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NOBEL PRIZE IN PHYSICS: Laurels for a New Type of Matter

Charles Seife*

Three new laureates per prize--the maximum number Nobel rules allow--gain recognition for fundamental advances in their fields

Wolfgang Ketterle, Eric Cornell, and Carl Wieman have gotten a warm reception for their chilly work: They have won the 2001 Nobel Prize in physics for creating the first Bose-Einstein condensates (BECs) in gases of rubidium, sodium, and other alkali metals.

"It's very well deserved," says Claude Cohen-Tannoudji, a physicist at the École Normale

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Supérieure in Paris. "There [are] a lot of new directions being explored" because of BECs, he adds.



By cooling gases to a few billionths of a degree above absolute zero and coaxing them into forming a new state of matter, the three laureates verified a prediction made by Albert Einstein 70 years earlier. Einstein, in turn, took his cue from physicist S. N. Bose, who, in the mid-1920s, investigated the properties of particles that have integer spin--now termed "bosons." Bosons, which include certain atoms, behave differently from their opposite numbers, fermions, which have half-integer spins. Fermions tend to avoid one another; that is why you can fit only a certain number of electrons, which are fermions, into each atomic shell. Bosons, on the other hand, have no such restrictions, so many of them can occupy the same atomic state at the same time.





Matter masters. Wolfgang Ketterle (*top*); Eric Cornell and Carl Wieman (*bottom*, left to right).

CREDITS: (TOP TO BOTTOM) UNIVERSITY OF COLORADO, BOULDER, OFFICE OF NEWS SERVICES;EPA/PRB

Einstein claimed that when cooled enough, bosons in a gas would stop jittering about and settle down into the lowest energy state, or ground state. Thanks to their sociable nature, thousands of bosons could all be in the ground state, forming, in a sense, one large "superboson": a BEC. BECs are playgrounds for bizarre physics. You can manipulate a BEC to create a very fine interference pattern, slow light down to a crawl within it (*Science*, 27 July, p. [663](#)), or use it as an almost macroscopic testing ground for quantum mechanics. "We brought it to an almost human scale," says Wieman. "We can poke it and prod it and look at this stuff in a way no one has been able to before."

For decades, researchers tried to inveigle matter into becoming a BEC, without success. Then, in 1995, Cornell and Wieman, physicists at the University of Colorado, Boulder, used a combination of optical and magnetic trapping techniques to bully about 2000 cooled rubidium atoms into forming a BEC. Shortly thereafter, Wolfgang Ketterle of the Massachusetts Institute of Technology created a considerably bigger BEC cloud out of sodium atoms. Those achievements set off a flurry of experiments in which teams watched BECs interfere with themselves, used them to create "atomic lasers," and watched as vortices formed and dissipated within the BECs. Researchers have also added new atoms to the roster of BEC-producing gases, including isotopes of hydrogen, lithium, and most recently potassium (www.sciencemag.org). "We've been surprised to see the explosive growth of the field," Ketterle says. "We thought it would be neat, but it has had an enormous impact on atomic

physics."

The prize, split evenly among the three winners, comes as no surprise to the physics community. In 1997, Cohen-Tannoudji, along with physicists Steven Chu of Stanford University and William Phillips of the National Institute of Standards and Technology in Gaithersburg, Maryland, won the Nobel Prize in physics for developing the cooling techniques that enabled physicists to make BECs. That prize was widely seen as an early acknowledgment of the importance of BEC research. Now the other shoe has dropped, and the physicists who created the first BECs can bask in glory that is far more than cold comfort.

A special Web feature on this year's physics laureates, including research, news, and commentary from the pages of *Science*, can be found at www.sciencemag.org/feature/data/nobelprize/2001/physics.shtml.

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Science Celebrates the 2001 Nobel Physics Laureates

