The Bose-Einstein Condensate

Three years ago in a Colorado laboratory, scientists realized a long-standing dream, bringing the quantum world closer to the one of everyday experience

by Eric A. Cornell and Carl E. Wieman

In June 1995 our research group at the Joint Institute for Laboratory Astrophysics (now called JILA) in Boulder, Colo., succeeded in creating a minuscule but marvelous droplet. By cooling 2,000 rubidium atoms to a temperature less than 100 billionths of a degree above absolute zero (100 billionths of a degree kelvin), we caused the atoms to lose for a full 10 seconds their individual identities and behave as though they were a single "superatom." The atoms' physical properties, such as their motions, became identical to one another. This Bose-Einstein condensate (BEC), the first observed in a gas, can be thought of as the matter counterpart of the laser—except that in the condensate it is atoms, rather than photons, that dance in perfect unison.

Our short-lived, gelid sample was the experimental realization of a theoretical construct that has intrigued scientists ever since it was predicted some 73 years ago by the work of physicists Albert Einstein and Satyendra Nath Bose. At ordinary temperatures, the atoms of a gas are scattered throughout the container holding them. Some have high energies (high speeds); others have low ones. Expanding on Bose's work, Einstein showed that if a sample of atoms were cooled sufficiently, a large fraction of them would settle into the single lowest possible energy state in the container. In mathematical terms, their individual wave equations—which describe such physical characteristics of an atom as its position and velocity—would in effect merge, and each atom would become indistinguishable from any other.

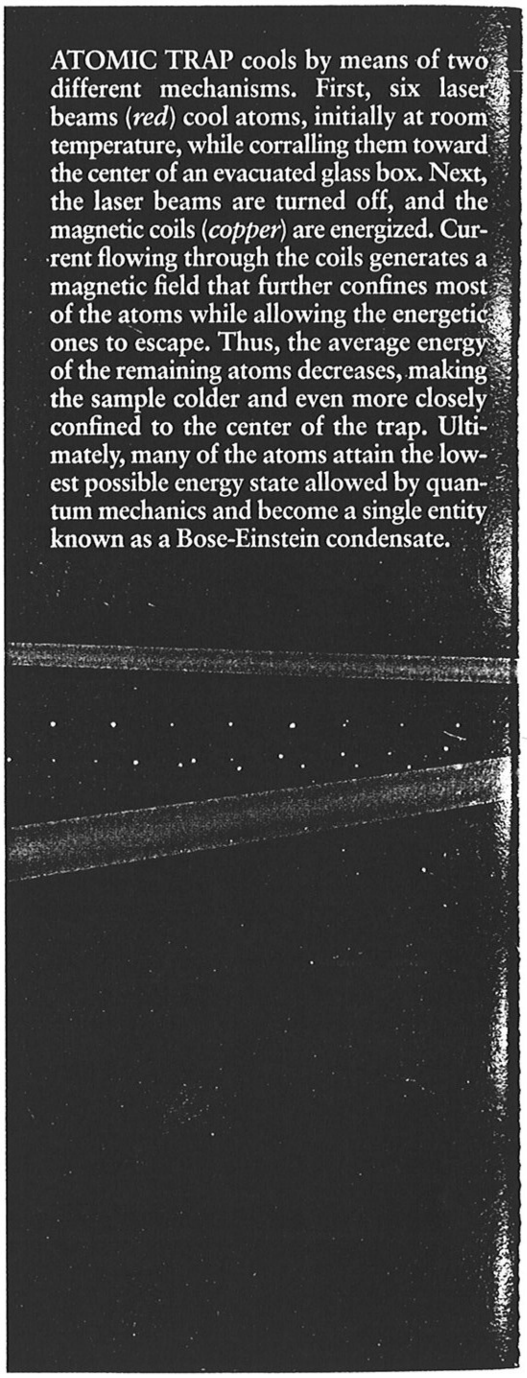
Progress in creating Bose-Einstein condensates has sparked great interest in the physics community and has even generated coverage in the mainstream press. At first, some of the attention derived from the drama inherent in the decades-long quest to prove Einstein's theory. But most of the fascination now stems from the fact that the condensate offers a macroscopic window into the strange world of quantum mechanics, the theory of matter based on the observation that elementary particles, such as electrons, have wave properties. Quantum mechanics, which encompasses the famous Heisenberg uncertainty principle, uses these wavelike properties to describe the structure and interactions of matter.

We can rarely observe the effects of quantum mechanics in the behavior of a macroscopic amount of material. In ordinary, so-called bulk matter, the incoherent contributions of the uncountably large number of constituent particles obscure the wave nature of quantum mechanics, and we can only infer its effects. But in Bose condensation, the wave nature of each atom is precisely in phase with that of every other. Quantum-mechanical waves extend across the sample of condensate and can be observed with the naked eye. The submicroscopic thus becomes macroscopic.

