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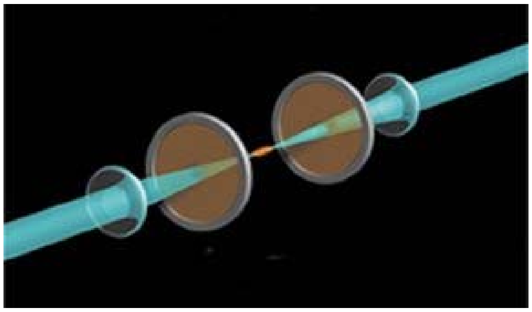
Extreme Impersonations

Frigid atomic clouds mimic neutron stars, exotic superconductors, and the newborn universe

Peter Weiss

Extreme physical conditions have a way of bringing out the strangest behaviors that nature can muster. Just ask physicist John E. Thomas. Two years ago, he and his colleagues at Duke University in Durham, N.C., were working with intense lasers in a high-vacuum chamber at temperatures next to absolute zero. They were manipulating tiny clouds of lithium gas. When the scientists turned off the lasers, peculiar things began to happen. At first, the microscopic puff of lithium billowed out of the spot where the lasers had held it. But then, instead of expanding evenly in all directions, as any normal gas would, the lithium cloud morphed into a pancake.



CAUGHT IN THE CROSSFIRE. In a step toward making an ultracold Fermi gas, a laser beam (light blue in diagram) traps a microscopic cloud of atoms (orange) at its focus. Such a trapping beam can be intense enough to cut steel.
A. McDonald Turner/amDESIGNS

That was the first glimpse of a new state of matter—a kind of ultrafrigid vapor—with the ponderous label "strongly interacting, degenerate Fermi gas." Named after the Italian-born physicist Enrico Fermi, these aggregations of particles can behave, according to quantum mechanics, as if they're a single entity.

The sighting of the odd cloud wasn't a total surprise. For years, research teams around the globe had been on the trail of these exotic gases.

They suspected that such gas clouds might bear an uncanny resemblance to several other types of exotic matter, including even certain solids, that have been extraordinarily difficult to study. Among these are materials known as high-temperature superconductors, which conduct electricity without resistance, and ultradense stars made mostly of neutrons. Fermi gases could also impersonate the hottest matter that has ever existed, which is the quark-gluon plasma.

For the most part, these substances have been extraordinarily difficult to explore. They're either inaccessible, as are neutron stars, or nearly impossible to make in the lab, as is the quark-gluon plasma. None of them readily submits to theoretical calculations and simulations. The new option of making Fermi gases in the lab may enable researchers to circumvent some of these obstacles and to experiment indirectly with these rare states.

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"This is a great model system for understanding those other quantum Fermi systems," says Deborah S. Jin of JILA, a Boulder, Colo., research center run jointly by the National Institute of Standards and Technology and the University of Colorado.

"I think it's going to revolutionize condensed-matter physics," which examines materials including solids and liquids, adds Kathryn J. Levin, a University of Chicago theorist.

In addition to opening new scientific windows on condensed matter, such studies might lead to practical payoffs in, for instance, new superconductors that work at room temperature.

Two's a crowd

Despite its endless variety, matter actually contains only two kinds of building blocks: bosons and fermions. Bosons, which include photons, are particles with a chummy nature. They readily share energy levels and physical space with other identical bosons.

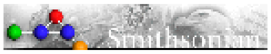
Fermions prefer to stay to themselves. A fermion, such as a quark, electron, or neutron, will cozy up with another fermion of the same type, such as two electrons, only under the right circumstances. For instance, every fermion can be thought of as containing a tiny bar magnet, a feature that physicists call the particle's "spin." If the spin of one fermion points in one direction, say up, and that of the other points down, then the two fermions can cohabit. Electrons in the same orbital of an atom are examples of this. If the spins of nearby fermions point in the same direction, however, the particles can't share space or assume the same energy level in an atom.

Although subatomic particles of matter are fermions, atoms can be either fermions or bosons. If an atom's total number of neutrons, protons, and electrons is even, as is the case for the most common isotope of helium, then the atom is a boson; if the sum is odd, as is the case with the lithium atoms that the Duke researchers used, then the atom is a fermion.

Atomic physicists made a big splash in 1995 when they chilled a cloud of bosons—rubidium-87 atoms—and induced it to coalesce into a never-before-seen entity, the Bose-Einstein condensate. These condensates are tantamount to superatoms in which all the atoms merge to share the same space and quantum energy state (SN: 7/15/95, p. 36). These experiments led to Nobel prizes and a flood of new research into the properties of the condensates and how they could be used—as atom lasers, for instance (SN: 5/8/99, p. 296).

Fermionic atoms are a more complicated story. First, they're much more difficult to cool to the near-zero temperatures required for such extreme condensates. However, in 1999, using potassium-40 atoms, Jin and her colleagues achieved a key milestone toward making a fermionic-type condensate (SN: 9/11/99, p. 166).

