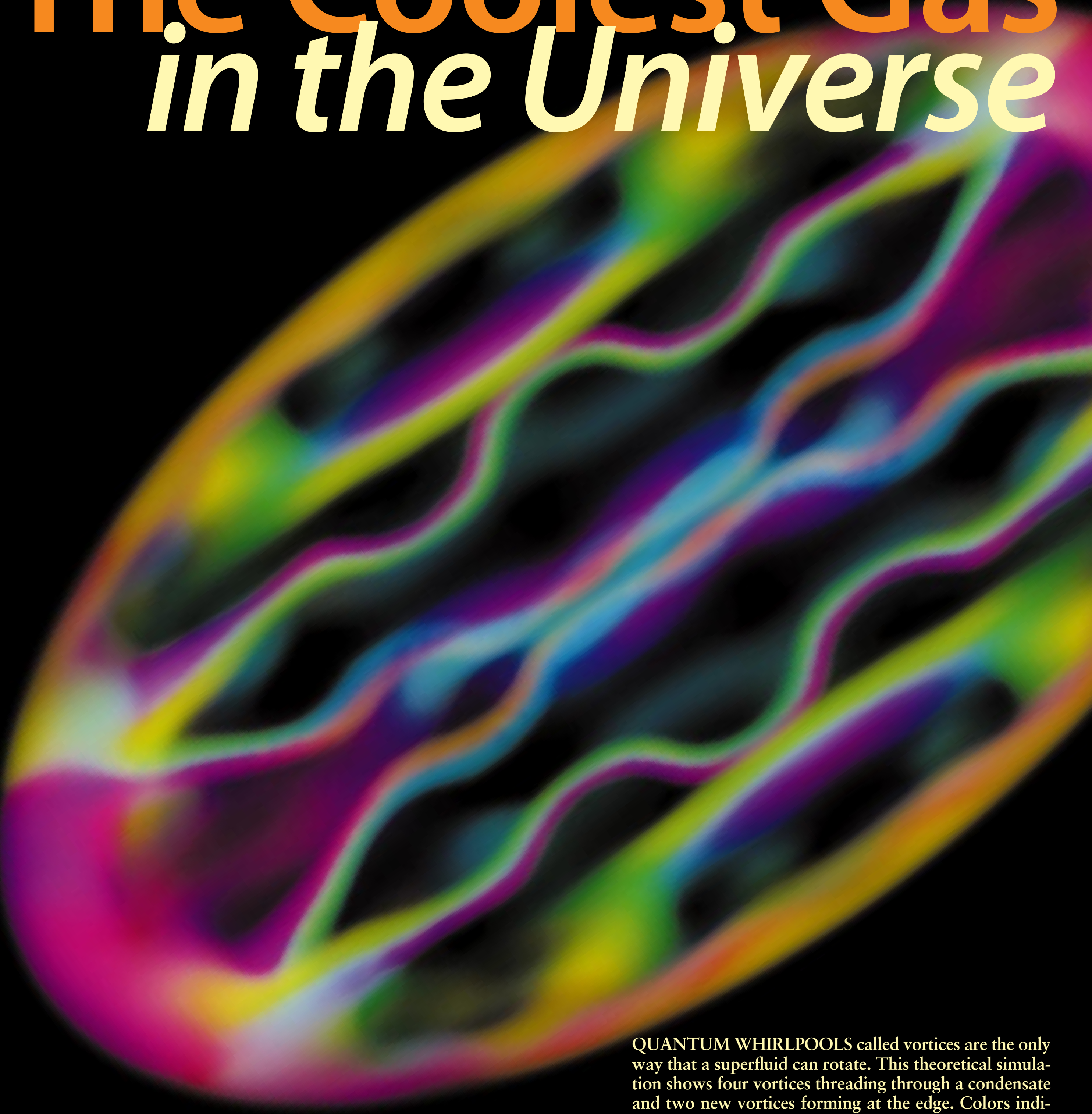
The Coolest Gas in the Universe



DAVID FEDER AND PETER KETCHAM *National Institute of Standards and Technology (NIST)*

QUANTUM WHIRLPOOLS called vortices are the only way that a superfluid can rotate. This theoretical simulation shows four vortices threading through a condensate and two new vortices forming at the edge. Colors indicate the quantum "phase" around each vortex.