New Light on Old Paradoxes

The creation of Bose-Einstein condensates has cast new light on long-standing paradoxes of quantum mechanics. For example, if two or more atoms are in a single quantum-mechanical state, as they are in a condensate, it is fundamentally impossible to distinguish them by any measurement. The two atoms occupy the same volume of space, move at the identical speed, scatter light of the same color and so on.

Nothing in our experience, based as it is on familiarity with matter at normal temperatures, helps us comprehend this paradox. That is because at normal temperatures and at the size scales we are all familiar with, it is possible to de-



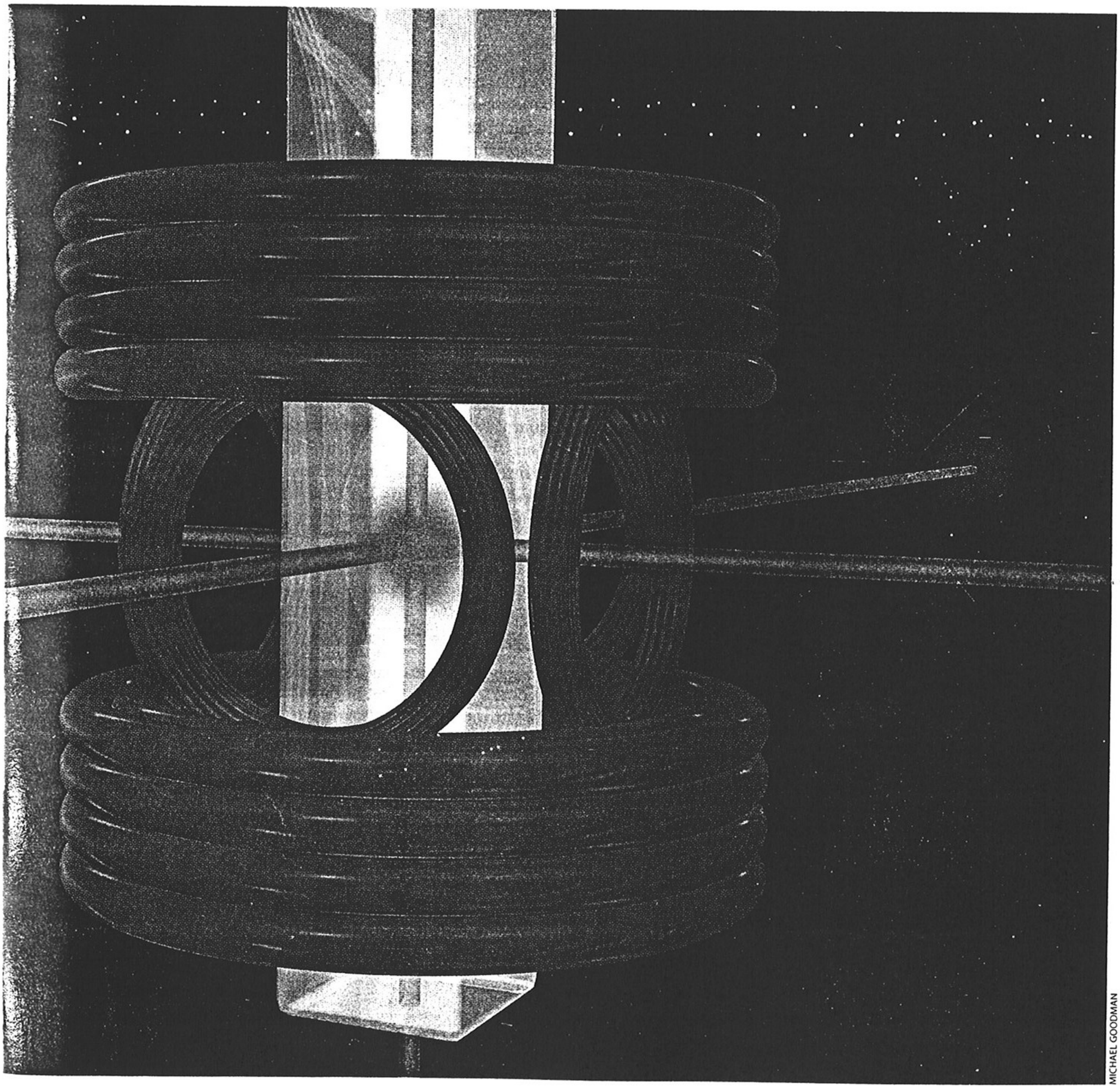
ATOMIC TRAP cools by means of two different mechanisms. First, six laser beams (*red*) cool atoms, initially at room temperature, while corralling them toward the center of an evacuated glass box. Next, the laser beams are turned off, and the magnetic coils (*copper*) are energized. Current flowing through the coils generates a magnetic field that further confines most of the atoms while allowing the energetic ones to escape. Thus, the average energy of the remaining atoms decreases, making the sample colder and even more closely confined to the center of the trap. Ultimately, many of the atoms attain the lowest possible energy state allowed by quantum mechanics and become a single entity known as a Bose-Einstein condensate.

