Atomic Fermi gases

Researchers have developed powerful new techniques over the past two decades for cooling atoms to ultralow temperatures. Among the most significant achievements made possible by these technical developments was the creation of the long-sought Bose-Einstein condensate in 1995. In a Bose-Einstein condensate, atoms are cooled to such a low temperature that they collect in the quantum-mechanical ground state of their confinement volume. Bose-Einstein condensation is possible only in the class of particles known as bosons. Particles of the other class, fermions, are forbidden to occupy the same quantum state and are thus prevented from directly condensing.

Progress in studying ultracold fermions has lagged behind that of bosons, not because of lack of interest but because they are experimentally more difficult to cool. In fact, fermions are especially significant because they comprise the fundamental building blocks of matter: protons, neutrons, and electrons are all fermions. Most of the subject of condensed-matter physics is concerned with the behavior of fermions, especially electrons. Of particular interest is the phenomenon of Cooper pairing, where fermions, such as the electrons in a superconductor, or the atoms in helium-3 (^{3}He), form correlated pairs when cooled to sufficiently low temperature. Recent experimental progress in cooling atomic Fermi gases may enable the realization of Cooper pairing in the gas phase. Because of the inherent simplicity and tunability of the atomic interactions in an ultracold gas, this work may help clarify many troubling issues in condensed-matter physics, including the mechanisms at work in high-temperature superconductors.

Behavior of bosons and fermions. It has been known since the work of Satyendranath Bose, Albert Einstein, Enrico Fermi, and Paul Dirac in the 1920s that there are two fundamental types of particles. Bosons are particles with integer spin angular momentum ($0, \hbar, 2\hbar, \ldots$, where $\hbar$ is Planck's constant divided by 2π), and fermions are those whose spin angular momentum has half-integer values ($\frac{1}{2}\hbar$, $\frac{3}{2}\hbar, \ldots$). Since protons, neutrons, and electrons are each spin-$\frac{1}{2}$ particles, atoms made with an odd number of these constituents are themselves composite fermions. Examples are lithium-6 (^{6}Li) and potassium-40 (^{40}K), which happen to be the only stable fermionic isotopes of the alkali-metal elements. The differences between bosons and fermions are significant only when they become quantum-degenerate, that is, when the size of the atoms' quantum-mechanical de Broglie wavelength Λ, which increases as temperature decreases, is comparable to the average separation between atoms. When this condition is met, bosons undergo the Bose-Einstein condensation phase transition. Identical fermions, on the other hand, are forbidden by the Pauli exclusion principle from occupying the same quantum level (**Fig. 1**). At zero absolute temperature, they completely fill the available energy states
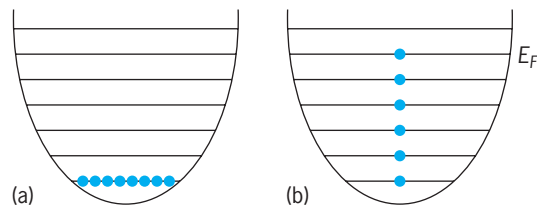

Fig. 1. Bosons and fermions at absolute temperature $T = 0$. Atoms in a magnetic trap feel a harmonic restoring potential, as indicated by the parabolic wells. The equally spaced lines in each well represent the quantized energy levels of the harmonic potential. (*a*) Bosons. At $T = 0$, they collectively occupy the ground state of the system. (*b*) Fermions. These particles must obey the Pauli exclusion principle, which forbids more than one identical fermion per state. At $T = 0$, they completely fill the energy-level ladder up to the Fermi energy E_F.

up to some energy, which is called the Fermi energy E_F. The filling of energy levels in this manner is analogous to the way electrons fill the lowest available atomic orbitals, thus forming the periodic table of the elements. As Cooper pairs are composite bosons, superconductivity and fermionic superfluidity (which is observed in liquid helium-3) are though to be related to Bose-Einstein condensation of these pairs of fermions.

Cooling methods. The methods for cooling Fermi gases and for confining them in atom traps are similar to those used for bosons. The primary methods are laser cooling, atom trapping, and evaporative cooling. Laser cooling utilizes radiation pressure to slow atoms. Since temperature is related to the atom's kinetic energy, reducing their speed is equivalent to cooling. Laser cooling is typically limited to temperatures in the range of 100 millionths of a degree above absolute zero, or 100 μK. Atom traps use laser radiation pressure or magnetic fields to confine atoms without walls. Since the atom temperatures are so low, isolation from physical boundaries is absolutely necessary to prevent heating.

