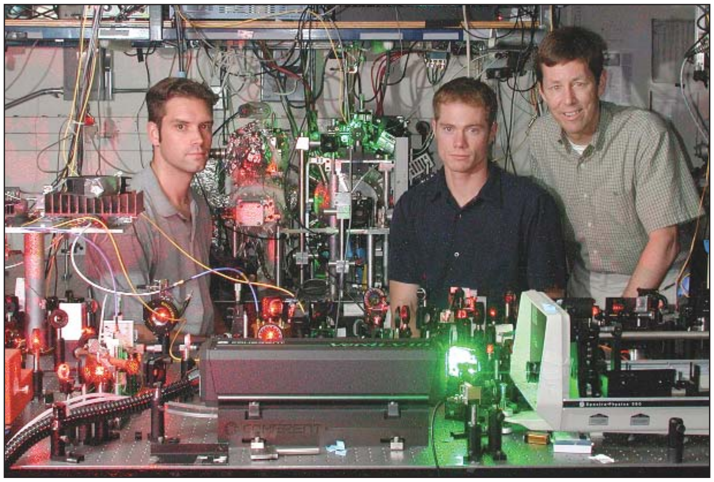
A much-anticipated atomic soup might lay bare the inner workings of high-temperature superconductors, neutron stars, and primordial matter—and perhaps win its creator a Nobel Prize

Ultracold Atoms Spark a Hot Race

In science as in movies, a sequel *can* be just as compelling as the original tale. Eight years ago, atomic physicists wowed the world by coaxing thousands of ultracold atoms into a single quantum wave. Known as a Bose-Einstein condensate (BEC), that weird state of matter fulfilled a 70-year-old prediction; opened the way to atom lasers and other fanciful technologies; and, in 2001, won its discoverers a Nobel Prize (*Science*, 19 October 2001, p. 503).

The mad dash to make a BEC seemed to set a standard for drama and gravity that atomic physicists could not hope to meet again, as three teams produced the strange stuff at nearly the same time. Yet, less than a decade later, researchers are closing in on an even more elusive and perhaps more revealing state of matter. And this time, the competition is even fiercer.

Physicists are struggling to make atoms in a gas pair like the electrons in a superconductor. Achieving such “Cooper pairing” could lead to new and useful quantum effects. The strongly interacting atoms should also mimic the behavior of electrons in high-temperature superconductors, protons and neutrons in atomic nuclei, neutrons in neutron stars, and even the quarks in primordial matter known as a quark-gluon plasma. So the odd atomic soup might make the perfect tool for teasing out the principles that unify seemingly disparate phenomena, says John Thomas of Duke University in Durham, North Carolina. “All of a sudden, you have a desktop experiment that cuts across all fields of physics,” Thomas says.



Cold warrior. Randall Hulet of Rice University (right) leads one of six teams vying to make atoms pair like electrons in a superconductor.

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Six groups—including some that vied to discover the BEC—have already reached a key milestone on the road toward Cooper pairing (see box below). And now, a powerful technique may take them the rest of the way. Researchers are intently tweaking the elaborate assemblages of lasers and magnetic coils that adorn their hydra-like vacuum chambers, in hopes of producing a microscopic puff of Cooper-paired gas. Although no one is willing to make a firm prediction, some suspect that the discovery—if it's possible—could come within months. “It's a horse race,” says Randall Hulet of Rice University in Houston, Texas. “We're all moving along at a good pace, and there's no overall leader at this point.”

Atoms, odd and even

Achieving Cooper pairing is even trickier than making a BEC because the atoms that can pair are inherently less cooperative than are those that can form a condensate. Atoms and particles generally act like little gyrating tops, and their sociability depends on how much spin they have. Some, called bosons, have spin equal to a multiple of a fundamental dollop known as Planck's constant. At temperatures close to absolute zero, identical bosons prefer to snuggle into the single lowest-energy quantum state to make a BEC, as physicists observed in 1995 when they chilled a gas of bosonic atoms to less than a millionth of a kelvin.

All other atoms and particles have spin equal to a multiple of Planck's constant plus an extra half and are known as fermions. Protons, neutrons, and electrons are all fermions with half a unit of spin. Consequently, any atom with an even number of protons, neutrons, and electrons is a boson; any atom with an odd number is a fermion.

Whereas bosons are gregarious, fermions are loners. A fundamental principle of quantum mechanics forbids two identical fermions to occupy the same quantum state. This “exclusion principle” explains why electrons fit into distinct shells in atoms and why atomic nuclei and neutron stars don't implode into infinitesimal knots.