scribe the position and motion of each and every object in a collection of objects. The numbered Ping-Pong balls bouncing in a rotating drum used to select lottery numbers exemplify the motions describable by classical mechanics.

At extremely low temperatures or at small size scales, on the other hand, the usefulness of classical mechanics begins to wane. The crisp analogy of atoms as Ping-Pong balls begins to blur. We cannot know the exact position of each atom, which is better thought of as a blurry spot. This spot—known as a wave packet—is the region of space in which we can expect to find the atom. As a collection of atoms becomes colder, the size of each wave packet grows. As long as each wave packet is spatially separated from the others, it is possible, at least in principle, to tell atoms apart. When the temperature becomes sufficiently low, however, each atom's wave packet begins to overlap with those of neighboring atoms. When this happens, the atoms "Bose-condense" into the lowest possible energy state, and the wave packets coalesce into a single, macroscopic packet. The atoms undergo a quantum identity crisis: we can no longer distinguish one atom from another.

The current excitement over these condensates contrasts sharply with the reaction to Einstein's discovery in 1925 that they could exist. Perhaps because of the impossibility then of reaching the required temperatures—less than a millionth of a degree kelvin—the hypothesized gaseous condensate was considered a curiosity of questionable validity and little physical significance. For perspective, even the coldest depths of intergalactic space are millions of times too hot for Bose condensation.

In the intervening decades, however,



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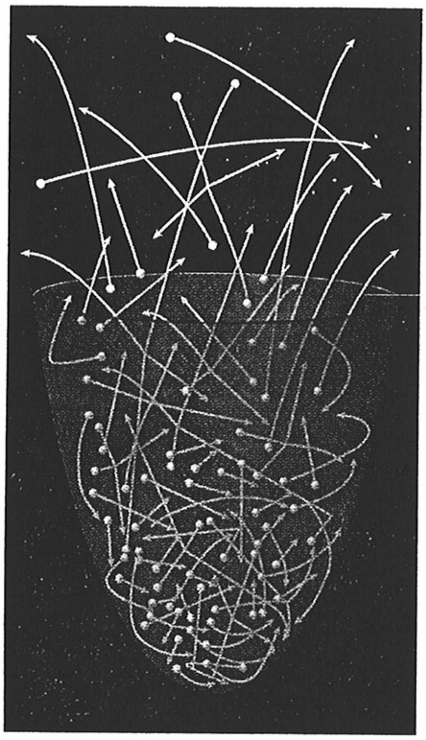
Bose condensation came back into fashion. Physicists realized that the concept could explain superfluidity in liquid helium, which occurs at much higher temperatures than gaseous Bose condensation. Below 2.2 kelvins, the viscosity of liquid helium completely disappears—putting the "super" in superfluidity.

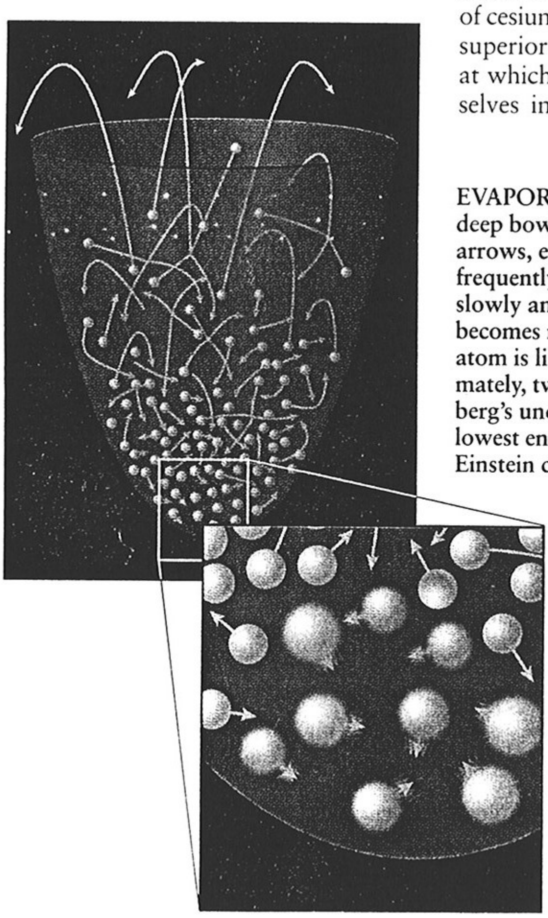
Not until the late 1970s did refrigeration technology advance to the point that physicists could entertain the notion of creating something like Einstein's original concept of a BEC in a gas. Laboratory workers at M.I.T., the University of Amsterdam, the University of British Columbia and Cornell University had to confront a fundamental difficulty. To achieve such a BEC, they had to cool the gas to far below the temperature at which the atoms would normally freeze into a solid. In other words, they had to create a supersaturated gas. Their expectation was that hydrogen would supersaturate, because the gas was known to resist the atom-by-atom clumping that precedes bulk freezing.