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Bose-Einstein condensates are one of the hottest areas in experimental physics

by Graham P. Collins, *staff writer*

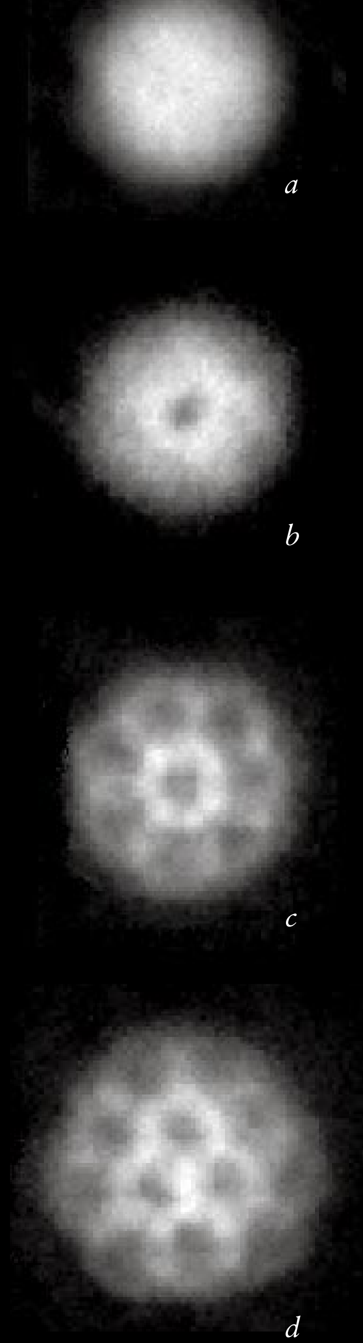
Imagine that you could magically shrink yourself down to the size of a large molecule and watch the motion of atoms in a gas. The atoms might appear to be unbreakable glass marbles, darting around an almost empty space before you, ricocheting off one another incessantly. You might nod to yourself, recognizing the scene from descriptions of an "ideal gas" from high school or college.

Now you notice that the marbles are flying around less frenetically than they were when you stepped out of the miniaturizer. Aha! Some process is cooling the gas down. At first the marbles merely lose speed and become somewhat less widely spaced; the density of the gas is rising as it cools. But then, contrary to expectation, you see that the marbles themselves are changing. The slowest-moving ones are growing thousands of times in size, and their formerly mirror-sharp surfaces have become indistinct. These increasingly wraithlike atoms pass through one another, sometimes without deflection, sometimes rebounding as if something hard inside collided.

Near the center of the region, two of the slowest, cloudiest atoms overlap and seem to merge, forming a single large globule. This ellipsoid absorbs other atoms in ones and twos and by the dozen, and with a startling suddenness only it remains, a huge motionless blimp. What has happened to all the individual atoms? What is this mysterious object?

It is a quantum-mechanical entity called a Bose-Einstein condensate (BEC), the coldest form of gas in the universe. And although the atoms still exist within it, composing it, they have lost their individuality.

Quantum mechanics rules the world. Most of the time the bizarre features of quantum mechanics are hidden behind a facade of classical physics. We mistake the facade for the substance of reality, and from it comes our com-



VORTEX LATTICES have been imaged in a stirred condensate of rubidium atoms. The condensate does not rotate (*a*) until the stirring is strong enough to generate a whole vortex (*b*), in which each atom has one quantum of angular momentum. Faster stirring increases the rotation by adding more vortices. The examples here have eight (*c*) and 12 (*d*). In the dark vortex cores, the rotation is fastest and the gas density is lowest.

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Cousins of BEC

Other Condensates

The condensates made in 1995 were not the first examples of Bose-Einstein condensation, but several properties distinguish them as uniquely pure examples of the phenomenon. To be precise, the new condensates are dilute, gaseous and made of atoms. Prior condensates and related systems include:

Superfluid helium. When liquid helium 4 is cooled below 2.2 kelvins, it takes on the astonishing property of superfluidity. The liquid flows totally without viscosity, enabling feats such as the helium fountain (*right*). The superfluid state occurs because a fraction (up to about 10 percent) of the helium atoms undergo Bose condensation. The strong interactions among the atoms in the liquid make it very hard to study the intrinsic quantum properties of the condensate fraction in detail, either in theory or experiment.

HELIUM FOUNTAIN, triggered by the heating coil, is a spectacular example of superfluidity. Up to one tenth of the helium atoms are in the form of a liquid Bose-Einstein condensate.

Lasers. Light from a laser shares many features of a Bose-Einstein condensate. Light is made up of wavelike particles called photons. In ordinary light, as from a lightbulb, the photons' waves are unsynchronized. In a laser, all the waves are "in phase," meaning that the crests and troughs are aligned; the photons march in lockstep, like soldiers on parade. That is, the photons are all in the same quantum state. The amplification process that produces a laser beam makes use of bosons' propensity to collect in the same quantum state.

