Hot on the Trail of a Cold Mystery

In a gas colder than any yet created on Earth, atoms should spread out, overlap, and merge, creating a mysterious new state of matter. Now physicists think they may finally be closing in on it

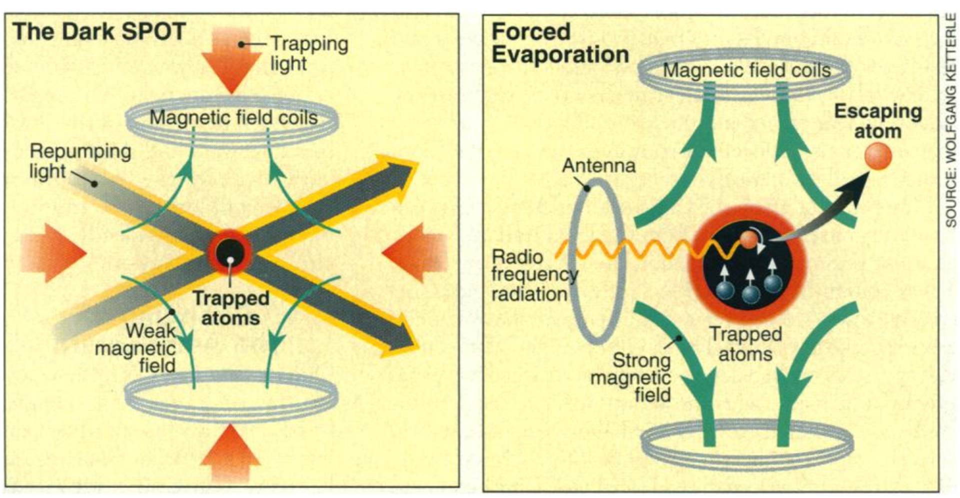
Cool a sufficiently dense gas to a few millionths of a degree above absolute zero and you will achieve a state of quantum-mechanical grace known as Bose-Einstein condensation. As the atoms slow almost to a standstill, they will shed their individual identities and become indistinguishable, creating not only an entirely new state of matter, but a remarkable testbed for studying mysterious quantum effects on a large scale. "Really quite an amazing juice" is how Eric Cornell of the National Institute of Standards and Technology (NIST) in Boulder, Colorado, describes it.

Cornell and his colleagues have a hard time being more specific, and that's part of the allure of this state of matter. Bose-Einstein condensation (BEC) might resemble superconductivity, they say, or it might be like superfluidity, in which a liquid's viscosity vanishes and heat no longer disperses in it but travels through it as a pulse. The fact that for decades BEC has eluded the best efforts of physicists to create it only adds to its mystique.

Recently, however, an unusual wave of optimism has flowed from advances in the two technologies that offer the best hope of reaching BEC, along with a promising marriage between them. One technology, forced evaporative cooling, traps chilled atoms in a magnetic field and continuously sweats out the hottest fraction of the atoms. The other, laser cooling, uses laser beams to trap and slow the atoms. Refinements in both techniques, reported in the 16 May *Physical Review Letters*, are putting higher densities and lower temperatures in reach. And at the International Quantum Electronics Conference (IQEC) in Anaheim, California, in May, researchers from the Massachusetts Institute of Technology (MIT) and the University of Colorado at Boulder independently announced that they had successfully merged the two approaches. MIT's Dan Kleppner, a member of the group that pioneered forced evaporative cooling, says he isn't putting his money on any one advance, "but if you look at developments collectively, Bose-Einstein condensation is really in the air now."

It was Einstein who first raised the possibility of this state of matter in 1925, building on work by the Indian physicist Satyendra Nath Bose. Einstein pointed out that as a gas is cooled and the velocity of each atom drops, the uncertainty in the atom's position grows, in a quantum-mechanical trade-off. The wave function, the mathematical equation that describes the atom, spreads out—and if the gas is cold and dense enough, Einstein proposed, the waves will merge. A good portion of the atoms will come to a dead stop, and the result will be Cornell's amazing juice: "a gas with unusual fluid mechanics properties and unusual thermodynamic properties and very unusual quantum optics properties."

It may be, says MIT's Wolfgang Ketterle, that the atoms in a Bose-condensed gas will tend to act in concert, like soldiers in a column, rather than jostling and colliding as atoms do in an ordinary gas—although just how that would affect its properties isn't clear. Equally uncertain is what will happen when researchers probe a Bose condensate with a laser. Laser light is coherent, and a Bose condensate is, in a sense, a counterpart of the laser: a coherent state of matter. As a result, the condensate might reflect every last photon and appear "shiny, metallic, like a Christmas tree ornament," says Cornell. On the other hand, it might ignore the laser completely and appear transparent like a clear glass marble; no one knows.