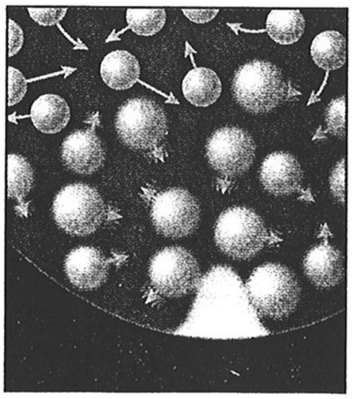
Although these investigators have not yet succeeded in creating a Bose-Einstein condensate with hydrogen, they did develop a much better understanding of the difficulties and found clever approaches for attacking them, which benefited us. In 1989, inspired by the hydrogen work and encouraged by our own research on the use of lasers to trap and cool alkali atoms, we began to suspect that these atoms, which include cesium, rubidium and sodium, would make much better candidates than hydrogen for producing a Bose condensate. Although the clumping properties of cesium, rubidium and sodium are not superior to those of hydrogen, the rate at which those atoms transform themselves into condensate is much faster than the rate for hydrogen atoms. These much larger atoms bounce off one another at much higher rates, sharing energy among themselves more quickly, which allows the condensate to form before clumping can occur.

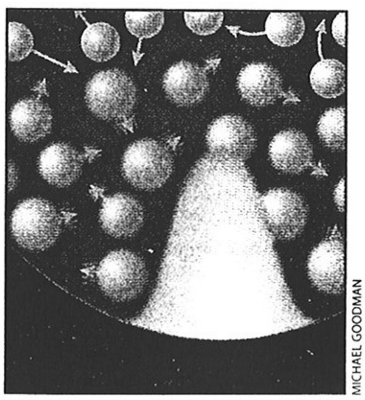
Also, it looked as if it might be relatively easy and inexpensive to get these atoms very cold by combining ingenious techniques developed for laser cooling and trapping of alkali atoms with the techniques for magnetic trapping and evaporative cooling developed by the researchers working with hydrogen. These ideas were developed in a series of discussions with our friend and former teacher, Daniel Kleppner, the co-leader of a group at M.I.T. that is attempting to create a condensate with hydrogen.

Our hypothesis about alkali atoms was ultimately fruitful. Just a few months after we succeeded with rubidium, Wolfgang Ketterle's group at M.I.T. produced a Bose condensate with sodium atoms; since that time, Ketterle's team has succeeded in creating a condensate with 10 million atoms. At the time of this writing, there are at least seven teams producing condensates. Besides our own group, others working with rubidium are Daniel J. Heinzen of the University of Texas at Austin, Gerhard Rempe of the University of Konstanz in Germany and Mark Kasevich of Yale University. In sodium, besides Ketterle's at M.I.T., there is a group led by Lene Vestergaard Hau of the Rowland Institute for Science in Cambridge,