Superconductors. Bose condensation of pairs of electrons generates superconductivity, the flow of electric current without resistance. Unpaired electrons cannot Bose-condense, because they are fermions, not bosons. Loosely bound pairs of electrons form only under certain conditions, such as in aluminum cooled to 1.2 kelvins. Such pairs *are* bosons, and they immediately Bose-condense. The pairing process and the electric charge of the pairs conspire to make superconductors a very different system from a neutral, dilute condensate. A similar pairing and condensation occurs in superfluid helium 3, whose atoms are fermions.

Excitons. In semiconductors, the absence of an electron can behave like a positively charged particle, called a hole. A hole and an electron, generated by a laser pulse, can pair up briefly as an entity called an exciton. In 1993 physicists observed evidence of such excitons forming a short-lived gaseous condensate in a copper oxide semiconductor. —*G.P.C.*

monsense understanding of how things work: objects have definite locations, motions and identities, and their behavior is rigidly prescribed by deterministic laws.

The very heart of quantum mechanics, in contrast, defies our everyday intuition. The locations and motions of particles are fundamentally equivocal and ruled by probabilities. Even the idea of objects having distinct identities is radically modified for quantum particles. A Bose-Einstein condensate is a collection of matter behaving in one of the purest quantum-mechanical fashions known.

What's more, condensates are huge—100,000 times larger than the biggest ordinary atoms, larger even than human cells—so physicists can watch the quantum behavior of a condensate in ways ordinarily unthinkable. As Steven L. Rolston of the National Institute of Standards and Technology (NIST) in Gaithersburg, Md., emphasizes, "The pictures we show of BECs are true pictures of quantum-mechanical wave functions—we can actually see quantum mechanics at work."

Gaseous Bose-Einstein condensates were first created in the laboratory in 1995, a full 70 years after the phenomenon was predicted by Albert Einstein based on work by Indian physicist Satyendra Nath Bose [see "The Bose-Einstein Condensate," by Eric A. Cornell and Carl E. Wieman; SCIENTIFIC AMERICAN, March 1998]. Experimenters create these condensates in atom traps—constructions of laser beams and magnetic fields that capture, hold and cool a very dilute cloud of atoms inside a vacuum chamber [*see box on page 97*]. The distinguished atomic physicist Daniel Kleppner of the Massachusetts Institute of Technology calls the creation of these condensates "the most exciting single development in atomic physics since the development of the laser."

Research groups around the world, some headed by Nobel laureates and laureates-to-be, have been working furiously for five years to explore the exotic realm opened up by that breakthrough. They have poked and prodded the condensates with laser beams, jiggled the traps that hold them, and watched as the gas has bounced, sloshed and vibrated in the expected quantum ways.

In addition to being exemplar quantum systems, condensates embody a curious amalgam of several broad fields of physics: atomic physics (individual atoms), quantum optics (laser beams and their interactions) and many-body physics (collections of matter that make up solids, liquids and gases, including the technologically vital realm of electrons flowing in metals and semiconductors). The study of condensates not only draws on all those fields in an interdisciplinary way, it contributes directly to our understanding of the basic laws that govern them.

This article can sample only a few of the amazing and diverse experimental achievements that physicists are obtaining with BECs. The results highlight some of the many faces that a condensate presents to experimenters: its behavior as a superfluid akin to liquid helium, as a finely controllable atomic gas and as a kind of laser beam made of matter instead of light.

BECs, Superfluids and Vortices

When liquid helium is cooled to within 2.2 kelvins of absolute zero, a number of strange things happen. As Soviet physicist Pyotr Kapitsa and Canadian John F. Allen discovered in 1938, below that temperature helium becomes a superfluid, flowing completely without viscosity and capable of

JOHN F. ALLEN *University of St. Andrews*; COURTESY OF RUSSELL DONNELLY *University of Oregon*

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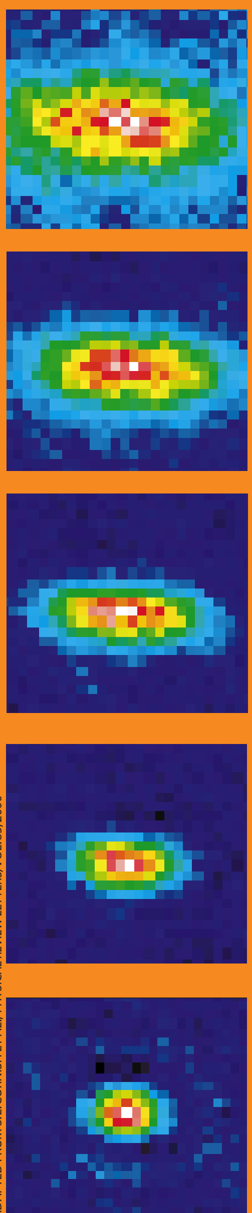
Physicists can modify the interactions in a condensate at will—an experimenter's dream



ADAPTED FROM S. L. CORNISH ET AL., *PHYSICAL REVIEW LETTERS*, VOL. 85; 2000

FORCES acting among the atoms of a condensate alter its size and proportions. Here researchers adjusted the forces from strongly repulsive (*top*) to almost zero strength (*bottom*). Tuning the forces further and making them weakly attractive caused the condensates to collapse and explode like miniature supernovae.

tricks such as slithering up the walls and out of an open container. Bose-Einstein condensation in the helium produces these effects [*see box on opposite page*].