In the same way, when cooled below their so-called Fermi temperature, identical fermions stack one by one into their

The Contenders

Six teams have stacked fermionic atoms into their lowest-energy states and are straining to see the atoms pair like the electrons in a superconductor. Deborah Jin and colleagues at JILA in Boulder, Colorado, use fermionic potassium-40 atoms in two different spin states to cool each other. Randall Hulet and his team at Rice University in Houston, Texas, refrigerate fermionic lithium-6 atoms with bosonic lithium-7 atoms, as do Christophe Salomon and his group at the École Normale Supérieure in Paris.

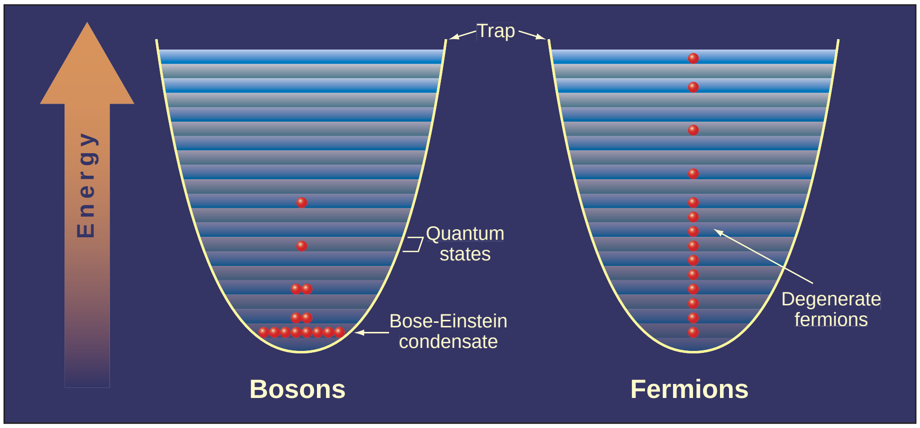
John Thomas's group at Duke University in Durham, North Carolina, chills two different spin states of fermionic lithium-6, and Wolfgang Ketterle and colleagues at the Massachusetts Institute of Technology in Cambridge cool lithium-6 with bosonic sodium-23. Massimo Inguscio and researchers at the University of Florence, Italy, cool potassium-40 atoms with bosonic rubidium-87—and they might leave the bosons in the mix to act as a kind of glue between the fermions. **–A.C.**

lowest-energy quantum states—like starlings alighting one to a rung on the bottom of a ladder (see figure, right). Such stacked fermions are said to be degenerate.

Even degenerate fermions exert forces on one another, however, and they can get together if conditions are just right. At a temperature even lower than the Fermi temperature, particles that attract each other can pair up like shy people circling each other in a crowded room (see figure, below). That happens only to the highest-energy fermions, which flit about in the energy levels just above the stack.

Although nebulous, these couplings exert a powerful effect: Nothing can deflect and slow either partner without breaking the pair. At such extremely low temperatures, energy is too scarce for that to happen, so the pairs can glide along without drag. That is what happens to the electrons in a superconductor.

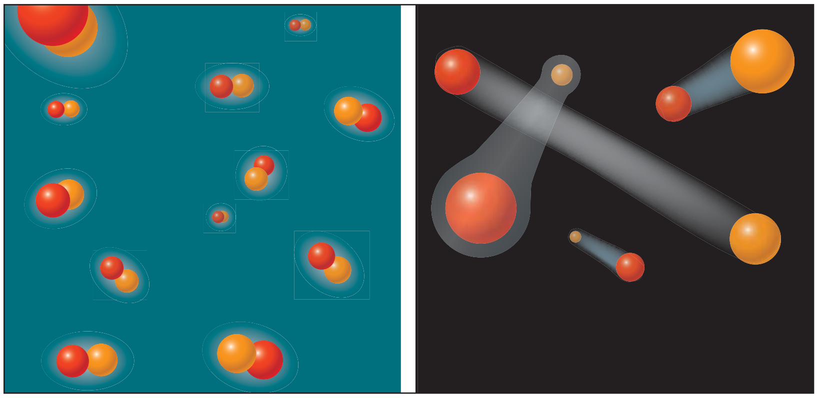
Physicists would like to see the same sort of pairing in a gas of fermionic atoms, in which case the paired atoms should flow without viscosity, a phenomenon known as superfluidity. But nature has thrown them a nasty curve ball: Fermionic atoms simply don't like to get cold.



Joiners and loners. Near absolute zero, identical bosons pile into the least energetic quantum state (left), whereas identical fermions stack into low-energy states one by one.