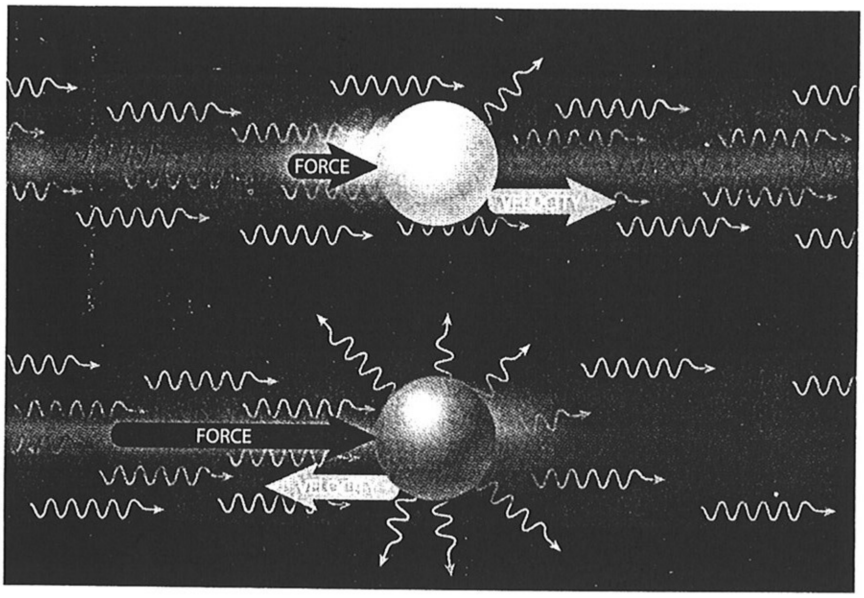








EVAPORATIVE COOLING occurs in a magnetic trap, which can be thought of as a deep bowl (*blue*). The most energetic atoms, depicted with the longest green trajectory arrows, escape from the bowl (*above, left*). Those that remain collide with one another frequently, apportioning out the remaining energy (*left*). Eventually, the atoms move so slowly and are so closely packed at the bottom of the bowl that their quantum nature becomes more pronounced. So-called wave packets, representing the region where each atom is likely to be found, become less distinct and begin to overlap (*below, left*). Ultimately, two atoms collide, and one is left as close to stationary as is allowed by Heisenberg's uncertainty principle. This event triggers an avalanche of atoms piling up in the lowest energy state of the trap, merging into the single ground-state blob that is a Bose-Einstein condensate (*below, center* and *right*).



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LASER COOLING of an atom makes use of the pressure, or force, exerted by repeated photon impacts. An atom moving against a laser beam encounters a higher frequency than an atom moving with the same beam. In cooling, the frequency of the beam is adjusted so that an atom moving into the beam scatters many more photons than an atom moving away from the beam. The net effect is to reduce the speed and thus cool the atom.

Mass. At Rice University Randall G. Hulet has succeeded in creating a condensate with lithium.

All these teams are using the same basic apparatus. As with any kind of refrigeration, the chilling of atoms requires a method of removing heat and also of insulating the chilled sample from its surroundings. Both functions are accomplished in each of two steps. In the first, the force of laser light on the atoms both cools and insulates them. In the second, we use magnetic fields to insulate, and we cool by evaporation.

Laser Cooling and Trapping

The heart of our apparatus is a small glass box with some coils of wire around it [*see illustration on pages 26 and 27*]. We completely evacuate the cell, producing in effect a superefficient thermos bottle. Next, we let in a tiny amount of rubidium gas. Six beams of laser light intersect in the middle of the box, converging on the gas. The laser light need not be intense, so we obtain it from inexpensive diode lasers, similar to those found in compact-disc players.

We adjust the frequency of the laser radiation so that the atoms absorb it and then reradiate photons. An atom can absorb and reradiate many millions of photons each second, and with each one, the atom receives a minuscule kick in the direction the absorbed photon is moving. These kicks are called radiation pressure. The trick to laser cooling is to get the atom to absorb mainly photons that are traveling in the direction opposite that of the atom's motion, thereby slowing the atom down (cooling it, in other words). We accomplish this feat by carefully adjusting the frequency of the laser light relative to the frequency of the light absorbed by the atoms [*see illustration above*].

In this setup, we use laser light not only to cool the atoms but also to "trap" them, keeping them away from the room-temperature walls of the cell. In fact, the two laser applications are similar. With trapping, we use the radiation pressure to oppose the tendency of the atoms to drift away from the center of the cell. A weak magnetic field tunes the resonance of the atom to absorb preferentially from the laser beam that is pointing toward the center of the cell (recall that six laser beams intersect at the center of the cell). The net effect is that all the atoms are pushed toward one spot and are held there just by the force of the laser light.

These techniques fill our laser trap in one minute with 10 million atoms captured from the room-temperature rubidium vapor in the cell. These trapped atoms are at a temperature of about 40 millionths of a degree above absolute zero—an extraordinarily low temperature by most standards but still 100 times too hot to form a BEC. In the presence of the laser light, the unavoidable random jostling the atoms receive from the impact of individual light photons keeps the atoms from getting any colder or denser.

To get around the limitations imposed by those random photon impacts, we turn off the lasers at this point and activate the second stage of the cooling process. This stage is based on the magnetic-trapping and evaporative-cooling technology developed in the quest to achieve a condensate with hydrogen atoms. A magnetic trap exploits the fact that each atom acts like a tiny bar magnet and thus is subjected to a force when placed in a magnetic field [*see illustration on opposite page*]. By carefully controlling the shape of the magnetic field and making it relatively strong, we can use the field to hold the atoms, which move around inside the field much like balls rolling about inside a deep bowl. In evaporative cooling, the most energetic atoms escape from this magnetic bowl. When they do, they carry away more than their share of the energy, leaving the remaining atoms colder.