Experimenters have been eager to see if the gaseous condensates could exhibit superfluidity, but doing so has not been a trivial task. Superfluid helium can be produced in large enough quantities for one to watch its tricks with the naked eye. The new condensates, in contrast, are minuscule wisps of gas barely more substantial than a vacuum, held in place by magnetic fields for a scant few minutes at best. What would it mean for such a gossamer vapor to be a superfluid?

A dramatic effect involves producing vortices in a rotating superfluid. If you rotate a bucket of ordinary liquid helium on a turntable, the helium rotates with the bucket, much as water would. Superfluid helium, in contrast, forms an array of quantum whirlpools called vortices. The minimum rotation allowed has a single vortex, spinning rapidly in the middle of the helium and slowly at the edges. If you try to rotate the superfluid more slowly, it will remain motionless.

These effects occur because the atoms in a condensate are in the same quantum state, and therefore all must have the same angular momentum. But angular momentum can exist only in discrete units, or quanta. In the motionless state the atoms all have zero angular momentum; in a vortex they each have one unit of it.

In 1999 a research group at JILA (formerly the Joint Institute for Laboratory Astrophysics) in Boulder, Colo., led by Carl E. Wieman and Eric A. Cornell produced vortices in BECs using a technique that their colleagues James E. Williams and Murray J. Holland had proposed. They started with a double condensate, a highly versatile system pioneered by the group involving two overlapping condensates made of the same element (rubidium) but in slightly different quantum states.

The researchers shone microwaves and a laser beam on the double condensate, with the effect of imprinting one condensate with the precise circular quantum phase required for a vortex. This process, which to anyone but a quantum physicist does not seem to be *moving* any of the atoms, produces the rotating vortex state. By looking at how the two condensates interfered with each other, the group was then able to verify the quantum phase properties of the vortex, something that had never been achieved so directly in 60 years of work on superfluid helium.

Later in 1999 a group at the École Normale Supérieure in Paris, led by Jean Dalibard, succeeded where previous efforts had failed in emulating the "rotating bucket" approach to generating vortices. To produce the rotation, Dalibard's team moved a laser beam around the edge of the trap, creating the semblance of a rotating distortion in its shape. These investigators have imaged arrays of up to 14 vortices. In a paper published this past September, they reported measuring the angular momentum of their condensates: in agreement with theory, the momentum is zero until the first vortex appears, at which point it jumps to one whole unit.

Beyond its interest as fundamental physics, the quantum dy-

Key Concepts

Quantum mechanics describes how nature works at the scale of atoms and has many features that are counterintuitive to our everyday experience. One feature of quantum mechanics is that particles have wavelike properties—the "wave function" of a particle defines its quantum state. Also, every elementary particle is intrinsically either a fermion or a boson.

Fermions behave claustrophobically—two fermions cannot occupy identical quantum states in the same location. Electrons, protons and neutrons are fermions. [See "Quantum Claustrophobia," News and Analysis, SCIENTIFIC AMERICAN, November 1999.]

Bosons behave gregariously. Bosons of a particular species tend to gather together in identical states if given the opportunity. Photons (particles of light) are bosons. Composite particles such as atoms are also either bosons or fermions. An atom made of an even number of protons, neutrons and electrons is a boson.

Bose-Einstein condensation (BEC) occurs when a collection of bosons of one species is made sufficiently cold and dense without locking together as a solid. Wave functions enlarge at extremely low temperatures, and when the bosons' wave functions overlap, all the bosons accumulate in one quantum state.

Behavior of BECs sheds light on the fundamentals of an assortment of subfields of physics. These include quantum mechanics, superfluidity, superconductivity, the properties and interactions of atoms, laser physics and nonlinear optics. *—G.P.C.*

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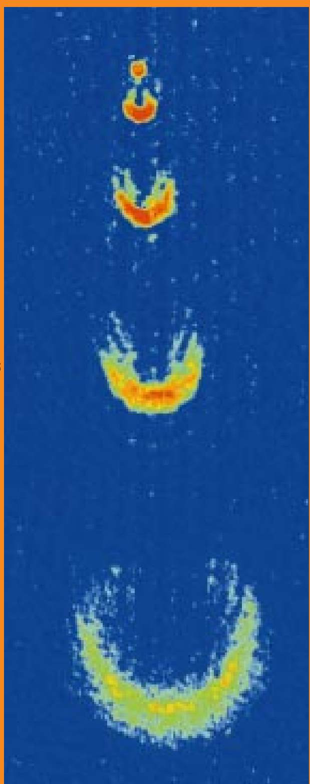
STEVEN L. ROLSTON *NIST*



