A Little Big Bang

Gases of ultracold atoms teach us how matter behaves under the strongest interactions that nature allows.

by Martin Zwierlein

A few billionths of a degree above Absolute Zero, ultracold gases of fermionic atoms allow the study of strongly interacting matter, relevant for many different fields of physics—from the behavior of electrons in modern materials, to neutron matter in the crust of neutron stars, and to the quark-gluon plasma of the early universe. Experiments can be performed in real time and with high spatial resolution, enabling precision tests of many-body theories and the creation of entirely new states of matter. Superfluids with high critical temperature, ultradilute gases that repel off one another, and a multitude of other fascinating quantum phenomena can be realized in pristine fashion.

ONE HUNDRED YEARS AGO, the Dutch physicist Heike Kammerlingh Onnes discovered superconductivity in mercury and other metals—the resistanceless flow of electrical currents near Absolute Zero. In a curious twist of science history, he had used ^{4}He, the first superfluid, as the coolant. After the successful liquefaction of ^{4}He, Onnes had cooled liquid helium below its superfluid transition temperature, where the helium atoms flow without friction—although without noticing helium's unusual transport properties. As would become clear only fifty years later, the two "super"-transport phenomena are related by more than their name.

Today, we know that the superfluid properties of ^{4}He arise from the fact that about ten percent of the atoms form a Bose-Einstein condensate, the quantum phenomenon where a large number of atoms share the same macroscopic matter wave. This is analogous to the light of a laser beam, where all photons are in the same state, sharing the same color and propagating in the same spatial mode. In gases of ultracold atoms, about one hundred million times colder than interstellar space and one hundred thousand times less dense than air, one can realize the phenomenon of Bose-Einstein condensation (BEC) in its purest form. In these ultradilute gases, over ninety-nine percent of the atoms, about ten million in total, share the same quantum mechanical state in a volume of a fraction of a cubic millimeter. The observation of BEC in alkali gases, the demonstration of coherence of these matter waves, and the observation of superfluidity of these gases were described in the 1997 and 2001 issues of *physics@mit* by Wolfgang Ketterle, who shared the 2001 Nobel Prize in physics with Eric Cornell (Ph.D. '90) and Carl Wieman (S.B. '73). Many of the laser cooling and atom trapping techniques that led to these breakthroughs were developed at MIT in the labs of Professors Pritchard, Greytak, and Kleppner.

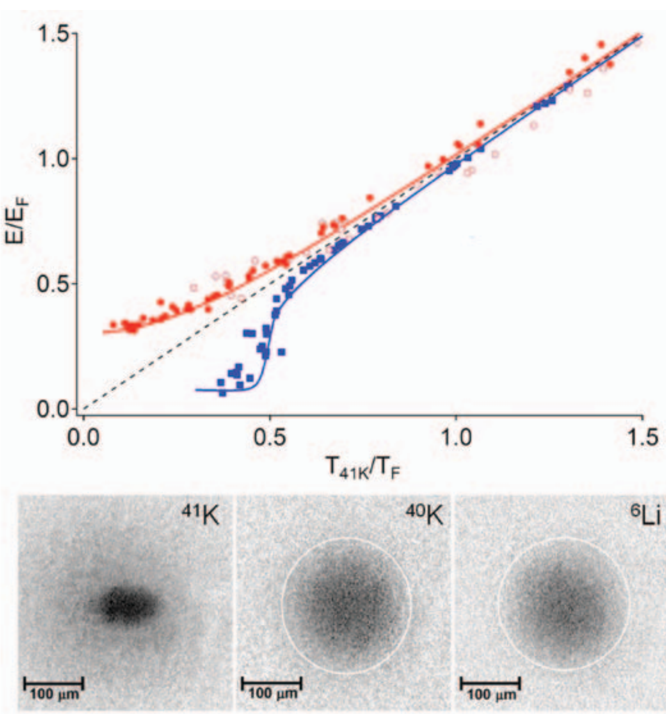


FIGURE 1

Pauli pressure and Bose condensation *in a triply quantum degenerate mixture. Two fermionic species ^{6}Li (solid red circles) and ^{40}K (open red circles) are cooled via bosonic ^{41}K (blue squares) to simultaneous degeneracy. At high temperatures their average kinetic energies E, measured in time of flight, are equal and set by the common temperature. As the temperature approaches the quantum regime, set by the Fermi temperature $T_F=E_F/k_B$, the bosonic species suddenly expands much more slowly, signaling condensation, while the fermionic species still expands quickly even at the lowest temperatures, signaling the release of Pauli pressure. The bottom row shows time of flight absorption images of the three species, with the white circles indicating the radius of a Fermi gas at zero temperature.* [1]

However, not all atomic species can share the same quantum state and undergo Bose-Einstein condensation. One hint of this fact is that the isotope ^{3}He, which has one neutron less than ^{4}He, does not become a superfluid at temperatures where its heavier twin does. The crucial difference lies in the total spin of the particles, *i.e.*, their intrinsic angular momentum. There are two classes of particles in the universe: those with integer spin are called BOSONS; they can share the same quantum state and can form a condensate. Those with half-integer spin (and that includes, in fact, all massive elementary particles) are FERMIONS—for example, electrons, protons, and neutrons, but also their constituents, the quarks. The famous Pauli exclusion principle prevents them from sharing the same quantum state. This explains the shell structure of atoms, where electrons must occupy different shells around the atomic nucleus, instead of all occupying the ground state as bosons would do.