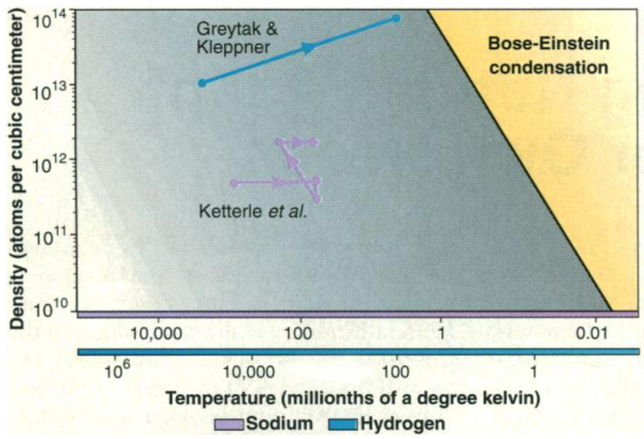
Two steps toward Bose condensation. A laser trap in which atoms "feel" the trapping beams only when stimulated by repumping beams does the initial cooling. The next stage is evaporation, in this case by radio waves that flip the spins of the hottest atoms and expel them from the trap.

The lure of the unknown

Having unknowns as big as this is "pretty unusual in these days of quantum physics," says Cornell. "A lot of atomic physicists are doing experiments they already know the answer to, but this is not one of them." Liquid helium at very low temperatures, when it loses all its viscosity and becomes a superfluid, may have some features of a Bose condensate, and researchers working with "gases" of electric charges may have fleetingly achieved this state (see box). But to study BEC in detail, physicists have to achieve it in an ordinary gas.

And that's why a handful of groups are now engaged in what they describe as a friendly competition to create it. For the last few years, MIT's Tom Greytak and his colleague Kleppner have been closest to the BEC threshold with their forced evaporation technique. They have cooled atomic hydrogen to 100 millionths of a degree above absolute zero (100 microkelvin) at a density of 10^{14} atoms per cubic centimeter. "At that density," says Kleppner, "we only have to go a factor of three lower in temperature. We're as close as anyone has ever been. That's the good news. The bad news is the progress we're making is quite slow because our apparatus is quite complicated."

Greytak and Kleppner start off by using liquid helium to refrigerate a gas of hydrogen atoms whose spins have been polarized so that they all point in the same direction. The polarization causes the hydrogen atoms to repel each other, preventing the gas from liquefying all the way down to absolute zero and therefore making it an ideal system for Bose condensing. The aligned spins also make it possible to trap the atoms in a magnetic field. The trap opens the way to forced evaporation, in which the experimenters re-



SOURCE: WOLFGANG KETTERLE

Inching toward the threshold. A group using evaporative cooling alone is still closer to achieving Bose condensation than a second group testing a new combination of evaporation and laser cooling.

duce the magnetic field step by step.

At each step, the more energetic atoms in the trap have enough energy to escape the magnetic field, just as hot molecules escape the surface of boiling water in evaporation. The atoms that remain bump against each other and come to equilibrium. When the field is turned down another notch, a second flock of energetic atoms escapes; the rest cool further. Each step of cooling also raises the density of the gas, as the atoms settle into the center of the magnetic trap.

One vexing shortfall of Greytak and Kleppner's system has slowed their quest for even greater densities and more efficient evaporative cooling: the tendency of the polarized hydrogen atoms to reverse their spins and duck out of the trap. As Harvard's Isaac Silvera explains, spins come in two varieties—"up" and "down"—and only spin-up atoms can be held in a magnetic trap. But the imposed magnetic field raises the energy of the spin-up state relative to spin-down, and the atoms tend to flip their spins when they collide. They then get kicked out of the trap.

As Greytak's group has struggled with that obstacle, others, using laser cooling, have achieved temperatures tens of times lower. In what may be the record so far, a group led by William Phillips of NIST in Gaithersburg, Maryland, has reached 700 nanokelvin, less than a millionth of a degree above absolute zero, although they have yet to publish the result. But as always, there's a catch: Although this technique has achieved dramatically low temperatures, those numbers are at the expense of the high densities needed for Bose condensation.