DALLIN DURFEE AND MICHAEL ANDREWS *Massachusetts Institute of Technology*

ATOM LASERS are in essence moving condensates, material analogues of optical laser pulses or beams. The first atom laser (*left*) was "powered" by gravity. Pulsed radio waves hitting a trapped condensate (*circle at top*) released clumps of condensate (*crescents*). Repulsion between the sodium atoms produces the crescent shape and accelerates the crescents' expansion. In the first directed atom laser (*above*), atoms were propelled sideways out of the trap by laser beams.

namics of vortices is important for high-temperature superconductor technology: Magnetic fields penetrate these materials by creating an array of vortices of electric current in the material. The motion of such flux vortices dissipates power, spoiling the highly desirable "zero-resistance" property of superconductors. Studies of the BECs may help tame this problem.

Malleable Atomic Interactions

Vortices in superfluid helium have cores only a tenth of a nanometer in diameter, making them virtually impossible to examine in detail. The cores of the Colorado and Paris vortices are about 5,000 times larger, because compared with liquid helium the gaseous condensates have extremely low density and their atoms interact very weakly.

Essentially nothing can be done about liquid helium's density and interactions, but the density of gaseous BECs can be adjusted by tightening or loosening the magnetic traps that hold the gas. In addition, physicists have the remarkable ability to modify the interactions in the gaseous BECs at the turn of a dial. Such an ability is an experimenter's dream—imagine how chemistry could be studied if we could weaken or strengthen the bonds between atoms at will.

The atoms in a gaseous condensate experience a small mutual repulsion or attraction, depending on their species. For example, atoms of sodium, rubidium 87 and hydrogen repel their own kind. Lithium 7 and rubidium 85 atoms attract. These forces, though tiny, modify innumerable properties of a condensate, such as its internal energy, its size, its modes of oscillation and its rate of formation. Most important, a repulsion stabilizes a condensate, whereas an attraction is destabilizing. Consequently, experiments using repulsive rubidium 87 or sodium routinely condense millions of atoms at a time, and the condensates can be 20 times larger than they would be in the absence of the repulsion. Conversely, the attraction limits lithium 7 condensates produced by Randall G. Hulet's group at Rice University to about 1,500 atoms. Above that size, the condensate contracts and becomes too dense, triggering collisions that spill atoms out of the trap. These results are now well understood by sophisticated theoretical modeling, but as recently as the early 1990s physicists doubted that attractive atoms could form a condensate at all.

The atoms' interactions can be modified by so-called Feshbach resonances, named after nuclear theorist Herman Feshbach of M.I.T., who studied an analogous phenomenon in colliding nuclei in the 1960s. In a gas, a strong magnetic field distorts the atoms and at certain strengths causes two atoms to resonate when they collide. In a condensate the atoms continuously feel the effects of these resonances because their quantum waves overlap; the resonances modify the forces between the atoms, with the largest effects occurring near the resonant magnetic-field strength.

One difficulty is that a strong magnetic field can ruin the magnetic trapping of the atoms. Wolfgang Ketterle's group at M.I.T. solved that problem in 1998 by transferring sodium condensates from a magnetic trap to a laser-based one. But although the M.I.T. group was able to observe the effects of Feshbach resonances, extended studies were impossible: to the researchers' great surprise, when the magnetic fields were tuned close to a resonance, the sodium condensates disintegrated within microseconds.

Long-lived condensates with tunable interactions were developed earlier this year by Cornell and Wieman's group, us-

A laser knocks atoms out of the trap through the "circle of death"

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ing rubidium 85 and a conventional magnetic trap. Ordinarily, rubidium 85's attractive interactions prevent its condensate from growing beyond a measly 80 atoms. But by using Feshbach resonances to switch these forces to be repulsive, the Colorado group achieved stable condensates of up to 10,000 atoms with lifetimes as long as 10 seconds.

The most spectacular effects occurred when the group gradually decreased the artificial repulsion. As predicted by theory, the giant condensates shrank smoothly in size and became dense. Finally, about five milliseconds after the interactions crossed back to attractive, the condensates exploded—a phenomenon that Wieman has whimsically dubbed a "Bose nova," by loose analogy with the implosion that fuels exploding stars. The explosions blasted perhaps a third of the condensate atoms completely out of the trap, leaving behind a remnant condensate surrounded by a hot cloud of atoms (if a temperature of 100 billionths of a degree can be called "hot").