The analogy here is to cooling coffee. The most energetic water molecules leap out of the cup into the room (as steam), thereby reducing the average energy of the liquid that is left in the cup. Meanwhile countless collisions among the remaining molecules in the cup apportion out the remaining energy among all those molecules. Our cloud of magnetically trapped atoms is at a much lower density than water molecules in a cup. So the primary experimental challenge we faced for five years was how to get the atoms to collide with one another enough times to share the energy before they were knocked out of the trap by a collision with one of the untrapped, room-temperature atoms remaining in our glass cell.

Many small improvements, rather than a single breakthrough, solved this problem. For instance, before assembling the cell and its connected vacuum pump, we took extreme care in cleaning each part, because any remaining residues from our hands on an inside surface would emit vapors that would degrade the vacuum. Also, we made sure that the tiny amount of rubidium vapor remaining in the cell was as small as it could be while providing a sufficient number of atoms to fill the optical trap.

Incremental steps such as these helped but still left us well shy of the density needed to get the evaporative cooling under way. The basic problem was the effectiveness of the magnetic trap. Although the magnetic fields that make up the confining magnetic "bowl" can be quite strong, the little "bar magnet" inside each individual atom is weak. This characteristic makes it difficult to push the atom around with a magnetic field, even if the atom is moving quite slowly (as are our laser-cooled atoms).

In 1994 we finally confronted the need to build a magnetic trap with a narrower, deeper bowl. Our quickly built, narrow-and-deep magnetic trap proved to be the final piece needed to cool evaporatively the rubidium atoms into a condensate. As it turns out, our particular trap design was hardly a unique solution. Currently there are almost as many different magnetic trap configurations as there are groups studying these condensates.

Shadow Snapshot of a "Superatom"

How do we know that we have in fact produced a Bose-Einstein condensate? To observe the cloud of cooled atoms, we take a so-called shadow snapshot with a flash of laser light. Because the atoms sink to the bottom of the magnetic bowl as they cool, the cold cloud is too small to see easily. To make it larger, we turn off the confining magnetic fields, allowing the atoms to fly out freely in all directions. After about 0.1 second, we illuminate the now expanded cloud with a flash of laser light. The atoms scatter this light out of the beam, casting a shadow that we observe with a video camera. From this shadow, we can determine the distribution of velocities of the atoms in the original trapped cloud. The velocity measurement also gives us the temperature of the sample.

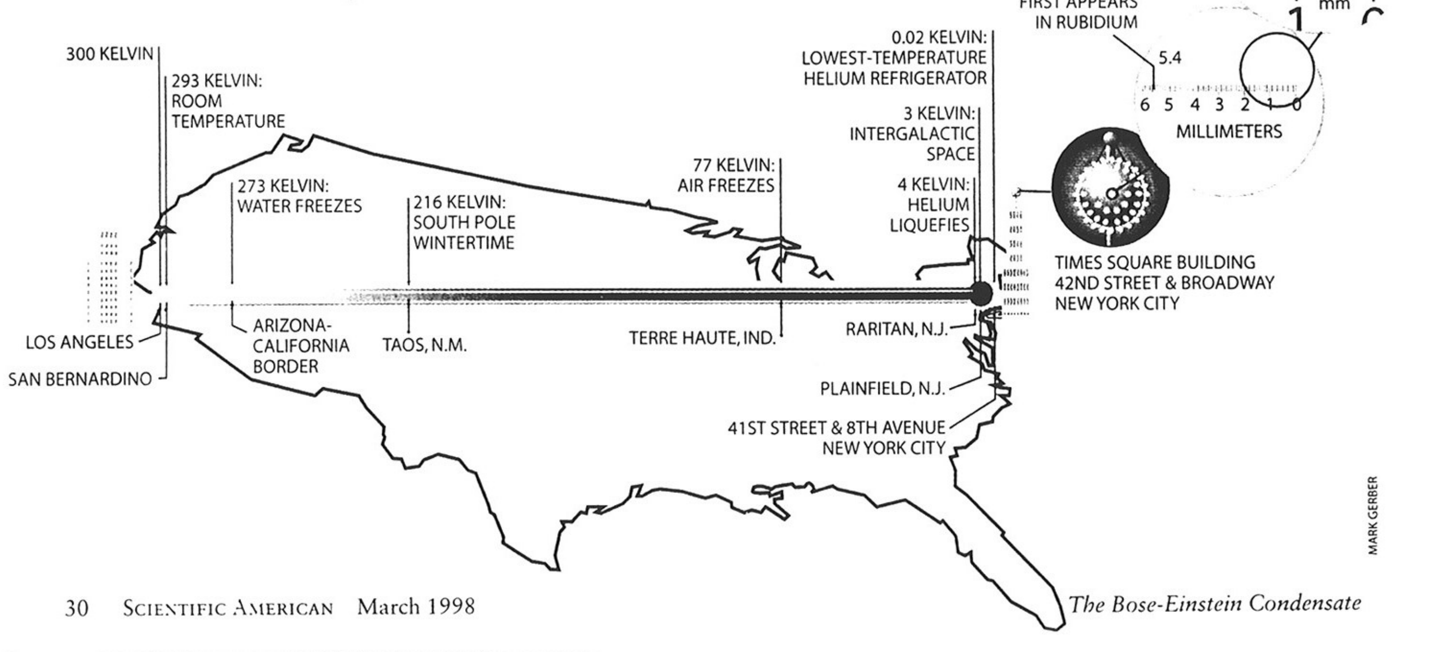
In the plot of the velocity distribution [*see illustration on opposite page*], the condensate appears as a dorsal-fin-shaped peak. The condensate atoms have the smallest possible velocity and thus remain in a dense cluster in the center of the cloud after it has expanded. This photograph of a condensate is further proof that there is something wrong with classical mechanics. The condensate forms with the lowest possible energy. In classical mechanics, "lowest energy" means that the atoms should be at the center of the trap and motionless, which would appear as an infinitely narrow and tall peak in our image. The peak differs from this classical conception because of quantum effects that can be summed up in three words: Heisenberg's uncertainty principle.