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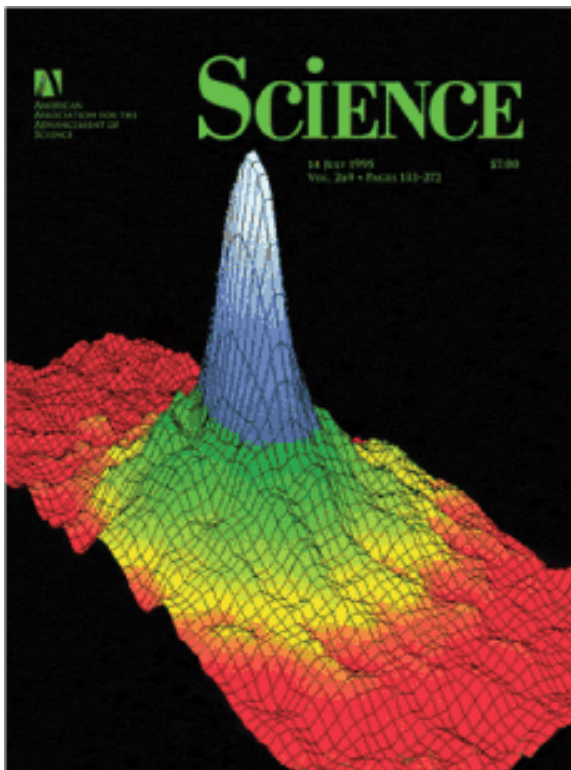
The 2001 Nobel Prize in Physics has been [awarded to Wolfgang Ketterle, Eric Cornell, and Carl Wieman](#), for their groundbreaking mid-1990s work in condensed-matter studies. Using revolutionary laser-cooling techniques pioneered by Stephen Chu, William Phillips, and Claude Cohen-Tannoudji (who themselves [shared the 1997 physics prize](#) for that work), the 2001 awardees were the first to succeed in cooling collections of bosonic particles such as rubidium and sodium atoms to the point where they share the same quantum state, and thereby behave as a single, giant particle. Achieving this weird state of matter, the existence of which was predicted by Satyendra Bose and Albert Einstein in the mid-1920s, had been a holy grail of physicists for seven decades. And the work of the three 2001 Nobel Laureates has catalyzed an amazing period of progress in condensed-matter physics.

Science is proud to have played a key role in this seminal pathway of intellectual development. Beginning with publication of the landmark first observation by Cornell and Wieman in the 14 July 1995, the journal has remained at the forefront of Bose-Einstein condensate studies and the many implications of this extreme state of matter -- from atom lasers to the first observations of Fermi degeneracy to the most recent studies in the weird behavior of BECs. To celebrate the accomplishment of the 2001 Nobel Physics Laureates, we present a roundup of some of the research papers in *Science* that have helped define this burgeoning field, coupled with news articles and Perspectives.

[Access note: Research articles and research reports that appeared more than 12 months ago are available free of charge (registration may be required). More recent research content, as well as news and Perspective articles, require a [subscription to Science Online](#).]

The Early Observations

In condensed-matter physics, it was the equivalent of the "shot heard 'round the world": The famous cover of the 14 July 1995 *Science* announced the isolation, by a group of scientists at the National Institute of Standards and Technology (NIST), of a Bose-Einstein condensate from a collection of supercooled rubidium atoms. Several months later, in a study published in *Physical Review Letters*, a separate group from the Massachusetts Institute of Technology reported the equally remarkable achievement of Bose-Einstein condensation in sodium atoms. As Elizabeth Culotta summed up in dubbing the Bose-Einstein condensate one of 1995's signal scientific accomplishments, the two discoveries ushered in "a new age of exploration in atomic and condensed-matter physics."



Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor

M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, E. A. Cornell

Science, v. 269, no. 5221 (1995), p. 198-201

[\[PDF\]](#) (1.6 MB)

[\[Fig. 1\]](#) (color image)

[\[Fig. 2\]](#) (color image)

News: Physicists Create New State of Matter

Gary Taubes

Science, v. 269, no. 5221 (1995), p. 152-153

[\[PDF\]](#) (0.6 MB)

Perspective: An Intimate Gathering of Bosons

Keith Burnett

Science, v. 269, no. 5221 (1995), p. 182-183

[\[PDF\]](#) (0.6 MB)

"Molecule of the Year": A New Form of Matter Unveiled

Elizabeth Culotta

Science, v. 270, no. 5244 (1995), p. 1902

[\[Full Text\]](#)

News: Bose-Einstein Condensates Display Their First Tricks

Gary Taubes

Science, v. 272, no. 5628 (1996), p. 1587-1588

[\[Summary\]](#) [\[PDF\]](#) (0.6 MB)

Direct, Nondestructive Observation of a Bose Condensate

M. R. Andrews, M.-O. Mewes, N. J. van Druten, D. S. Durfee, D. M. Kurn, W. Ketterle

Science, v. 273, no. 5271 (1996), p. 84-87

[\[Abstract\]](#) [\[PDF\]](#) (1.2 MB)

[\[Fig. 1\]](#) (color image)

[\[Fig. 3\]](#) (color image)

[\[Fig. 4\]](#) (grayscale image)