Atom Lasers

A possible application of the interaction tuning is the delicate control of beams of atoms emitted from condensates. Such beams are known as atom lasers. Atomic beams are already used in a variety of scientific and industrial applications, including atomic clocks, precision measurements of fundamental constants and production of computer chips. But all those beams lack the brightness and "coherence" of an atom laser, just as ordinary light lacks the brightness and coherence (and thus the versatility) of a laser beam. (Coherence means that all the atoms or photons in the beam move in a kind of quantum synchrony, with their associated waves closely aligned.)

It took the laser decades to go from being an esoteric experimental device in 1960 to an almost ubiquitous element of consumer electronics. Some researchers suggest that in the decades to come, atom lasers could have an equally fruitful future, in ways as inconceivable now as today's uses of lasers were in the 1960s. Major obstacles lie in the path of this prophecy, of course, not least being the need to send atom beams through a vacuum instead of through air.

The earliest atom lasers generated their pulses and beams in a fashion completely unlike optical lasers (prompting some to insist that atom "laser" was a misnomer). In essence, an atom laser is any coherent, freely moving lump or stream of BEC. The atoms of a BEC are confined in a magnetic trap by their own tiny magnetic dipole, or spin. Correctly tuned radio waves will flip the spins of atoms and make them immune to the trapping fields. Ketterle's group took advantage of this effect in 1997 to create the first atom laser. They pelted a sodium condensate with pulses of radio waves. Atoms whose spins had been flipped dropped out of the trap—crescent-

Machines for Cooling and Trapping Atoms

Quantum Coolers

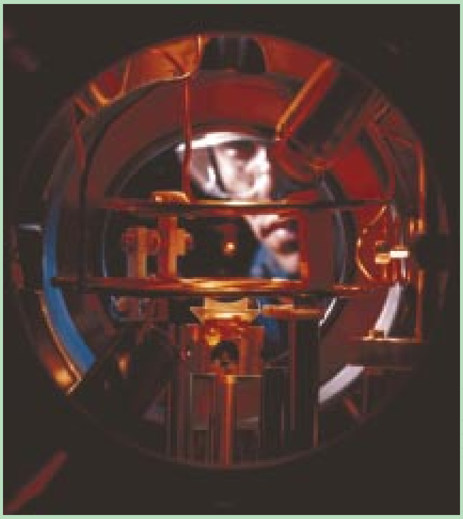
Laser cooling. To create a gaseous Bose-Einstein condensate, experimenters must cool a dilute gas of atoms in a vacuum chamber to an extremely low temperature. The first step in almost all the experiments is laser cooling, in which laser beams slow down the motion of atoms, cooling them from perhaps room temperature (300 kelvins) or much higher to about 50 microkelvins—one twenty-thousandth of a degree above absolute zero.

Magneto-optical trap (MOT). The most common precooling device used in BEC experiments is the magneto-optical trap, which combines laser cooling with trapping of the atoms by magnetic fields. The magnetic fields help to compress the gas to a higher density. Many groups use a sequence of two MOTs, optimized respectively for collecting atoms and then for cooling them.

Evaporative cooling. The final cooling stage in BEC experiments is analogous to the cooling of a cup of coffee. While a magnetic trap holds the atoms, the hottest fraction of atoms is continuously removed, so that increasingly lower-temperature gas remains. Unlike laser cooling, evaporative cooling works best at higher densities.

TOP trap. Used by the group of Eric A. Cornell and Carl E. Wieman at JILA to create the first gaseous atomic condensate in 1995, the time-averaged orbiting potential magnetic trap has been adopted by several groups. Its coils produce a magnetic field that has a zero point from which atoms can leak. By moving the field rapidly around in a circle, the trap confines the atoms in an ellipsoidal region inside the orbit of the leak (the "circle of death").

Ioffe-Pritchard (IP) traps. Named after Russian physicist M. S. Ioffe (whose Ioffe trap was for trapping plasmas of charged ions) and David Pritchard of M.I.T., Ioffe-Pritchard traps produce a trapping field without a leaky zero point. They are the main alternative to TOP traps and come in a diverse array of designs, with condensates ranging from nearly spherical to long cigar shapes. Their magnetic fields are produced by running current through four parallel bars or through coils shaped like letter D's, the seams of a baseball or four-leaf clovers.


STEVEN L. ROLSTON *NIST*

GLOWING SODIUM ATOMS are held in a magneto-optical trap and watched by Kristian Helmerson of the National Institute of Standards and Technology. Coils produce a magnetic field, and laser beams enter from six directions, holding and cooling the atoms.