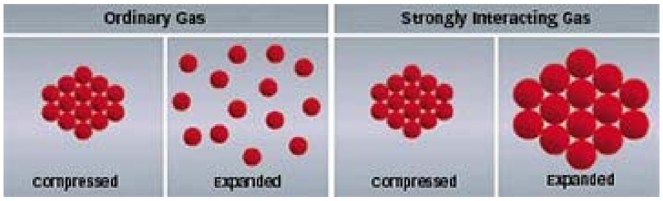
The experiment also proved to be a step toward strongly interacting Fermi gases. By driving down the Fermi gas' temperature to a few hundred nanokelvins, the JILA team forced its potassium atoms into a state known as degeneracy. In that state, pairs of atoms of differing spins neatly divvy up the available energy of the gas, much as electrons stack up at increasing energy levels within atoms. In later experiments, Jin's and Thomas' groups and other research teams lowered temperatures to less than 50 nanokelvins. Although the jury is still out, evidence is mounting that such extreme cold causes condensation of the pairs into a single, minimal energy level (SN: 2/21/04, p. 125: Available to subscribers at http://www.sciencenews.org/articles/20040221/note13.asp).



As some theorists had predicted, such gases turned out to be remarkably sensitive to the strength of magnetic fields. In their late-2002 experiment, for example, the Duke researchers adjusted a magnetic field permeating their frigid cloud of lithium-6 atoms in order to produce the pancaking effect.

The bizarre expansion signified that the fermions in the gas were in what researchers call a "strongly interacting" state never observed before in a laboratory.

When researchers had tried similar manipulations to induce strong interactions among the particles in Bose-Einstein condensates, they had also seen dramatic effects. However, the end results had been miniexplosions, dubbed "bosenovas," which obliterated the condensates (SN: 8/12/00, p. 102: Available to subscribers at http://www.sciencenews.org/articles/20000812/fob5.asp).



QUANTUM JOSTLING. Atoms of a confined, ordinary gas don't collide much after the gas expands. However, when a trapped gas of strongly interacting, fermionic atoms is released, the atoms themselves effectively grow in size. Sustained jostling and pressure among those ballooning atoms can cause telltale, lopsided gas expansion.
E. Roell

What does "strongly interacting" really mean? In such gas clouds or other groupings of fermions, particles of opposite spins can develop attractions for each other that extend over many intervening neighbors and that arise even if, as electrons do, the particles would ordinarily repel each other. In fact, as dictated by quantum physics, such pairings simultaneously link every particle to every opposite-spin particle in the cloud. Those linkages, however, are constantly forming, breaking apart, and re-forming, resulting in a liquid-like state that's still a gas.

At many magnetic field settings, the bonds between the atoms in even a supercooled gas are weak and floppy, as if the particles were balls tied together by Slinkies, Thomas says. Adjusting the field can step up the attractions' intensities, transforming them into strong interactions.

When that happens, it's as if much stiffer springs replace the Slinkies and cinch the fermionic particles together. At the low temperatures of these experiments, an atom effectively expands to a huge size—as much as a micrometer across. The tightened bonds pull all these inflated particles in the cloud up against each other, so they're constantly bumping together.

When such a gas is permitted to swell, say, by turning off the lasers that had been confining it, the effective size of each atom grows. It's as if a bunch of expanding balloons were pushing each other apart. That odd quantum ballooning caused the asymmetric pancaking expansion in the little lithium cloud that Thomas and his coworkers studied in 2002.

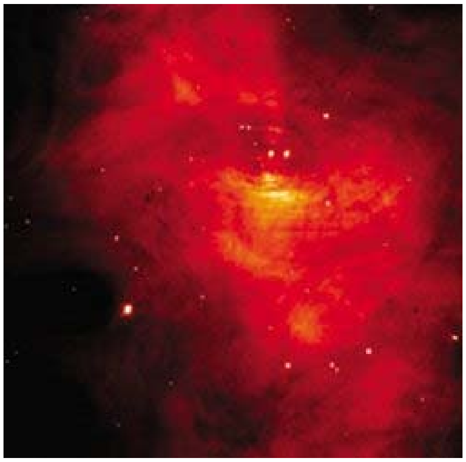
In the agitated, strongly interacting state, particles in a Fermi gas experience much greater contact with each other than do particles in an ordinarily gas. That's what makes them potential new tools for studying other systems of strongly interacting fermions.

What's the matter?

Henning Heiselberg of the Danish Defense Research Establishment in Copenhagen is a theoretical nuclear physicist who specializes in neutron stars. Those are the ultradense remnants of imploded stars and are composed of 90 percent neutrons, the rest being protons and electrons. A teaspoon of a neutron star weighs more than a billion tons.

The only nuclear matter that physicists can study directly lies within the cores of atoms. But to extrapolate from those tiny points to neutron stars is "very dangerous," Heiselberg says. That's because a vast chasm—physicists call it "the nuclear desert"—yawns between the size of the biggest known stable atomic nucleus and neutron stars. There is no stable configuration of nuclear particles in between.

Fermi gases offer an alternative to nuclei for studying neutron stars. Several research groups have determined the value of a key factor that describes the strength of attraction between fermions in these gases. That measurement can be applied to many types of strongly interacting matter, including neutron stars, to predict varying densities within such matter, Heiselberg has theorized.