A fascinating example of the Pauli principle at work is provided by neutron stars: more massive than our sun, these stars are extremely dense, just about ten miles in radius. The only thing that prevents them from collapsing due to their own gravity is the Pauli principle, which does not allow neutrons to "sit on top of each other."

This phenomenon of "Pauli pressure" can also be observed with ultracold fermionic atoms in atom traps, at about 28 orders of magnitude lower density compared to neutron stars. The role of gravity is here played by the magnetic forces used to trap the atoms. *Figure 1* demonstrates the difference between bosons and fermions in a recent experiment in the Zwierlein group at MIT, where two fermionic species of atoms, ^{6}Li and ^{40}K, were cooled by a bosonic species, ^{41}K. [1] The bosonic gas forms a Bose-Einstein condensate at low temperatures, only occupying a small volume in the trap, while the fermionic species remain large in size due to Pauli pressure. They form what is called a Fermi sea, with each atom occupying a different quantum state. It is especially striking to directly compare ^{40}K and ^{41}K, two isotopes of potassium that differ by a mere neutron, but which behave so differently because of their bosonic and fermionic nature.

We now encounter a puzzle: if fermions cannot condense into one and the same state, but condensation and superfluidity are intrinsically linked, how can electrons ever become superconducting? The solution seems obvious: fermions might team up in bosonic pairs with integer spin that can undergo Bose-Einstein condensation. After all, one can think of ^{4}He as a composite boson, formed by a fermionic ^{4}He$^+$-Ion and an electron. For such a form of pairing one would, however, need a rather strong attraction between two fermions. As in the case of the hydrogen atom, the attractive potential must balance the kinetic energy of zero point motion. Weaker attraction between two fermions in free space would not result in a bound state. It was the ingenious idea of Cooper (1956) that the presence of the Fermi sea of all other electrons might allow two electrons to bind—even for the weakest interaction. Finally, in 1957, having found a many-body wavefunction that incorporates electron pairing from the outset, Bardeen, Cooper, and Schrieffer wrote down their celebrated BCS theory of superconductivity in metals. Superconductivity is therefore simply superfluidity of charged electron pairs.

The mechanism of Cooper pairing is subtle; pairing is fragile and requires the presence of all other electrons—it is intrinsically a many-body effect. For that reason it was initially believed that BCS superfluidity of fermion pairs and Bose-Einstein condensation of bosonic particles were intrinsically different phenomena. However, it was later realized that BEC and BCS are just two limits of fermion pair superfluidity, connected by a smooth crossover from weak to strong binding between fermions.

Feshbach Resonances

A big goal in the research on ultracold Fermi gases was the experimental observation of fermionic superfluidity. [2] However, typical interaction strengths between atoms are so weak that pairing seemed too fragile and the critical temperature for superfluidity unattainably low. To the rescue came a powerful mechanism, the Feshbach resonances, named after the late MIT Professor Herman Feshbach. This effect allowed one to tune the interactions between atoms at will and make them as strong as quantum mechanics allows. The mechanism is described alongside Frank Wilczek's article about Herman Feshbach in the 2006 issue of *physics@mit*. With the help of these Feshbach resonances, ultracold gases of fermionic atoms became the first substance in which the crossover from tightly bound fermion pairs ("molecules") to long-range, fragile Cooper pairs could be studied. Here, atoms in

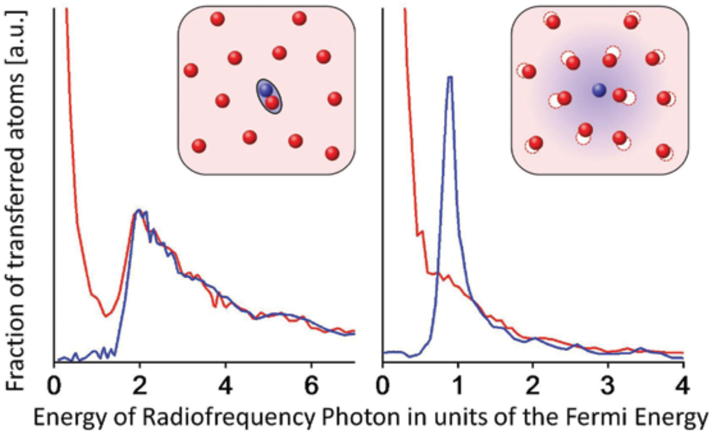


FIGURE 2

Observation of Fermi polarons *in a highly imbalanced spin mixture. Left: for strong interactions, the impurity atom binds an atom from the Fermi sea and forms a molecule, leading to identical spectra of impurity and environment atoms. Right: for weaker interactions, the impurity interacts with many environment fermions at once, forming a Fermi polaron. The spectral peak directly yields the polaron energy.* [4]