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Atom Lasers Make the Scene

It wasn't long after the achievement of Bose-Einstein condensation that physicists started putting the strange state of matter to work. Perhaps the most natural application was the development of "atom lasers" -- devices that exploit the in-phase properties of BECs to form coherent beams of atoms. Much of the pioneering work on these potentially revolutionary devices was executed by 2001 Nobel Laureate Wolfgang Ketterle and his group at MIT, and appeared in the pages of *Science*

Observation of Interference Between Two Bose Condensates

M. R. Andrews, C. G. Townsend, H.-J. Miesner, D. S. Durfee,
D. M. Kurn, W. Ketterle

Science, v. 275, no. 5300 (1997), p. 637-641

[\[Abstract\]](#) [\[Full Text\]](#)

News: First Atom Laser Shoots Pulses of Coherent Matter

Gary Taubes

Science, v. 275, no. 5300 (1997), p. 617-618

[\[Summary\]](#) [\[Full Text\]](#)

News: A New Recipe for Atom Condensates

Gary Taubes

Science, v. 275, no. 5300 (1997), p. 617

[\[Summary\]](#) [\[Full Text\]](#)

Bosonic Stimulation in the Formation of a Bose-Einstein Condensate

H.-J. Miesner, D. M. Stamper-Kurn, M. R. Andrews, D. S. Durfee, S. Inouye, and W. Ketterle

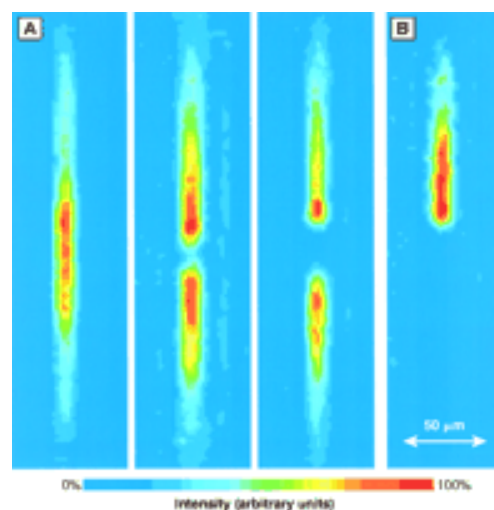
Science, v. 279, no. 5353 (1998), p. 1005-1007

[\[Abstract\]](#) [\[Full Text\]](#)

News: Atom Laser Shows That It Is Worthy of the Name

Alexander Hellemans

Science, v. 279, no. 5353 (1998), p. 986-987



[\[Summary\]](#) [\[Full Text\]](#)

Macroscopic Quantum Interference from Atomic Tunnel Arrays

B. P. Anderson and M. A. Kasevich

Science, v. 282, no. 5394 (1998), p. 1686-1689

[\[Abstract\]](#) [\[Full Text\]](#)

A Well-Collimated Quasi-Continuous Atom Laser

E. W. Hagley, L. Deng, M. Kozuma, J. Wen, K. Helmerson, S. L. Rolston, and W. D. Phillips

Science, v. 283, no. 5408 (1999), p. 1706-1709

[\[Abstract\]](#) [\[Full Text\]](#)

News: Atom Lasers Get More Laserlike

David Voss

Science, v. 283, no. 5408 (1999), p. 1611-1613

[\[Summary\]](#) [\[Full Text\]](#)

Superradiant Rayleigh Scattering from a Bose-Einstein Condensate

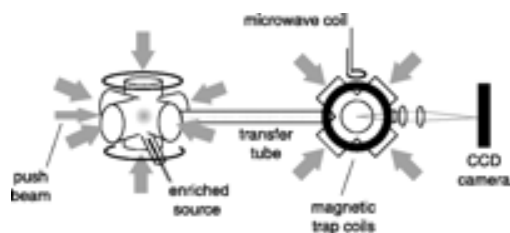
S. Inouye, A. P. Chikkatur, D. M. Stamper-Kurn, J. Stenger, D. E. Pritchard, and W. Ketterle

Science, v. 285, no. 5427 (1999), p. 571-574

[\[Abstract\]](#) [\[Full Text\]](#)

Fermions and Molecules

Another research pathway marked out after 1995 involved using the new techniques to explore odd quantum phases in other kinds of particles. Notable landmarks here included, in 1999, the accomplishment of a quantum degenerate state analogous to Bose-Einstein condensation in fermions -- particles, like electrons, neutrons, and protons, that obey Fermi-Dirac statistics rather than Bose-Einstein statistics -- and, in 2000, the assembly of actual molecules in the ultracold milieu of a rubidium Bose-Einstein condensate.



