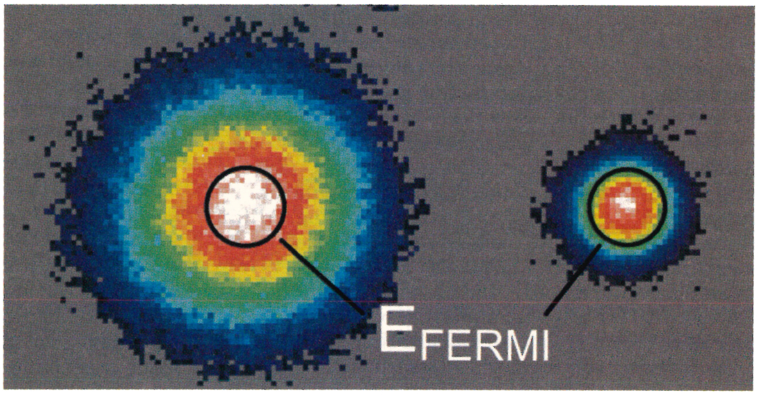
The Fermionic Cousin of a Bose–Einstein Condensate Makes Its Debut

Measurements on an ultracold gas of fermionic atoms indicate that its lowest energy levels are filling up as the temperature is lowered.

Experimenters have been romping in the BEC playground ever since a gaseous Bose–Einstein condensate was first produced four years ago. It was almost inevitable, then, that researchers would also want to explore its fermionic cousin—the quantum degenerate state one expects to get by cooling a gas of atoms with half-integer spins. Whereas the integer-spin atoms (bosons) in a Bose–Einstein condensate all pile into the lowest energy state, the half-integer spin atoms (fermions) are prevented from doing so by the Pauli exclusion principle, which prohibits two identical fermions from occupying the same quantum state. Instead, the atoms fill all the lowest energy levels up to the Fermi energy, just as electrons do in a solid. The crossover into this quantum degenerate state is gradual, compared to the abrupt phase transition into a Bose condensate. But that crossover has now been convincingly detected[1] by Deborah Jin, a physicist at the National Institute of Standards and Technology, and Brian DeMarco, a physics graduate student at the University of Colorado at Boulder, both working at JILA.

Even though the quantum degenerate state manifests itself more subtly than a Bose–Einstein condensate, it is potentially every bit as interesting and may yield its own set of surprises. Some of the predicted behavior—suppression of inelastic collisions and damping of spontaneous emission rates—stems directly from the full occupation of the lowest lying energy levels. But the most alluring prospect is the possibility of forming and studying Cooper pairs of the fermions and the condensation of these pairs into a superfluid state.

Other quantum degenerate Fermi systems are the electrons in a solid or normal liquid helium-3, both of which are often called Fermi liquids, following the seminal treatment by Lev Landau over 50 years ago. But the newly formed atomic system is less dense and more weakly interacting than the known Fermi liquids (aside from dilute mixtures of ^{3}He in ^{4}He). Moreover, the atomic system should allow us more easily to tweak such parameters as density and interaction strength and observe the resulting behavior.



APPROACH TO THE FERMI SURFACE. The absorption images of an expanded ultracold Fermi gas show that more of the atoms lie within the Fermi surface (black circles) below the Fermi temperature (right) than above it (left). (In the false color images, white indicates the highest density; blue/black, the lowest.) The images were taken 15 milliseconds after release from a magnetic trap. The hotter cloud ($T = 2.4\ \mu$K) has 2.5 million atoms; the colder cloud ($T = 0.29\ \mu$K) has 0.78 million, having lost atoms through evaporative cooling. (Adapted from ref. 1.)

Roadblocks to cooling

It has been more difficult to produce and detect a quantum degenerate Fermi gas than a Bose–Einstein condensate. That's because the Pauli principle limits the effectiveness of forced evaporative cooling, which has been very successful in condensing bosons. In evaporative cooling, the highest energy atoms are removed and the remaining gas equilibrates by elastic collisions between the atoms. Unfortunately for fermionic atoms, the elastic collision rate decreases sharply as the temperature drops because most elastic collisions are s-wave interactions, which are prohibited between identical fermions. (In s-wave collisions, the two particles have zero angular momentum relative to one another.)

DeMarco and Jin circumvented this roadblock to cooling by using a mixture of two nuclear spin states of the same atom, between which s-wave collisions are allowed. In earlier work with other JILA colleagues, they had shown that the collision rate remained fairly constant down to a few microkelvin in a magnetic trap loaded with atoms in two magnetic sublevels of the hyperfine ground state of potassium-40 with total atomic spin $F = 9/2$. With the second spin state present, elastic collisions can continue to promote the cooling.

DeMarco and Jin needed to reach thermal energies below the Fermi energy—that is, the energy of the highest level that would be occupied at absolute zero. According to their calculations, with roughly one million ^{40}K atoms in their trap, the Fermi energy corresponds to a Fermi temperature (T_F) of 0.6 μK. The JILA experimenters were able to cool roughly 8×10^5 atoms to about $T = 0.5\ T_F$.

DeMarco and Jin cooled in two stages, starting with a double magneto-optic trap developed by their JILA colleague Carl Wieman and his group. The double trap is particularly felicitous for cooling a rare and expensive sample like ^{40}K. The final, evaporative cooling was done in a magnetic trap with a characteristic holding time of 300 seconds. Once the gas was cooled, DeMarco and Jin ejected one of the two spin states, being left with a single-component gas.

