

Physics

QUANTUM CLAUSTROPHOBIA

Physicists create Fermi degenerate matter, the stuff of neutron stars, in an ultracold gas

Deep down, the world is made of fermions. The familiar proton and neutron are fermions, and so are their constituent quarks. The fermionic nature of electrons underlies the structure of the periodic table of elements (and hence all of chemistry). Their cousins the bosons have received much attention in recent years, with the landmark 1995 achievement of [Bose-Einstein condensation](#) in a dilute gas. Now it is the fermions' turn in the spotlight, with the creation of atomic "[Fermi degenerate](#)" matter at a chilly 0.3 microkelvin above absolute zero by two young physicists, Deborah S. Jin of the [National Institute of Standards and Technology](#) and the University of Colorado at Boulder and her graduate student Brian DeMarco.

Bosons represent the gregarious side of the quantum particle family, and they exhibit this most strikingly in a condensate, in which millions gather in the same exact quantum state. Fermions, in contrast, are quantum individualists, and it is impossible to put two of them into an identical state in the same place. Thus, fermions, named in honor of Italian physicist [Enrico Fermi](#), obey the Pauli exclusion principle: the presence of one forbids the presence of another.

Technically, bosons have whole-integer values of spin, or intrinsic angular momentum, whereas fermions have half-integer spin, such as $1/2$, $3/2$ and so on. But what really defines their quantum personalities is their behavior in groups, especially at extremely low temperatures where particles collect in the lowest available energy states. Cooled bosons abruptly slip en masse into the lowest level. Fermions behave more like people standing on a narrow staircase, at most one to a step, reluctantly filling the lower steps more completely as absolute zero is approached. Known as Fermi degeneracy, this crowded state plays a vital role in the electrical properties of metals and semiconductors and in stabilizing white dwarf and neutron stars against collapse.

To create their Fermi degenerate system, Jin and DeMarco used evaporative cooling of a gas of atoms in a magnetic trap, extending the technique that produced the first dilute Bose condensates. Jin's atom of choice was the rare potassium 40 isotope, and she and DeMarco exploited its unusual properties ingeniously. Most important, potassium 40 is fermionic, which follows simply because it is made of an odd number of more elementary fermions: 40 protons and neutrons and 19 orbiting electrons.

Producing Fermi degeneracy is more difficult than just throwing some fermions into a Bose condenser; fermions are harder to cool than bosons. Evaporative cooling depends on collisions between the particles to redistribute their energy continuously while the hottest particles are removed. But collisions between identical fermions become almost impossible near the quantum degenerate regime. Associated with every quantum particle is a wave, with a characteristic wavelength that becomes longer at lower energies. The exclusion principle prevents a pair of identical fermions from getting much closer together than this wavelength. Contrary to everyday intuition, as the atoms' waves get bigger it becomes next to impossible for them to collide!

To get around this loss of collisions, Jin and DeMarco ensured that their atoms were in a nearly equal blend of two slightly different magnetic states, called Zeeman states. The existence of two such states that can be simultaneously caught in a magnetic trap is another key attribute of potassium 40. Two atoms in different Zeeman states can collide even in the degenerate regime, because they are not identical. The mixed collisions permit evaporative cooling of the two varieties of atoms. "It's a brilliant experiment," says [Daniel Kleppner](#) of the Massachusetts Institute of Technology, a pioneer in the quest to achieve Bose condensation.

The Colorado team detected several signals of their atoms' degeneracy. Below 0.3 microkelvin, the atoms had more energy and a different pattern of velocities than classical physics predicts. These features occur because when the lowest levels are filled, the remaining atoms must stack up in higher energy levels. Another signal was a marked degradation of the evaporative cooling a short way into the degenerate regime.

The new gaseous system provides a unique experimental testbed for studying the Fermi degenerate state. "When Bose condensates were discovered people were very excited, but I don't think anyone had an idea of the Pandora's box that was being opened," Kleppner points out. He expects that the Fermi gas will also lead to interesting new phenomena.

Other researchers are also pursuing Fermi degeneracy. [John E. Thomas's](#) team at Duke University recently demonstrated the first entirely laser-based trap that can hold ultracold atoms for long enough to implement evaporative cooling. His group plans to cool a mixture of two states of lithium 6 that cannot be held together in a magnetic trap. [Randall G. Hulet's](#) group at Rice University will be cooling a mixture of lithium 6 (fermionic) and lithium 7 (bosonic) using a magnetic trap. Hulet expects to be able to push deeper into the degenerate regime with a boson-fermion mixture.

Lithium 6 is of great interest because its atoms attract one another at ultracold temperatures, as is needed to form yet another degenerate state: the Cooper pairing state, which, when it occurs with electrons, produces superconductivity. Lithium 6 atoms would pair up, becoming composite bosons that would then deny their components' fermionic claustrophobia by undergoing Bose condensation.

--Graham P. Collins