The basis of the technique is straightforward: Simply tune a laser beam to a frequency just below one the atoms tend to absorb. When an atom is moving toward the laser, the same Doppler effect that raises the pitch of an approaching siren will shift the laser's frequency upward, as seen by the atom, and it will absorb a laser photon—along with the photon's momentum, which slows and cools the atom. "You bombard atoms from all sides with photons," says Wolfgang Ketterle of MIT, "and no matter which direction the atom is moving it preferentially absorbs a photon from the forward direction and slows down." While laser cooling works poorly on hydrogen, because the resonant frequency of hydrogen is at a wavelength that lasers have trouble reaching, it works well with atoms of metals such as sodium or rubidium.

Unfortunately, each photon that cools an atom is later re-emitted, and once the gas is dense enough, these secondhand photons have a good chance of being reabsorbed by other atoms, pushing the atoms apart. "This scattered laser light produces an outward radiation pressure," explains Ketterle—an effect that limits the density of gas that can be achieved and has prevented researchers from trying to push down the temperature still further through evaporative cooling.

Still, both techniques have recently gotten a boost. Silvera and Phillips and their collaborators have developed a new kind of trap that combines microwave radiation and a magnetic field to pin atomic hydrogen in a single spin state, so that the spin-flipping that has plagued Greytak and Kleppner will no longer be a factor. Meanwhile, Steven Chu of Stanford University is making progress with a variant of laser cooling, known as Raman cooling, that he developed with his former graduate student Mark Kasevich. Raman cooling takes advantage of energy transitions that are very choosy about the photon wavelengths they absorb, making it possible to apply the brakes very delicately and slow atoms that are already nearly at a standstill, thereby reaching even lower temperatures.

A happy marriage?

Given time, say many researchers, either forced evaporative cooling or laser cooling might be enough to reach BEC. But the union of the two techniques, first proposed by the University of Colorado's Carl Wieman, promises faster progress. The key development came last year, when MIT's Dave Pritchard and

An Early Claim on Bose Condensation

By working in an unusual medium, two physicists may have made an end run to the exotic state of matter known as Bose condensation. Other researchers have struggled for decades to slow atoms of hydrogen or metal vapor to a near standstill so that they can attain this state of quantum mechanical harmony (see main text). But Jim Wolfe and Jia Ling Lin of the University of Illinois may already have Bose condensed another, more exotic gas: a swarm of paired positive and negative charges briefly created in a crystal of semiconductor.

This short-lived gas forms when a semiconductor is jolted with a laser beam. The pulse knocks electrons from the ground state, known as the valence band, into the higher energy conduction band, in which they can move freely. The displaced electrons leave behind positively charged "holes." Holes and electrons can combine into excitons—ephemeral, atom-like pairings—that survive for a few billionths of a second before the electrons fall back into the holes. Excitons have a very low mass, 1000 to 10,000 times smaller than the lightest atoms. And the smaller the mass of the particles, the longer their quantum-mechanical wavelength and the easier it is to cool them until the waves overlap, leading to Bose condensation. While atomic hydrogen at attainable densities won't Bose condense until cooled to within a few millionths of a degree of absolute zero, excitons should do so at 30 degrees kelvin.

Ten years ago, Wolfe and his collaborators set out to test this promise by chilling a cuprous oxide crystal and then hitting it with a pulse of laser light. They watched for the photons released over the next 15 nanoseconds by the annihilating excitons. "Those photons," says Wolfe, "tell us the state of the excitons before they recombined." The results showed that the excitons had slowed almost enough to Bose condense.

Last year, Lin and Wolfe went one step further by mechanically squeezing the crystal to modify its electronic properties. This time they detected a spectrum of annihilation photons with a narrow peak indicating that many of the excitons had near-zero kinetic energy—the hallmark of Bose condensation. After Wolfe presented his work at a BEC conference last summer, says Allan Griffin, a physicist at the University of Toronto, researchers trying to Bose condense hydrogen and metal vapor were enthusiastic. "They could see that the problems they're likely to face…have already appeared in the exciton work, so they were picking up a lot of useful hints."

–G.T.

Ketterle demonstrated a new laser trap that could yield higher densities. This variant is called the Dark SPOT trap, for dark SPontaneous force Optical Trap. This new trap works by hiding most of the atoms in a "dark" state, in which they can't absorb photons and thus can't be pushed apart by scattered light. The concealment scheme takes advantage of the atoms' two ground states, one in which the spins of the nucleus and the electrons are parallel and the other, slightly lower energy state in which they are anti-parallel.

The cooling and trapping lasers are tuned to the higher of these "hyperfine" states, so that the atoms can be cooled only when they are in that state. A very weak laser tuned to the lower, "dark" state sometimes lifts an atom into the upper state, where it undergoes a brief bout of cooling. "Every atom gets its turn and is cooled," says Ketterle. Afterward, it settles back into the lower state, in which it is oblivious to light. "By doing this," he continues, "we can get a high enough density to do evaporative cooling."

