ATOMIC PHYSICS

# Insights Flow From Ultracold Atoms That Mimic Superconductors

**They're the technological progeny of famed Bose-Einstein condensates. But chilly gases called Fermi condensates are proving even richer in new physics**

In 1995, experimenters unveiled the coolest thing ever seen in atomic physics. Using lasers and electromagnetic fields, they chilled gases of certain atoms, known collectively as bosons, to within a millionth of a degree of absolute zero to coax them into a single quantum wave, giving the gas bizarre new properties. Known as a Bose-Einstein condensate (BEC), that atomic tsunami had been predicted 70 years earlier; its discoverers won a Nobel Prize in 2001.

Then in 2004, physicists pulled off a tougher trick by making other atoms, known as fermions, behave like the electrons in a superconductor, which pair and waltz along without resistance. Merely producing such a "Fermi condensate" was a more impressive feat, many researchers argued. But was it as important as the discovery of BECs? All agreed that that depended on what grew out of it. Fermi condensates could open new realms of research—or prove a conceptual dead end.

Now, only 4 years after they first were made, Fermi condensates are exceeding expectations. BECs have been used to make atom lasers and stop light dead, but Fermi condensates may be more fruitful, physicists say. "One of the biggest impacts of BECs is that they provided the technology and tools to do fermions," says Wolfgang Ketterle, an experimenter at the Massachusetts Institute of Technology (MIT) in Cambridge and co-winner of the Nobel Prize for BECs. "I see a lot of deeper conceptual issues" with fermions.

Like the electrons in a superconductor, the paired atoms flow without resistance to form a "superfluid." By tuning the tugs between atoms, researchers are mapping a new landscape of superfluidity. The gases are also providing insights into other forms of matter, such as the soup of fundamental particles called quark-gluon plasma that filled the infant universe and has been recreated at particle colliders.

Experiments with ultracold fermions might even crack the mystery of high-temperature superconductivity, says Randall Hulet, an experimenter at Rice University in Houston, Texas. "The promise is still enormous," he says. "There's much more to be done than has been done already."

### Atoms, social and otherwise

Atoms are either joiners or loners, depending on how they spin. And that depends on how many protons, neutrons, and electrons they contain. If an atom has an even number of parts, as rubidium-87 does, its spin is a multiple of an iota known as Planck's constant. That makes it a boson, and any number of identical bosons can squeeze into one quantum wave. So when physicists chill rubidium-87 gas to below a millionth of a kelvin, the atoms pile into the lowest energy wave to make a superfluid BEC.

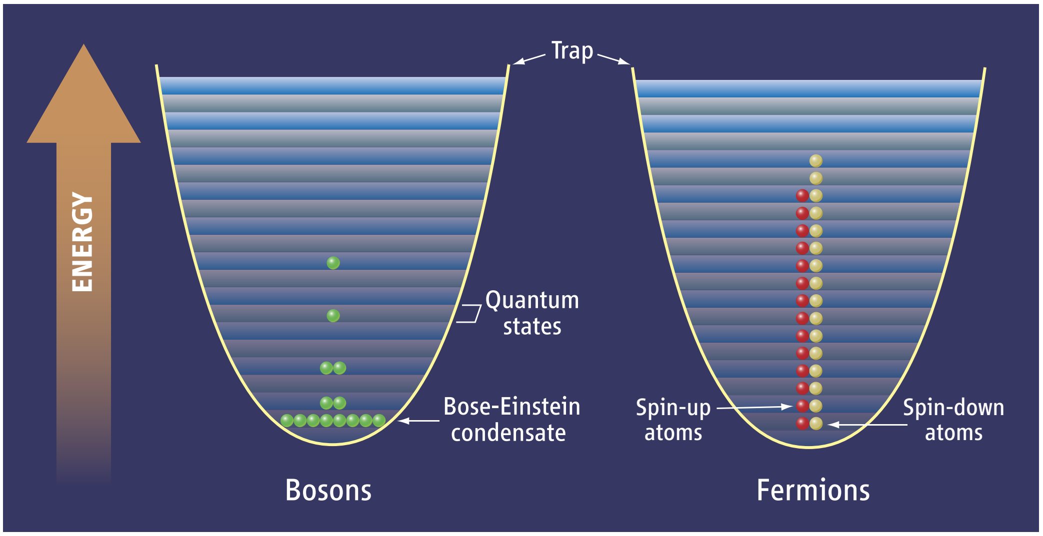
Atoms with an odd number of protons, neutrons, and electrons are far less gregarious. Known as fermions, they have an extra half-serving of spin, and a law of nature says that two identical fermions cannot occupy the same quantum state. So when fermions get cold, they stack one each into the lowest energy waves like so many plates in a cupboard (see figure, below).