Hit or miss

The key technique invented to cool bosons doesn't work for identical fermions. To reach the rock-bottom temperatures needed to make a BEC, physicists trapped bosonic atoms in a bowl-like magnetic field and blew off the most energetic ones with radio waves, thereby siphoning away heat in much the same way that blowing on hot soup will cool it. But that technique works only if the atoms jostle one another, constantly transferring energy among themselves so that some will be nudged into higher energy levels and be blown away. Unfortunately, that doesn't happen with identical fermionic atoms. Because of the exclusion principle, the atoms avoid one another instead of colliding.



Tango or twist? In a magnetic field, atoms in different spin states can form molecules (*left*). Vary the field, and they might also form loose-knit Cooper pairs.

ILLUSTRATIONS: A. STONEBRAKER/*SCIENCE*

To overcome this problem, researchers devised two main schemes to make fermions collide. First to succeed and reach degeneracy was Deborah Jin of JILA, a laboratory run jointly by the National Institute of Standards and Technology and the University of Colorado, Boulder (*Science*, 10 September 1999, p. 1646). Jin and colleagues trapped fermionic potassium-40 atoms, which contain 19 protons, 21 neutrons, and 19 electrons. By applying the right combination of laser pulses, magnetic fields, and radio waves, the researchers ensured that the nuclei of some of the atoms spun in a different direction from the others. The no-longer-identical atoms could then collide, share energy, and cool one another. In 1999, Jin and her team chilled their atoms to less than a millionth of a kelvin to achieve the stacked state, now with one atom from each spin state in every energy level.

In contrast, 2 years ago Rice's Hulet mixed bosonic lithium-7 atoms with fermionic lithium-6 atoms, which contain one fewer neutron. The bosons collided with the fermions, and when Hulet and colleagues tuned the radio waves to blow away the bosons, the evaporating atoms drew heat away from the fermions. Since then, four other groups have also reached degeneracy using techniques similar to Jin's or Hulet's.

From the way station of degeneracy to the destination of Cooper pairing still seemed to be a long trek. Atoms generally attract one another so feebly that the critical temperature for Cooper pairing is a tiny fraction of the Fermi temperature—typically a few billionths of a kelvin. But physicists may have found a way to bring the critical temperature up to a more manageable level.

The trick is to trap atoms in two different spin states in laser light and then apply a hefty magnetic field. If the field is tuned to just the right strength, when atoms in different states collide, they may almost bind to form a molecule, in a phenomenon known as a Feshbach resonance. That fleeting embrace effectively amplifies the force between the atoms, says Murray Holland, a theorist at JILA. "It leads to a very large amount of time in which the atoms are involved in this scattering process," he says. "It's like a very strong interaction." In the right magnetic field, theorists predict, atoms may form Cooper pairs at temperatures as high as a quarter of the Fermi temperature, a readily achievable mark.

No one knows precisely how to use a Feshbach resonance to achieve Cooper pairing, or which atoms will prove most cooperative. So researchers are striving to figure out just the right plan of attack and to implement it in their intricate and persnickety rigs. "There are a variety of approaches, and one of them may work," says Christophe Salomon of the École Normale Supérieure in Paris. "I wish I knew which one."

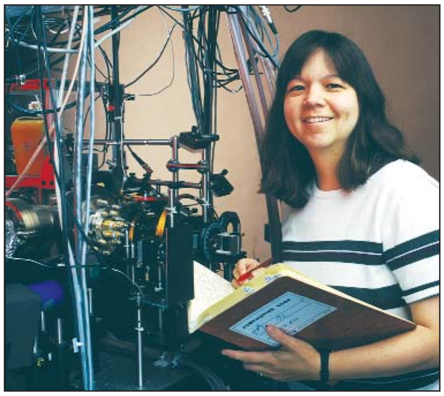
Some physicists, however, doubt that Feshbach resonances hold the key to high-temperature Cooper pairs. The hopes rest on calculations that assume that each atom collides with the others one at a time, says Henk Stoof, a theorist at Utrecht University in the Netherlands. But very near a Feshbach resonance, the interactions are so strong that each atom feels a tug from many others all at once, Stoof says, and such many-body effects may keep the pairing temperature unattainably low. But others hope many-body effects may prove more of a help than a hindrance. "I'm always optimistic," says Wolfgang Ketterle of the Massachusetts Institute of Technology in Cambridge. "If nature is kind to us, these effects may be just what we need to see Cooper pairing."