At IQEC, both Ketterle's MIT group and the Colorado group led by Cornell and Wieman reported that they had managed to combine dark SPOT traps and evaporative cooling. Reaching the threshold for BEC, however, will require an improvement of another three or four orders of magnitude in density and temperature. "The big excitement now," says Ketterle, "is that we saw the first step of cooling, and people expect this will carry us down by several more orders of magnitude." Cornell isn't so upbeat; he notes that the results so far are "not even in the ballpark" for BEC. But when he was told that Ketterle is optimistic, he said, "Well, I'm plenty optimistic. I'd just hate to open up *Science* magazine and read myself saying that three or four orders of magnitude is close."

One reason for not abandoning the caution traditional in this field is that nobody has ever approached BEC with metal atoms, only with hydrogen. As Wieman explains, "the whole business of laser-cooled atoms for Bose condensation is at an early enough stage that the kinds of problems encountered by people doing hydrogen have not yet shown up." And that complicates the betting about which technique, if any, will reach BEC first.

Greytak, for instance, notes that the evaporative cooling technique developed by his group is still closest in terms of combined cooling and density; if they can get their extremely complicated apparatus to work properly, he says, they still have the best shot. But the laser cooling/evaporation strategy, he adds, is moving fastest, and one more breakthrough could put that technique even closer. As for Chu, he takes the view that the past is prologue: "I'm betting on nature to hide Bose condensation from us. The last 15 years she's been doing a great job."

–Gary Taubes

AGRICULTURAL BIOTECHNOLOGY

Developing Nations Adapt Biotech for Own Needs

On 18 May, the biotechnology industry in the United States marked a major milestone: The first product of a genetically engineered plant—the Flavr-Savr tomato, which was modified to retard spoilage and improve flavor—received approval from the Food and Drug Administration (FDA). But as some presentations at a recent meeting of the National Agricultural Biotechnology Council (NABC)* made clear, developed countries like the United States aren't alone in applying gene transfer and other biotechnology techniques to the improvement of crop plants.

Despite early concerns that developing countries would reap little benefit from these technologies because they lacked the advanced research facilities needed to apply them to native crops, those countries are in fact aggressively adapting advances made in the West to local needs, says Robb Fraley, group vice president and general manager for new products at Monsanto Corp. in St. Louis. "What has stunned me is the energy developing countries are putting into biotechnology" in agriculture, Fraley asserts. "The progress made in the last 18 months has been breathtaking."

One significant sign of that progress is the speed with which biotech crops are moving through the research pipeline in developing countries. Many—including potatoes, cotton, rice, and tomatoes, as well as native species such as papaya—are currently in or near field tests. Some have gone into commercial production well ahead of similar crops in the United States. In China, for example, vegetables such as tomatoes, which have been genetically engineered for resistance to viruses, have been on the market for about 18 months, while comparable plants are only now reaching the final stages of approval at the U.S. Department of Agriculture (USDA).

Biotech crops may be moving into commercialization faster in the developing world partly because some of the countries do not have tight regulatory mechanisms like those imposed by agencies such as the FDA and USDA. But there's also a more fundamental reason: hungrier populations. "Genetic engineering has more potential for developing nations than for the First World," says Luis Herrera-Estrella, a molecular biologist at the Centro de Investigación y Estudios Avanzados (CINVESTAV) in Irapuato, Mexico. "In developed countries [agricultural] biotechnology's main value will be to reduce costs. But in the developing world it will allow us to produce more food."

The developing countries are adopting several strategies to achieve this goal of greater food production, several of which were on view at the annual meeting of the NABC, an organization of agricultural research centers established in 1989 to provide a forum for exploring the pros and cons of agricultural biotechnology. In some cases, the countries have reorganized established labs such as CINVESTAV, veterans of the classical plant breeding work that produced the high yielding crops of the "Green Revolution," to handle biotechnology. In others, they've set up new labs, such as the Agricultural Genetic Engineering Research Institute (AGERI) in Giza, Egypt. And they've been forging collaborations with Western researchers who bring their own biotech expertise to bear on foodstuffs of the developing world.

DENNIS GONSALVES/CORNELL UNIV.

Papaya protection. A gene introduced into the papaya plant on the left makes it resistant to ringspot virus, while the control plant *(right)* has a damaging infection.

Among these are local variants of the same species previously genetically engineered by the Western researchers. For example, in the late 1980s, scientists in Europe and the United States showed that they could "immunize" potatoes and other vegetable species against viruses by giving them

*The meeting was held on 23 and 24 May in East Lansing, Michigan.