Fermions can still form a superfluid, however. For example, in a superconductor, electrons (also fermions) fill two energy stacks: one for electrons spinning one way and another for electrons spinning the opposite way, as particles with opposite spins are in different states. Vibrations in the material then attract the electrons to one another, allowing opposite-spinning electrons to form loose, overlapping "Cooper pairs." At low temperature, there isn't enough energy about to break up the pairs, so they flow without hindrance.

Physicists aimed to mimic that effect in gases containing atoms spinning two different ways, to make them flow without resistance and show other weird quantum effects. To draw the atoms together, they apply a magnetic field. The field then produces a "Feshbach resonance" that greatly increases the interactions between the atoms.

Progress came in quick steps. In November 2003, Rudolf Grimm of the University of Innsbruck, Austria, and colleagues formed diatomic molecules of lithium-6 and produced a molecular BEC (*Science*, 14 November 2003, p. 1129). Three months later, Deborah Jin and her team at JILA, a laboratory run by the U.S. National Institute of Standards and Technology and the University of Colorado, Boulder, adjusted the magnetic field to create looser Cooper pairs of potassium-40 atoms and achieve a Fermi condensate (*Science*, 6 February 2004, p. 741). In 2005, Ketterle proved that a Fermi condensate is a superfluid by spinning one and observing a telltale pattern of tiny whirlpools called vortices (*Science*, 24 June 2005, p. 1848).

Fermi condensates don't behave exactly as expected, Jin says. "The superfluid didn't turn out to be like an ordinary superconductor," she says. "It's more like a high-temperature superconductor, but it's not really that,




**La différence.** Bosons crowd into a single spatially extended quantum wave to flow without resistance. Fermions stack into the waves but then can pair to flow freely.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either." That's because the atoms attract one another so strongly. If the electrons in a metal pulled as hard, superconductivity would set in at thousands of degrees.

### Charting new territory

Ultracold atoms can be manipulated far more easily than electrons in a superconductor. So like kids playing with a radio, physicists are turning every knob on their experiments to see what happens.

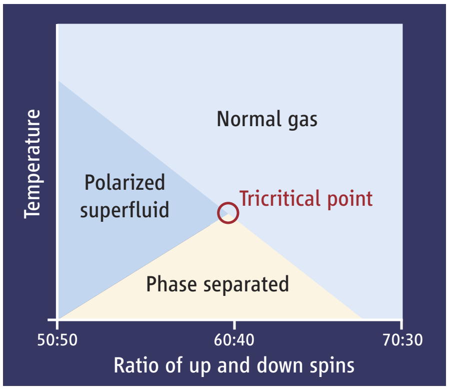
For example, researchers have varied the ratio of atoms spinning in the two directions. Such experiments could lend insight into the hearts of neutrons stars, which contain different numbers of different kinds of quarks (which are also fermions). The imbalance throws standard theory out of kilter and could result in new types of superfluid, such as the so-called FFLO state that is patterned like striped cloth.

In December 2005, Ketterle and his team reported that in lithium-6, superfluidity vanished when the ratio of up spins to down spins exceeded 85:15. In contrast, Hulet and colleagues found that superfluidity endured to a ratio of 93:7, the highest they could measure. For ratios above 55:45, it appeared that an evenly paired superfluid core forced the excess spins to the edges of the gas puff, like unpaired dancers squeezed off a crowded dance floor (*Science*, 23 December 2005, p. 1892). Hulet's results for nearly equal ratios even seemed to leave room for an exotic superfluid.

The experiments sparked a heated debate, however. Ketterle argued that, in theory, superfluidity had to disappear if the ratio got too lopsided. He questioned the claim of a sharp "phase separation" between an evenly paired superfluid and the excess spins. But theorist Henk Stoof of Utrecht University in the Netherlands suggested that the MIT team simply didn't get their atoms cold enough to see the separation, which sets in below a so-called "tricritical point" (see figure).