Onset of Fermi Degeneracy in a Trapped Atomic Gas

B. DeMarco and D. S. Jin

Science, v. 285, no. 5434 (1999), p. 1703-1706

[\[Abstract\]](#) [\[Full Text\]](#)

News: After Bosons, Physicists Tame the Rest of the Particle

Kingdom

David Voss

Science, v. 285, no. 5434 (1999), p. 1646-1647

[\[Summary\]](#) [\[Full Text\]](#)

Phase-Coherent Amplification of Matter Waves

Mikio Kozuma, Yoichi Suzuki, Yoshio Torii, Toshiaki Sugiura, Takahiro Kuga, E. W. Hagley, and L.

Deng

Science, v. 286, no. 5448 (1999), p. 2309-2312

[\[Abstract\]](#) [\[Full Text\]](#)

Molecules in a Bose-Einstein Condensate

Roahn Wynar, R. S. Freeland, D. J. Han, C. Ryu, and D. J. Heinzen

Science, v. 287, no. 5455 (2000), p. 1016-1019

[\[Abstract\]](#) [\[Full Text\]](#)

Perspective: Molecules at Rest

C. J. Williams and P. S. Julienne

Science, v. 287, no. 5455 (2000), p. 986-987

[\[Summary\]](#) [\[Full Text\]](#)

Observation of Fermi Pressure in a Gas of Trapped Atoms

Andrew G. Truscott, Kevin E. Strecker, William I. McAlexander, Guthrie B. Partridge, and Randall G. Hulet

Science, v. 291, no. 5513 (2001), p. 2570-2572 (published online March 1, 2001; 10.1126/science.1059318)

[\[Abstract\]](#) [\[Full Text\]](#)

New BEC Tricks: Squeezing, Superfluid Vortices, and Metastable States

One of the most interesting aspects of BECs is that, because they have, in a sense, the characteristics of a single large particle, they provide a window into the bizarre world of quantum mechanics. Some of the most interesting recent work on Bose-Einstein condensates has involved investigations that have pushed this already peculiar state of matter to new and different extremes: "squeezed" states that allow an end run around Heisenberg uncertainty; weird quantum "superfluids" with zero viscosity, in which lattices of vortices, initially set spinning by laser beams, twirl on, seemingly without end; and condensates of "metastable" helium, kicked up to an increased energy level -- "like a cloud of little flying sticks of dynamite," in the words of a recent [news article](#) by David Voss.

Squeezed States in a Bose-Einstein Condensate

C. Orzel, A. K. Tuchman, M. L. Fenselau, M. Yasuda, and M. A. Kasevich

Science, v. 291, no. 5512 (2001), p. 2386-2389

[\[Abstract\]](#) [\[Full Text\]](#)

Observation of Vortex Lattices in Bose-Einstein Condensates

J. R. Abo-Shaeer, C. Raman, J. M. Vogels, and W. Ketterle

Science, v. 292, no. 5516 (2001), p. 476-79 (published online March 22, 2001; 10.1126/science.1060182)

[\[Abstract\]](#) [\[Full Text\]](#)

A Bose-Einstein Condensate of Metastable Atoms

A. Robert, O. Sirjean, A. Browaeys, J. Poupard, S. Nowak, D. Boiron, C. I. Westbrook, and A. Aspect
Science, v. 292, no. 5516 (2001), p. 461-464 (published online March 22, 2001, 10.1126/science.1060622)

[\[Abstract\]](#) [\[Full Text\]](#)

News: Doing the Bose Nova With Your Main Squeeze

David Voss
Science, v. 291, no. 5512 (2001), p. 2301-2303

[\[Summary\]](#) [\[Full Text\]](#)

Perspective: A New Trick of the Trade

Massimo Inguscio
Science, v. 292, no. 5516 (2001), p. 452

[\[Summary\]](#) [\[Full Text\]](#)

Observation of Quantum Shock Waves Created with Ultra-Compressed Slow Light Pulses in a Bose-Einstein Condensate

Zachary Dutton, Michael Budde, Christopher Slowe, and Lene Vestergaard Hau
Science, v. 293, no. 5530 (2001), p. 663-668 (published online June 28, 2001, 10.1126/science.1062527)

[\[Abstract\]](#) [\[Full Text\]](#)

Josephson Junction Arrays with Bose-Einstein Condensates

F. S. Cataliotti, S. Burger, C. Fort, P. Maddaloni, F. Minardi, A. Trombettoni, A. Smerzi, and M. Inguscio
Science, v. 293, no. 5531 (2001), p. 843-846

[\[Abstract\]](#) [\[Full Text\]](#)

News: Quantum Condensate Gets a Fresh Squeeze

Charles Seife
Science, v. 293, no. 5539 (2001), p. 2368

[\[Summary\]](#) [\[Full Text\]](#)

