figure 2).



MIT

Figure 1. When a Bose-Einstein condensate of sodium atoms about 60 µm in diameter is rotated with a laser beam, vortex lattices are "crystallized" in a triangular pattern (clockwise from top) with 0, 16, 70, and 130 vortices.

Although it is too early to say whether BECs will give rise to the same vast applications in technology that lasers have, it is probable that they will serve as the basis for instruments of unprecedented sensitivity. For example, gravitation sensors using BEC interferometers may provide geologists, archeologists, and engineers with a powerful new tool for seeing beneath Earth's surface; and BECs are already delivering new insights into the quantum effects that must be understood in fields such as nanotechnology and quantum computing.

Nature of BECs

The theoretical possibility of BECs was discovered in the early days of the development of quantum mechanics. Researchers learned that microscopic particles—atoms, nuclei, protons, neutrons, and electrons—have very different quantum-mechanical properties depending on their spin. If a particle's spin (angular momentum) is an integer times $h/2\pi$ (where h is Planck's constant), it has one set of behaviors; if its spin is a half-integer times $h/2\pi$, it has an entirely different set.

Enrico Fermi showed that some particles with half-integer spins, now known as fermions, cannot share the same quantum state—each one has to be in a unique state. It is this requirement that leads electrons, which are fermions, to stack up neatly around atoms in shells. A few years later fermions were shown to have half-integer spins. But the Indian physicist S. N. Bose, working with photons, had earlier shown that other particles, now termed bosons, could share the exact same state. In 1924, Einstein generalized Bose's work on photons to particles with mass. Einstein showed that if bosons moved slowly enough and were sufficiently close, they would condense into a single coherent state, the BEC. The bosons, researchers soon found, had integral spins and included the atoms of many isotopes.

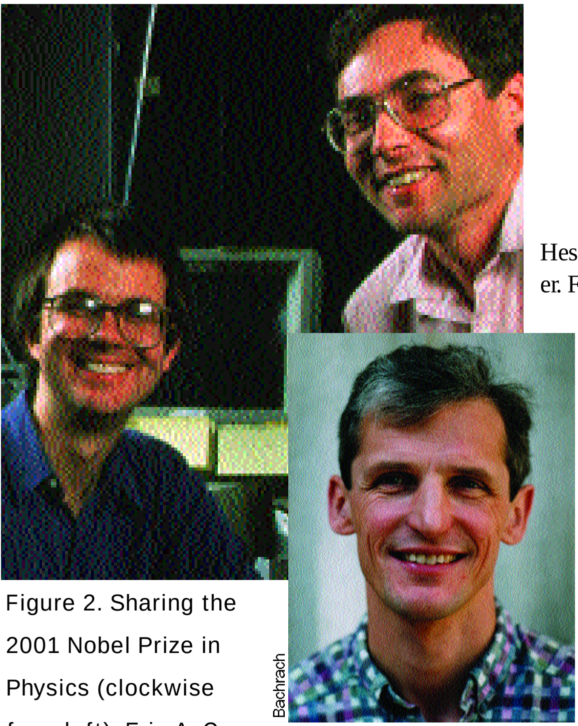
The difficulty in producing such a state is that the atoms or other bosons must be sufficiently close to each other that their quantum-mechanical wavefunctions overlap. Because the quantum wavelength increases as momentum decreases, this means that the atoms must be very cold, yet in a dense cloud. However, when atoms are cold and close together, they either condense into a liquid or solid, or join to form molecules. In either case, the atoms merge into larger and more complex entities, preventing their condensation into the Bose-Einstein state. Somehow, the atoms have to be kept separate as they cool.

So the trick is to cool the atoms to sufficiently low temperature so that their wavefunctions overlap but keep their densities low enough to prevent formation of molecules, liquids, or solids. In practice, this requires keeping the atoms about 200 nm apart from each other, a thousand times their diameters, and cooling to about 10^{-7} K.

Laser and magnetic cooling

How this year's Nobel laureates achieved this feat shows how new technology and applied research make possible the pursuit of basic research goals, which in turn leads to a new revolution in technology. Wieman led the development of tunable diode lasers, whose emitted frequency can vary over a wide range, without the size, complexity, and expense of dye lasers. "I initially started this research because I was fed up with using expensive dye lasers and wanted a better technique for tunable lasers," he recalls. "Having this new technology, I looked around for things that I could do with it and turned to laser cooling."