Even if Ketterle's optimism proves justified, physicists will still face a daunting challenge: proving that they've reached their goal. When bosonic atoms pile into a single quantum state, physicists can practically see the matter wave they create. They need merely shine a laser on the cloud and take a picture of the shadow it casts. The distinctive shape of the matter wave stands out like Mount Kilimanjaro rising above the plains. In contrast, Cooper pairing in atoms should produce no such spectacular effect, because only a small fraction of the atoms will join in the process and the pairs will signal their presence in much more subtle ways.

Some researchers envision shaking their cloud of atoms, in which case the atoms' superfluidity should enable the cloud to jiggle almost indefinitely, like an indefatigable blob of gelatin. Others hope to use radio waves to flip atoms from one spin state into another. If those atoms are tied into Cooper pairs, then the radio waves will have to pack extra energy to break the pairs as well. But even these experiments may be hard to interpret, warns Massimo Inguscio of the University of Florence, Italy. "All of these ideas to test the superfluidity of a fermionic gas are not black and white," he says. "One must be very careful."

The N-word

Ask physicists whether the observation of Cooper pairing will merit a Nobel Prize, and they tend to get cagey. It depends on how many avenues of exploration the new state of matter opens, says Ketterle, who shared the 2001 Nobel Prize in physics for the discovery of the BEC with Carl Wieman and Eric Cornell of JILA and the University of Colorado.



Chillin'. JILA's Deborah Jin first stacked cold fermionic atoms into the "degenerate" state.

Strongly interacting fermions—quarks, protons and neutrons, or electrons—underlie some of the most important unanswered questions in cosmology, astrophysics, and solid state and nuclear physics. So many researchers expect that cold fermionic atoms will provide an extremely useful model of these systems. Moreover, experiments on cold fermionic atoms might span the conceptual gulf between Cooper pairs and BECs. A Feshbach resonance can also be used to generate true molecules, so by tuning the magnetic field through a resonance, researchers might transform a gas of paired fermionic atoms into a BEC of bosonic molecules. "My guess is, yeah, the impact is going to be large enough that [Cooper pairing] will be worth a Nobel," Jin says cautiously. "Of course, I'm probably of the opinion that more things are worth the Nobel than it's given out for."

Nobel or no, Cooper pairing will likely prove more important scientifically than the BEC, says Rice's Hulet, a veteran of the race for the BEC. "I think that when we look back 20 years from now, we'll find that the fermions had a lot bigger impact than the bosons," he says. With advanced billing like that, it's no wonder that so many physicists want to be the first to see this next cool state of matter.

—ADRIAN CHO

Adrian Cho is a freelance writer in Grosse Pointe Woods, Michigan.

Scientific Workforce

Poor Job Market Blunts Impact Of New Master's Programs

The Sloan Foundation believes that industry needs graduates with both scientific and professional skills. But tradition and a poor economy pose difficult obstacles

Everett Salas thought that enrolling in a new professional master's program in computational biology at the University of Southern California (USC) in Los Angeles would lead to a sure-fire job in the biotech sector. After all, the novel 2-year program was specifically tailored to train science graduates for careers in industry. But this spring, as graduation neared, the 28-year-old found out that few companies were hiring and that none seemed interested in his degree. So Salas, who had earlier earned a master's degree in pathology, stepped back onto the academic treadmill, signing up for the university's Ph.D. program in geobiology.

He's not alone. In fact, seven of the first 15 students in USC's professional science master's (PSM) program have decided to stay in school. Only three have joined industry.

Those numbers are not what the Alfred P. Sloan Foundation had in mind when it began backing such programs in 1997. At the time, the biotech industry was booming, and doctoral students were peering down a long road with uncertain job prospects. The solution, to Sloan and many others, seemed to be a degree between that of a technician and a full-fledged researcher that would lead directly to a desirable job.

Over the next 4 years, Sloan handed out grants ranging up to $450,000 to seed 64 programs at 30 universities. Offering a mix of courses in science, business, and law, many were billed as an alternative to the MBA and Ph.D. The idea was to bridge the gap between the bench and the boardroom by training students proficient in the skills needed by both worlds.

Two cohorts have now completed their training. But a sluggish economy and the reluctance of employers to hire scientists without Ph.D.s have forced many graduates to continue their education or accept academic jobs. "We didn't have our eyes on the pin that was going to deflate the biotech bubble," says USC statistician Michael Waterman, who helped start the program. "Our expectation was that it would be easy to place our graduates in industry."

Instead, the proportion of PSM graduates entering industry has been small. That's especially true in the bioscience-related programs, which account for more than half of the 631 students so far enrolled or graduated under the Sloan initiative (see graphic). For example, out of 11 graduates in computational biology at New Jersey Institute of

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