That cloudy situation is clearing. Ketterle and team have used laser light to trace the three-dimensional distribution of spins in their gas puffs. At the lowest temperatures, they observed a sharp boundary between core and periphery, they reported in the 7 February issue of *Nature*. That suggests that the MIT group had reached very low temperatures all along. But it also shows that the atoms phase-separate, as the Rice group claimed.

Meanwhile, Stoof and others have calculated that the tricritical point should lie pretty much at the temperature and spin ratio that the MIT group says it does. "It looks kind of settled," Stoof says. All agree that the Rice experiments must be taken seriously, however. Hulet's team traps their atoms in a very long, thin trap, Stoof notes, and the trap's shape may play a role and even stabilize the superfluid core in some way.




**Terra nova.** At lowest temperatures, a Fermi condensate separates into an evenly paired core and a shell of excess spins.

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### Quintessential fermions

Experimenters have also found extraordinary similarities between different types of cold atoms. In February 2007, John Thomas and colleagues at Duke University in Durham, North Carolina, traced how entropy varies with the energy in a lithium-6 gas. In April, theorist Peter Drummond of the University of Queensland in Brisbane, Australia, and colleagues showed that data for potassium-40, collected by JILA's Jin, lay along precisely the same curve.

Such "universal" thermodynamics arises because the atoms pull on one another so strongly that the details of their interactions cease to matter. But that means exactly the same relations should hold for hard-tugging quarks in a quark-gluon plasma or electrons in a high-$T_c$ superconductor. "The big picture is that *all* strongly interacting fermions have to behave this way," Thomas says.

Universality has piqued the interest of nuclear physicists. They have created a quark-gluon plasma by smashing nuclei together at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory in Upton, New York. A collision typically produces a cigar-shaped droplet of the 2-trillion-degree plasma, which expands oddly—much faster widthwise than lengthwise. Measuring that "elliptic flow," researchers have shown that the plasma is a nearly perfect liquid with almost no viscosity.

A cloud of fermionic atoms expands in the same strange way. Setting a puff of lithium-6 jiggling, Thomas found that its viscosity was nearly as low as the plasma's. The precise origins of that similarity remain to be determined, says nuclear theorist Krishna Rajagopal of MIT. "Nature is trying to tell us something," he says. "There is clearly some universality between these two very different liquids."

Some researchers hope to make connections to the ultracold, ultradense nuclear matter within a neutron star. There, different types of quarks may pair like the atoms in an imbalanced Fermi condensate. But there are key differences, Rajagopal says. The atoms spontaneously form a paired core surrounded by unpaired atoms. Such phase separation isn't possible with electrically charged quarks, he says, because it would cause a massive buildup of charge. Instead, a neutron star may contain the theorized FFLO superfluid, says Rajagopal, who hopes experimenters can prove that it does exist, perhaps in extremely elongated atom clouds.

### The ultimate superconductor

Perhaps the grandest goal is to explain high-$T_c$ superconductors, which carry electricity without resistance at temperatures as high as 164 K and have defied explanation for 20 years.

The superconducting compounds contain planes of copper and oxygen atoms arranged in a square pattern. Electrons hop from copper to copper, avoiding each other because their charges repel but somehow pairing by interacting through their spins and magnetic fields. The mathematical formulation of this scheme, known as the Fermi-Hubbard model, is simple to describe but too complex to solve even with the best computers.

So physicists hope to simply simulate the thing with cold atoms. The idea is to load ultracold fermions into a corrugated pattern of laser light. The atoms would hop from bright spot to bright spot like the electrons hopping from copper to copper. "If you're given one goal you want to accomplish in the next 5 years, it's to produce in the lab a Hubbard model" that mimics high-$T_c$ superconductivity, Ketterle says.

Several groups around the world are pushing to do just that. But it may not be as easy as some expect, says Tin-Lun "Jason" Ho, a theorist at Ohio State University in Columbus. To form a Fermi condensate, researchers chilled their atoms to a few billionths of a kelvin. To probe the Hubbard model, Ho says, they may have to reach a few trillionths of a degree.

Still, in just a few years, Fermi condensates have opened new vistas and forged connections between distant fields. Likely, important results will continue to flow.

**–ADRIAN CHO**