Laser cooling, first proposed in 1975 by T. W. Hänsch and A. L. Schawlow, potentially could chill atoms to extremely low temperatures. The idea is to tune a laser to the frequency that a particular atom will absorb when it is moving toward the laser at a specific velocity. Because of the Doppler shift, this frequency is different from that of



University of Colorado at Boulder, Office of News Services

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Figure 2. Sharing the 2001 Nobel Prize in Physics (clockwise from left): Eric A. Cornell, National Institute of Standards and Technology, Boulder, Colorado; Carl E. Wieman, University of Colorado at Boulder; and Wolfgang Ketterle, Massachusetts Institute of Technology.

atoms traveling in other directions or at other speeds. The photon's momentum slows the atom, and when it reemits the photon in a random direction, there is a net loss of momentum in the direction of the laser. With a three-dimensional array of tunable lasers, all velocities can be slowed as the moving atoms are closer to resonance with the lasers they are approaching than the motionless atoms are.

"Initially, I just wanted to see how far we could cool the atoms, but I realized that the achievement of a BEC was a reasonable goal," explains Wieman. In 1990, together with Cornell, Wieman began to use and further refine cooling and trapping techniques developed by Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips, for which they received the 1997 Nobel Prize in Physics, as well as D. E. Pritchard.

But laser cooling could not by itself achieve the low temperature needed for BECs. Wieman suggested that the atoms could be transferred to a purely magnetic trap and their cooling continued by an evaporative process in which the fastest atoms were selectively removed. This cooling technique was invented in the 1980s by Harald Hess, Tom Greytak, and Dan Kleppner. Following a suggestion by Pritchard, this was done by using a radio-frequency field that was tuned to excite atoms in the strongest part of the magnetic field—nearest the outside of the trap. Because these are the fastest-moving atoms, they are removed, leaving behind the coolest ones.

To implement these ideas, Wieman and Cornell used rubidium-87 atoms, while Ketterle, working along independent but parallel lines, decided on sodium. "We picked these atoms mainly because their absorption matched frequencies that happened to be emitted by the available tunable lasers," says Ketterle. "It was stroke of luck. Sodium and rubidium are ideal for BECs because they have the best balance between the 'good' collisions that are necessary for evaporative cooling and the 'bad' collisions that lead to heating and molecule formation. But we only learned about that later."

The final barrier to overcome was the tendency of atoms to be expelled from the center of the magnetic trap, where the field fell to zero. Here, atoms could flip their spin, and once the spins were flipped, the atoms would be expelled from the trap because the direction of their magnetic moment would simultaneously flip. To prevent this, Cornell developed a rapidly rotating magnetic field that moved the zero-field region away from the atoms. Ketterle solved the same problem by plugging the central region with a laser beam that prevented atoms from entering the zero-field region. In 1995, within a few months of each other, the Colorado and MIT groups achieved Bose-Einstein condensation.

Atomic-laser applications

Since 1995, research on BECs has grown rapidly and is done by dozens of research groups around the world. Ketterle showed that bunches of BEC atoms could be released from the trap, forming a rough beam that drifted downward under the influence of gravity. "BECs give us unprecedented control over atoms and an ideal way to study quantum phenomena," he says (Figure 1).

Perhaps the nearest-term applications lie in the field of measurement. "Just as lasers allowed huge advances in interferometers using light, BECs allow interferometric measurements using the far shorter wavelengths of atoms," Cornell points out. For example, a laser gyroscope, widely used in inertial navigation, allows the measurement of rotation by the interference of two beams of laser light that circulate in opposite directions in an optical fiber. A similar BEC interferometer, using a BEC circulating around a figure-eight track, could, in theory, be 10^{11} times as sensitive because the wavelength of moving BEC atoms can be much smaller than the wavelength of visible light.

"Such a sensor could detect extremely small gradients in gravitational fields," explains Cornell. "A mobile sensor could be used to detect geological formations, oil or ore deposits, or artificial structures such as tunnels or archeological sites." Many groups are now competing to put the entire BEC apparatus onto a chip. This is a practical near-term goal because the laser diodes and other equipment needed can be miniaturized. Cornell expects that such an instrument might be in use within six or seven years.

In the longer term, applications of this coherent state of matter are open-ended and unpredictable, as they were for lasers in the first years after their development. "We can also use BECs to study the sort of phenomena we need to know about in quantum computing and nanotechnology," Cornell says. For example, the process of quantum decoherence, in which outside influences cause the quantum state to "collapse" to a definite condition, is easy to observe in BECs and must be thoroughly quantified before quantum-computing devices could be practical. In all probability, however, the most important applications are those yet to be conceived, as was the case with lasers 35 years ago.