FAR REACHING. Minuscule, laboratory-made mists of frigid atoms can mimic ultradense neutron stars such as the one lurking in this cosmic gas cloud, the Crab nebula.
J. Hester and P. Scowen/Arizona State Univ. and NASA

Even so, some scientists remain skeptical about how far Fermi-gas findings can stretch. "The analogy is there, but it's not obvious to me that we can really answer questions that are of astrophysical interest," says atomic physicist Wolfgang Ketterle of the Massachusetts Institute of Technology.

As he and other atomic physicists consider other types of exotic matter to mimic using Fermi gases, no prospect generates as much excitement as superconductors. Physicists have known for almost a century that some materials can conduct electricity with no resistance when they're cooled to near absolute zero. In 1986, scientists discovered another class of materials that can remain superconducting at much higher temperatures—as high as –139°C, to date.

Given other evidence that the electrons in these so-called high-temperature superconductors are strongly interacting particles, researchers now hope to use fermionic gases to investigate these materials. If scientists could figure out what's behind the high-temperature superconductivity, they might be able to design materials that would remain superconducting even at room temperature. Among the anticipated payoffs would be enormous global reductions in energy consumption, huge business opportunities, and, perhaps, more Nobel prizes.

It's not certain that Fermi gases will help superconductor researchers. For that to happen, scientists will have to show that the gases have another exotic property found in all superconductors: superfluidity, or the ability to flow without friction. Theorists have predicted that neutron stars are superfluidic. Even atomic nuclei are tiny dots of superfluids. Lately, scientists studying Fermi gases have made tests of superfluidity a major thrust of their experiments.

In independent tests, for example, the Duke group and a research team led by Rudolf Grimm of the University of Innsbruck in Austria briefly turned their atom-trapping lasers off and then on again to induce oscillations in clouds of strongly interacting atoms. They then measured how rapidly the gas clouds jiggled and how quickly the motion settled down.

As the Duke and Innsbruck teams report in, respectively, the April 16 and May 21 *Physical Review Letters*, the oscillations' rates and long durations are compatible with theorists' expectations for a superfluid.

More recently, Grimm's group pumped radio waves into a strongly interacting Fermi gas of lithium-6 atoms. By monitoring which radio wave energies were most strongly absorbed, the team could tell how much energy was needed to break the springlike attractions between the atoms. Again, the experimental results correspond closely to theoretical predictions for a superfluid. The scientists describe those findings in the Aug. 20 *Science*.

These and other recent measurements of Fermi gases are giving a boost to an unorthodox theory of high-temperature superconductivity. Most theorists consider the phenomenon to be intrinsically different from the low-temperature version. However, Levin and a handful of other theoretical physicists contend that both phenomena stem from a single type of superfluidity, which includes the superfluidity of the electrons in superconductors as well as the expected superfluidity of fermionic gases.

Expansion team

So far, the parallels between fermionic gases and superconductors, neutron stars, or other exotic forms of matter rest almost exclusively on a skeleton of theoretical arguments.

However, one striking parallel between purely experimental findings seems to put flesh on such comparisons. Both the gas clouds like the one in Thomas' lab and quark-gluon plasmas, a primordial form of matter of great interest to cosmologists, can evidently undergo similar asymmetric expansions.

In theory, the quark-gluon plasma is an unimaginably hot fluid of quarks and gluons—the fundamental entities that make up protons, neutrons, and many other types of particles—that came into being within the first microseconds of the Big Bang (SN: 6/21/03, p. 387: http://www.sciencenews.org/articles/20030621/fob1.asp). Scientists hold that all the matter in the universe derived from this plasma. Since the early 1980s, physicists at particle accelerators in Europe and the United States have been smashing together ions of heavy elements in attempts to recreate tiny samples of the plasma.

For decades, cosmologists and particle physicists had expected the plasma to be a gas of weakly interacting fermions, in this case quarks. Yet even before the Fermi gas experiments, researchers using a heavy ion accelerator at Brookhaven National Laboratory in Upton, N.Y., found startling evidence that the plasma expands in an asymmetric fashion, indicating that it's a strongly interacting gas. That was in 2000, says Ulrich W. Heinz of Ohio State University in Columbus, a theorist who specializes in quark-gluon plasma.

Last year, when Heinz saw the Thomas group's images of the ultracold lithium gas' asymmetric expansion, he was stunned. "I thought, 'Wow! This is exactly [the type of expansion] we have, but we can't take those beautiful pictures'" in the accelerator, he recalls.

A team led by researcher Christophe Salomon of the École Normale

Supérieure in Paris has also observed the asymmetric expansion of a lithium-6 Fermi gas. To Salomon, the similar behavior of a wildly different type of matter in the Brookhaven accelerator is "a beautiful example of overlap with our system."

Such overlaps in properties with other physical entities aren't the exclusive province of Fermi gases. The atoms in a Bose-Einstein condensate for instance, behave in many ways like the photons in a laser. Still, these condensates have never shown anything like the potential of Fermi gases for exploring other realms. As Salomon puts it, "this is a whole universe that opens to the cold-atom guys."

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