Even lower temperatures, of the order of 100 nK (100 billionths of a degree above absolute zero), are needed to achieve quantum degeneracy in low-density atomic gases. These temperatures, as low as any produced by any method or found anywhere in the universe, are attainable using evaporative cooling. Evaporative cooling exploits the fact that there is always a distribution of energies in a gas, including some very energetic atoms in the "tail" of the distribution, and these few atoms account for much of the total energy. By systematically removing only the hottest atoms from the trap, a large fraction of energy can be removed, while minimizing the number of atoms lost. In the actual experiments, a microwave field is tuned to a particular frequency to drive atoms with energies above a certain cutoff E_c to untrapped states (**Fig. 2**).

Effective evaporative cooling requires that the atoms in the gas undergo elastic thermalizing collisions to continuously replenish the tail of hot atoms. The main experimental difficulty encountered with
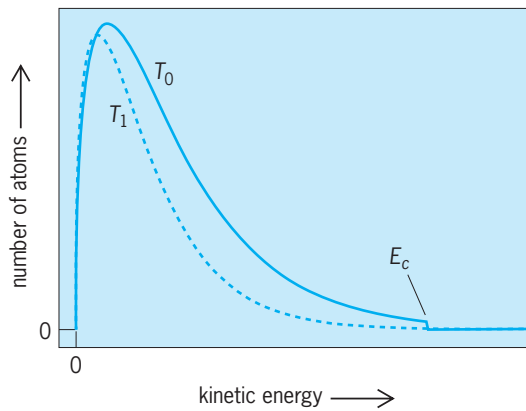
Fig. 2. Evaporative cooling. The graph shows the distributions of the kinetic energies of atoms at an initial temperature T_0 and at a lower temperature T_1. After the removal from the distribution at T_0 of all atoms with energies above E_c, collisions among the atoms cause the gas to rethermalize to the lower temperature T_1.

fermions is that the Pauli exclusion principle prevents identical fermions from interacting, so they are unable to thermalize. Several ways around this difficulty have been developed. First, one can make use of the different projections of the nuclear and atomic spin of the atom to make subsets of atoms that are distinguishable from other subsets. For example, one can make a mixture of ^{40}K atoms in two different nuclear spin states, so that the nuclear spins of some of the atoms point in a different direction from the others. Atoms in the same spin state will not interact, but two atoms in different spin states will. Unfortunately, this method cannot be universally used, because some spin states cannot be magnetically trapped, and because collisions between some spin states can result in the creation of atoms in a third state, with a release of excess energy that sends the atoms flying from the trap.

A more useful way to cool fermions is to "sympathetically" cool them with bosons. The bosons are evaporatively cooled as usual, while the fermions are cooled by interaction with the bosons. In this way, ^6Li has been cooled to temperatures as low as 200 nK using either lithium-7 (^7Li) or sodium-23 (^{23}Na) atoms as the "refrigerant." After the fermions have been cooled, the bosons can be selectively removed from the trap by making them undergo transitions to untrapped quantum states using microwave or optical pulses. The gas is probed by shining a laser beam through the gas of atoms and imaging the shadow cast by the atoms onto a charge-coupled device (CCD) camera.

Fermi pressure. In 1926, Fermi realized that, as a result of the Pauli exclusion principle, the energy of a gas of fermions is greater than zero at zero absolute temperature (Fig. 1), and consequently it exerts a pressure. This Fermi pressure is a purely quantum-mechanical result, as the pressure p from the classical ideal gas law, $p = nkT$, vanishes as the temperature T approaches 0 (n is the number density of the gas, and k is the Boltzmann constant). The implications of this result were soon realized by S. Chandrasekhar:

Under certain conditions, electron Fermi pressure could prevent the gravitational collapse of relatively cold, aging stars known as white dwarfs. This prediction was verified by observation, and the same stabilization method was later found to apply to neutron stars.