Permanent magnet trap. This style of IP trap employs permanent magnets to produce the fields. Randall G. Hulet's group at Rice University uses it to produce condensates in lithium. The permanent magnets cannot be turned off, so the condensate can only be imaged in situ. *—G.P.C.*

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shaped pulses of moving condensate propelled by gravity!

In late 1998 Theodore Hänsch's group at the University of Munich demonstrated a similar system that emitted a continuous beam of rubidium atoms. The Munich group estimated that its atomic beam was more than a million times brighter than similar (but nonlaser) beams of atoms produced by other techniques. Around the same time, William D. Phillips, Steven Rolston and their co-workers at NIST finally produced an atom laser that could be pointed in a direction other than down. Optical-laser pulses knocked atoms out of the condensate and through a circulating hole on the outskirts of their trap (a location known as the circle of death). A sequence of laser pulses carefully synchronized with the circle of death produced a finely collimated, essentially continuous beam—described in one report as "an atomic ray gun with laserlike precision," which sounds like hyperbole but is technically factual.

The "a" in "LASER" stands for "amplification," but in the atom lasers described so far, the only amplification to speak of occurs in the initial creation of the BEC, when the population of atoms in the single quantum state is "amplified" by Bose condensation. Amplification of atom-laser beams, also known as matter-wave amplification, was only achieved in late 1999, by an M.I.T. group led by Ketterle and Pritchard and, independently, by Takahiro Kuga and his co-workers at the University of Tokyo.

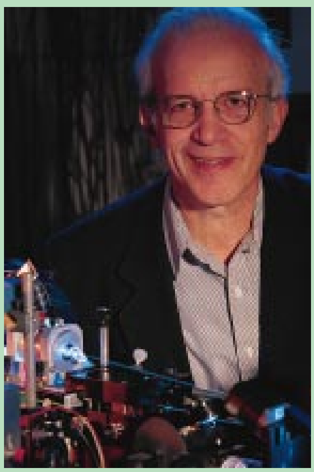
Matter-wave amplification does not mean that matter is created out of energy by the amplifier. Rather a small atom-laser pulse is created in a BEC, and that pulse is amplified

Hydrogen Man

The Godfather of BEC

In the year or two after the creation of BEC, Daniel Kleppner of M.I.T. would be introduced at conferences as "the godfather of BEC." He couldn't be "the father of BEC," after all, because his own group, distressingly, still hadn't produced a condensate. And yet he loomed paternally over the field as both pioneer and continuing participant and as a mentor to the young upstarts who had seized the grail as their own.

The three groups that first demonstrated BECs in 1995 and 1996 were led by Kleppner's students and "grandstudents." Wieman worked in his laboratory as an undergraduate in the early 1970s. Cornell was a graduate student of Pritchard's, who in turn was a graduate student of Kleppner's. Ketterle first worked on cold atoms as a postdoc of Pritchard's. Hulet was a grad student in Kleppner's group, as was Nobel laureate Phillips, whose group made a BEC in 1998. Like any teacher, Kleppner takes great pride in his students' accomplishments. "But they can overdo it," he quips.



DANIEL KLEPPNER began pursuing Bose-Einstein condensation in hydrogen back in 1976, racing against a Dutch group: "It took a little longer than any of us expected."

When his former students were making their spectacular condensates of rubidium, sodium and lithium (alkali atoms), Kleppner was battling with his career-long atom of choice: hydrogen. He has been studying hydrogen since he was a graduate student and postdoc at Harvard University in the late 1950s. Working there with Norman Ramsey, Kleppner helped to invent the hydrogen maser, a kind of laser operating at microwave frequencies that has seen applications in extremely precise measurements, including tests of Einstein's general relativity. (The maser was among the work cited when Ramsey won the Nobel Prize in 1989.) In 1966 Kleppner moved across town from Harvard to M.I.T., where he is now acting director of the Research Laboratory of Electronics.

Kleppner got into the Bose-Einstein game around 1976, working with a form of hydrogen called spin-polarized. "I thought the idea was nutty," Kleppner recalls, but a young professor named Thomas Greytak persuaded him of its merits. They have worked together ever since.

In spin-polarized hydrogen, all the atoms have their spins aligned the same way (think of the spin as a tiny magnetic compass needle that each atom carries around). Such a gas is as inert as helium because two hydrogen atoms must have oppositely aligned spins to form a molecule. Alone among all the elements, this form of hydrogen should remain a gas all the way down to absolute zero.

Inspired by these predicted properties, in the late 1970s Kleppner and Greytak at M.I.T. and competitors at the University of Amsterdam began work to create a BEC in spin-polarized hydrogen, never dreaming how long the quest would take or that condensates in *metallic* atoms, of all things, would beat them to the punch.