The uncertainty principle puts limits on what is knowable about anything, including atoms. The more precisely you know an atom's location, the less well you can know its velocity, and vice versa. That is why the condensate peak is not infinitely narrow. If it were, we would know that the atoms were in the exact center of the trap and had exactly zero energy. According to the uncertainty principle, we cannot know both these things simultaneously.

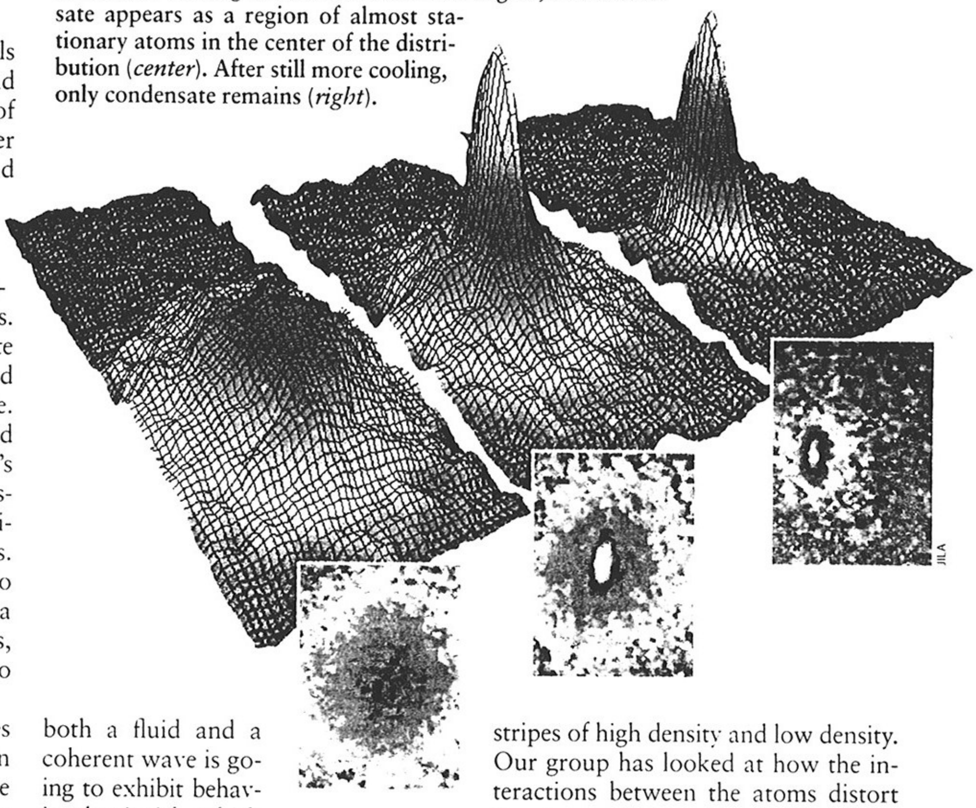
Einstein's theory requires that the atoms in a condensate have energy that is as low as possible, whereas Heisenberg's uncertainty principle forbids them from being at the very bottom of the trap. Quantum mechanics resolves this conflict by postulating that the energy of an atom in any container, including our trap, can only be one of a set of discrete, allowed values—and the lowest of these values is not quite zero. This lowest allowed energy is called the zero-point energy, because even atoms whose temperature is exactly zero have this minimum energy. Atoms with this energy move around slowly near—but not quite at—the center of the trap. The uncertainty principle and the other laws of quantum mechanics are normally seen only in the behavior of submicroscopic objects such as a single atom or smaller. The Bose-Einstein condensate therefore is a rare example of the uncertainty principle in action in the macroscopic world.