The effect of Fermi pressure has also been demonstrated for a trapped gas of ^6Li atoms. **Figure 3** shows a gas containing both bosons (^7Li) and fermions (^6Li), at three different temperatures. Although both types of atoms are mixed together in the trap at the same time, they can be individually imaged. The images are separated horizontally in the figure to show the difference in behavior between bosons and fermions. Figure 3a corresponds to the highest temperature, $T \simeq T_F$, where T_F is the Fermi temperature, which corresponds to the Fermi energy (Fig. 1) through the relation $T_F = E_F/k$. At this relatively high temperature, there is little difference in the spatial size of the fermions compared with the bosons. However, as the temperature is reduced to $\sim$0.5 T_F in Fig. 3b, and finally to $\sim$0.25 T_F in Fig. 3c, it becomes clear that the fermions occupy more volume than do the bosons. This difference is a manifestation of Fermi pressure, albeit on a much different size and energy scale than for stars.

Prospects for Cooper pairing. Cooper pairing in an ultracold atomic Fermi gas will require that the gas be cooled to even lower temperatures than have been demonstrated thus far. Furthermore, the atoms must have a strong attractive interaction. Since identical ultracold fermions cannot interact, as was the case for evaporative cooling, the experimental schemes will rely on a mixture of fermions in two spin states. A powerful technique for producing strong tunable interactions has been developed for atoms in Bose-Einstein condensates. The technique employs a phenomenon known as a Feshbach resonance, in which magnetic fields tune the energy of a bound state of the two colliding atoms, a diatomic molecule, to the same energy as the pair of unbound colliding atoms. The resulting resonance can be used to create strong or weak interatomic
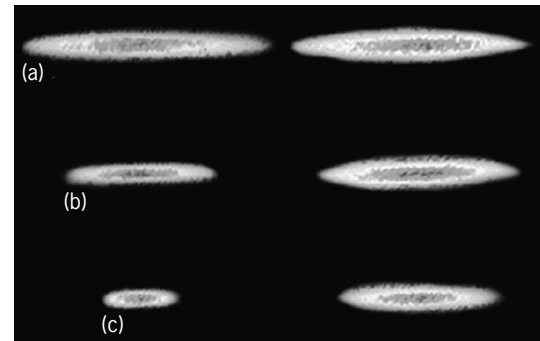

Fig. 3. Fermi pressure in a gas of trapped atoms. The images on the left are of the bosons (^7Li), while those on the right are of the fermions (^6Li), taken at progressively lower temperatures. Each pair of images corresponds to a particular temperature: (a) 810 nK, (b) 510 nK, (c) 240 nK. The ^6Li and ^7Li atoms are simultaneously trapped in the same volume, but the images are separated for clarity.

interactions that are either repulsive or attractive depending on the value of the magnetic field. Because of the versatility it affords, this interaction "knob" is one of the most compelling aspects of quantum gas research. Traditional superconductors and superfluid ^{3}He form pairs in the weak-coupling limit, where the size of the Cooper pairs is much larger than the average distance between fermions. This situation is very well described by the BCS (Bardeen-Cooper-Schrieffer) theory of superconductivity. On the other hand, Feshbach resonances may permit the exploration of the strongly coupled regime, for which there is yet no complete theory of Cooper pairing. Feshbach resonances in fermions are just now being explored and, although no clear demonstrations of fermion superfluidity have been made, experimentalists are beginning to reveal new aspects of strongly interacting Fermi gases.

For background information *see* BOSE-EINSTEIN CONDENSATION; EXCLUSION PRINCIPLE; FERMI-DIRAC STATISTICS; LASER COOLING; LIQUID HELIUM; NEUTRON STAR; PARTICLE TRAP; QUANTUM MECHANICS; QUANTUM STATISTICS; RESONANCE (QUANTUM MECHANICS); SUPERCONDUCTIVITY; SUPERFLUIDITY; WHITE DWARF STAR in the McGraw-Hill Encyclopedia of Science & Technology.   Randall Hulet

Bibliography. B. DeMarco and D. S. Jin, Onset of Fermi degeneracy in a trapped atomic gas, *Science*, 285:1703–1706, 1999; D. Jin, A Fermi gas of atoms, *Phys. World*, 15(4):27–32, April 2002; H. J. Metcalf and P. van der Straten, *Laser Cooling and Trapping*, Springer, 1999; C. J. Pethick and H. Smith, *Bose-Einstein Condensation in Dilute Gases*, Cambridge University Press, 2002; A. G. Truscott et al., Observation of Fermi pressure in a gas of trapped atoms, *Science*, 291:2570–2572, 2001.