Manifestations of quantum statistics

The JILA team was rewarded with several indications of quantum behavior that began to appear as T dropped below T_F. First, the forced evaporation became markedly less efficient; many more atoms had to be ejected from the trap to get the same drop in temperature. Such behavior might be explained by the increased occupation of the lower energy levels (which was up to 60% at $T = 0.5\ T_F$, resulting in fewer final states into which atoms could scatter. Additionally, the evaporation, which depends on a continual increase in the density of the trapped cloud, might be hindered by the resistance of a Fermi gas to compression. Such Fermi pressure is known to stabilize white dwarfs and neutron stars against gravitational collapse.

A second manifestation of the quantum degenerate state was the nature of the momentum distribution. In contrast to the sharp peak in momentum distribution that signals BEC, the momentum spread of the Fermi gas is altered in more subtle ways. Classically, the momentum should have a Gaussian distribution, but as quantum effects grow larger, the momentum peak becomes lower and fatter. To study the momentum distribution, Jin and her coworkers turned off the magnetic fields that confined the gas and let it expand freely for 15–20 ms. They then shone light onto this expanded cloud and measured its absorption. They fitted the absorption curve with an assumed shape, having one parameter that registered the deviation of the fitted shape from a classical Gaussian. For the ^{40}K gas below T_F, this parameter moved away from its classical value of 1.0.

The figure on page 17 shows the shape of the expanded Fermi gas, as measured by its absorption intensity, at two different temperatures. At the lower temperature, more of the cloud lies within the Fermi surface.

The same absorption data can be used to determine the total energy of the atomic gas. Classically, the energy should equal $3Nk_BT$ (where k_B is the Boltzmann constant). This energy goes to zero with the temperature. Quantum mechanically, however, the particles in a harmonic confining potential occupy every level up to an energy of $\frac{3}{4}\, k_BT_F$ and the energy remains finite even as the temperature drops to zero. Thus, the total energy should be higher at low temperatures than one would predict classically. That's exactly what's seen in Jin's lab.

Tuning the interaction

Now that Jin and her colleagues have entered the regime of quantum degeneracy, expeditions into the new territory will no doubt be quickly organized. One tool in this exploration may be the so-called Feshbach resonances, which should allow researchers to vary the interaction strength between atoms. Near a Feshbach resonance, the system is highly sensitive to any slight changes in interatomic potential. Thus, for example, a tiny change in the magnetic field strength can switch the interaction from attractive to repulsive. Feshbach resonances have already been seen in Bose condensates.[3–6] Jin suggests that one might use them to go smoothly from an ideal Fermi gas, with free particles, to a Fermi liquid, having repulsive interactions.

Farther down the road, explorers may find Cooper pairs and witness their condensation into a superfluid. Condensed-matter theorist Allan Griffin (University of Toronto) hopes that the atomic systems will enable researchers to study the dynamics of Cooper pairs in a way that's not possible with superfluid ^{3}He or superconductors. Such studies might shed light on a topic currently in vogue among high-T_c theorists: the crossover from a weakly interacting gas of small Cooper pairs, like a Bose–Einstein condensate, to a phase composed of large Cooper pairs that strongly overlap, as in a conventional BCS superconductor.

It would also be interesting, Griffin feels, to form an optical lattice and fill it with fermions, as researchers are currently trying to do with bosons. Such a regular array of fermions would simulate a Hubbard Hamiltonian—the subject of countless theoretical papers.

Theorist Sandro Stringari of the University of Trento in Italy hopes that, in the future, we might also be able to form a superfluid mixture of fermions and bosons. He also feels that the trapped Fermi gases represent some additional, challenging perspectives because the quantum degeneracy shows up not only in momentum space, as in uniform systems, but also in coordinate space. In the presence of harmonic trapping, the effects of inhomogeneity are always important, he says, because the gas is never uniform.

Other approaches

Experimenters in a number of other laboratories are also seeking to form a quantum degenerate Fermi gas in magneto-optic traps. Their approaches vary, some groups choosing to cool ^{40}K; others opting for lithium-6. Many of these groups have adopted a different approach to cooling: sympathetic cooling, in which the trap is loaded with a mixture of bosons and fermions; the fermion gas can continue to lose energy through elastic collisions with the bosons. No doubt, the ultimate aim of many researchers is to form Cooper pairs. Randall Hulet of Rice University and his coworkers, who are among those trying to get a Fermi gas of ^{6}Li, have proposed a method for detecting the pairs once they are formed.[7]

Yet another approach to cooling fermions is to use a purely optical trap, which allows one to trap simultaneously any number of spin states of an atom. All-optical traps may be needed for forming Cooper pairs, and they should facilitate the use of Feshbach resonances by avoiding interference between the magnetic fields used to trap and those used to tune. Researchers like Jin are considering transferring a quantum degenerate gas into an optical trap once it's formed.

One type of optical trap used for confining ultracold atoms is a tightly focused laser beam detuned far from the atomic resonance (to avoid heating by absorption). Such optical traps have been plagued by very short lifetimes and unexplained heating rates, but John Thomas and his colleagues at Duke University[8] have tracked down what appears to be the culprit: noise in the intensity and pointing direction of the laser. With a highly stable CO_2 laser, they confined a cloud of ^{6}Li fermions for up to 300 seconds.[9] They are now trying to evaporatively cool a two-state mixture of the atoms directly within the optical trap, but the task is daunting: No one has yet formed even a Bose condensate in an optical trap. However, two groups have recently made good progress in cooling cesium atoms at high densities in three-dimensional optical lattices.[10,11]

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