Bose-Einstein condensation of atoms is too new, and too different, for us to say if its usefulness will eventually extend beyond lecture demonstrations for quantum mechanics. Any discussion of practical applications for condensates must necessarily be speculative. Never-

CONTINENT-WIDE THERMOMETER is 4,100 kilometers (2,548 miles) long and shows how low the temperature must be before a condensate can form. With zero degrees kelvin in Times Square in New York City and 300 degrees assigned to City Hall in Los Angeles, room temperature corresponds to San Bernardino, Calif., and the temperature of air, frozen solid, to Terre Haute, Ind. The temperature of a nearly pure condensate is a mere 0.683 millimeter from the thermometer's zero point.



theless, our musings can be guided by a striking physical analogy: the atoms that make up a Bose condensate are in many ways the analogue to the photons that make up a laser beam.



SHADOW IMAGE of a forming Bose-Einstein condensate was processed by a computer to show more clearly the distribution of velocities of atoms in the cold cloud. Top and bottom images show the same data but from different angles. In the upper set, where the surface appears highest corresponds to where the atoms are the most closely packed and are barely moving. Before the condensate appears (*left*), the cloud, at about 200 billionths of a degree kelvin, is a single, relatively smooth velocity distribution. After further cooling to 100 billionths of a degree, the condensate appears as a region of almost stationary atoms in the center of the distribution (*center*). After still more cooling, only condensate remains (*right*).

The Ultimate in Precise Control?

Every photon in a laser beam travels in exactly the same direction and has the same frequency and phase of oscillation. This property makes laser light very easy to control precisely and leads to its utility in compact-disc players, laser printers and other appliances. Similarly, Bose condensation represents the ultimate in precise control—but for atoms rather than photons. The matter waves of a Bose condensate can be reflected, focused, diffracted and modulated in frequency and amplitude. This kind of control will very likely lead to improved timekeeping; the world's best clocks are already based on the oscillations of laser-cooled atoms. Applications may also turn up in other areas. In a flight of fancy, it is possible to imagine a beam of atoms focused to a spot only a millionth of a meter across, "airbrushing" a transistor directly onto an integrated circuit.

But for now, many of the properties of the Bose-Einstein condensate remain unknown. Of particular interest is the condensate's viscosity. The speculation now is that the viscosity will be vanishingly small, making the condensate a kind of "supergas," in which ripples and swirls, once excited, will never damp down. Another area of curiosity centers on a basic difference between laser light and a condensate. Laser beams are noninteracting—they can cross without affecting one another at all. A condensate, on the other hand, has some resistance to compression and some springiness—it is, in short, a fluid. A material that is both a fluid and a coherent wave is going to exhibit behavior that is rich, which is a physicist's way of saying that it is going to take a long time to figure out.

Meanwhile many groups have begun a variety of measurements on the condensates. In a lovely experiment, Ketterle's group has already shown that when two separate clouds of Bose condensate overlap, the result is a fringe pattern of alternating constructive and destructive interference, just as occurs with intersecting laser radiation. In the atom cloud, these regions appear respectively as stripes of high density and low density. Our group has looked at how the interactions between the atoms distort the shape of the atom cloud and the manner in which it quivers after we have "poked" it gently with magnetic fields. A number of other teams are now devising their own experiments to join in this work.

As the results begin to accrue from these and other experiments over the next several years, we will improve our understanding of this singular state of matter. As we do, the strange, fascinating quantum-mechanical world will come a little bit closer to our own. SA

The Authors

ERIC A. CORNELL and CARL E. WIEMAN are both fellows of JILA, the former Joint Institute for Laboratory Astrophysics, which is staffed by the National Institute of Standards and Technology (NIST) and the University of Colorado. Cornell, a physicist at NIST and a professor adjoint at the university, was co-leader, with Wieman, of the team at JILA that produced the first Bose-Einstein condensate in a gas. Wieman, a professor of physics at the university, is also known for his studies of the breakdown of symmetry in the interactions of elementary particles.

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Further Reading

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