Although it wasn't first to the prize, Kleppner's group made several key advances on the road to BEC, such as demonstrating evaporative cooling in spin-polarized hydrogen in 1987, a feat that the alkali-atom groups only duplicated seven years later. By 1991 the Kleppner-Greytak group had pushed to within a factor of three of the temperature and density needed for a condensate (alkali atoms were about a factor of a million behind). Alas, some perverse properties of hydrogen threw up roadblocks at this point, including difficulties in observing key properties of the gas to confirm creation of a condensate. In the alkali-atom gases, visible light and standard laser techniques can be used. The corresponding light for hydrogen is ultraviolet and requires a more sophisticated approach.

Finally, in June 1998, Kleppner received a late-night phone call from two of his current students to come into the lab. A Bose-Einstein condensate in hydrogen had been observed at last! A month later, at a conference in Varenna, Italy, Kleppner announced his group's success. The assembled experts—colleagues, competitors and former students—gave the proud new parent a long standing ovation. *—G.P.C.*

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when additional BEC atoms follow their Bose nature and join it. Concurrent scattering of light from a pump laser beam ensures that momentum and energy are properly conserved.

The M.I.T. group realized that matter-wave amplification by this process was possible when, earlier in 1999, they hit one of their cigar-shaped condensates with a polarized laser beam and were startled to see clumps of atoms emerging at 45 degrees and light beaming out of each end of the "cigar." The process was a form of scattering called superradiance that involved rudimentary amplification.

These processes amount to condensates acting in their most lightlike manner, in sharp contrast to their liquid behavior as superfluids. A tremendously active field in optics over the past decade has been nonlinear optics, involving the interactions of light with itself. Nonlinear effects are increasingly important, for example, in optical fibers operating at the highest data rates.

Normally, light barely interacts with itself, so high intensities or special media are needed to achieve these nonlinear effects. The weak interactions of atoms in condensates automatically produce nonlinear effects, which makes them ideal for studying such processes. The simple classical notion of atoms as particles colliding like tiny marbles utterly fails to account for the observed results of these experiments.

CHRIS H. GREENE *University of Colorado at Boulder*

"TRILOBITE MOLECULE" of two rubidium atoms, 1,000 times larger than a typical diatomic molecule, could be formed within a condensate by appropriate laser excitation. Gold curves indicate the density of the calculated electron cloud forming the bond. The green ball is one atom; the other is obscured under the "twin towers." Groups have produced more ordinary ultracold molecules in condensates by similar laser techniques but have not yet demonstrated a condensate of molecules.

Ersatz Black Holes?

One feat of nonlinear optics is to slow light down to a stunning degree. In a vacuum, electromagnetic waves—including radio, x-ray and light waves—travel at the ultimate speed limit: 300,000 kilometers (186,000 miles) per second. Light zips along less swiftly in a medium, moving at about three fourths of its top speed in water and two thirds in a typical glass. In 1999, by shining a beam through an ultracold and optically modified gas, Lene Vestergard Hau of the Rowland Institute for Science in Cambridge, Mass., slowed light down to 17 meters per second, the pace of a speedy bicycle. In a November paper, Ketterle's group reported observing light traveling at one meter per second through a condensate, a walking pace. One does not need a condensate to produce such effects, but the intense cold of condensate gases has features that are ideal for inducing the most extreme examples.

Sound waves near vortices might mimic black hole phenomena

Intriguingly, Ulf Leonhardt and Paul Piwnicki of the Royal Institute of Technology in Stockholm suggested in 1999 that slow light propagating near a vortex in a condensate might serve as a tabletop analogue for processes near rotating black holes. For example, the light could be dragged into the core of a vortex, particularly if the beam was moving "upstream" against the rotational flow.

In unpublished papers Peter Zoller, Ignacio Cirac and their co-workers at the University of Innsbruck in Austria show that with current state-of-the-art technology, it should be possible to build *sonic* models of black holes—that is, ersatz black holes in which sound waves take the place of light. Their calculations indicate that such black holes would explode in a burst of phonons, the quanta of sound waves. Such explosions might be analogous to the evaporation of microscopic gravitational black holes via Hawking radiation, a thermal mix of particles predicted to emerge as a result of quantum effects.

In an August paper, Wayne Hu and his co-workers at Princeton University speculate that the unseen "dark matter" that makes up perhaps 90 percent of the universe could exist in the form of a Bose-Einstein condensate of exceedingly low mass particles permeating space. Such a condensate form of dark matter might, they suggest, solve some problems that dog the otherwise quite successful "cold dark matter" cosmology theories. If that remarkable hypothesis is true, the coolest gases in the universe may also turn out to be the most abundant. SA

Further Information

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BOSE-EINSTEIN CONDENSATION HOMEPAGE at Georgia Southern University is at http://amo.phy.gasou.edu/bec.html

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