two different hyperfine spin states, labeled "spin up" and "spin down" analogous to the case of electrons in a conventional superconductor, can be made to pair up. The strength of pairing and therefore the size of pairs can be freely tuned. In 2005, the group of Ketterle, with former graduate students Zwierlein, Abo-Shaeer, Schirotzek, and Schunck, was able to directly observe superfluidity in Fermi gases via the observation of quantized vortex lattices (see *physics@mit* 2006). [3] This form of superfluidity, in the crossover between BEC and BCS, features a high critical temperature for superfluidity, relative to the low density of the gas. Scaled to the density of electrons in metals, superfluidity would already occur far above room temperature.

Strongly interacting fermions provide some of the greatest challenges to current many-body theory. A prominent example is given by electrons in high-temperature superconductors, for which we still lack a full understanding. Neutrons in neutron stars essentially interact as strongly as the atoms at a Feshbach resonance. With the ability to control the interaction strength, the dimensionality and the spin composition, ultracold atom experiments are now in a unique position to shed new light onto the properties of fermionic systems.

Current research on Fermi gases has two major goals. The first is to realize model systems of strongly interacting fermions that can serve to benchmark many-body theories and help to understand systems realized elsewhere in nature. The other goal is to create new systems that do not have a counterpart in traditional condensed matter or nuclear systems. Of special interest here are systems far out-of-equilibrium. They are very difficult to study with electrons due to the extremely fast equilibration times, but with a cold atomic gas one can follow the system's evolution in real time. In this article, both directions will be illustrated with recent results from Zwierlein's group. The observation of Fermi polarons in highly spin-imbalanced gases combined the creation of a novel system with a benchmark test of many-body theories. The second topic presents an out-of-equilibrium study, the "Little Fermi Collider," where two gases of fermions were brought onto a collision course.

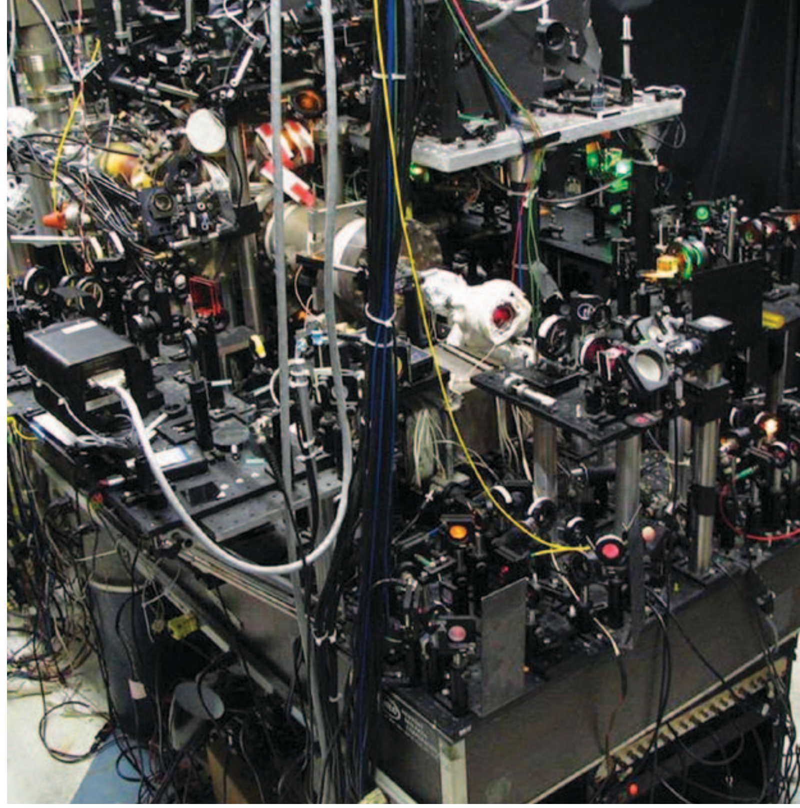
Swimming in the Fermi Sea

Impurities are ubiquitous in materials, and their influence on various states of matter is a central question for condensed matter physics. Generally, the interaction of a particle with its environment is one of the grand themes in physics. A classic example is that of an electron moving through the crystal lattice of ions in a metal. The electron distorts the lattice and thus locally polarizes its environment. The electron and the surrounding lattice distortions form a new "quasi-particle," the POLARON. As the electron now has to "drag" the lattice distortions with it, the mass of the polaron is higher than that of a bare electron, and its energy is changed due to the interactions with the lattice.

In this example the electron impurity moves in a bath of lattice distortions, sound waves that have bosonic character. In spin-mixtures of ultracold Fermi gases, Zwierlein's team realized a new situation where the impurity—a single spin down atom—moved in a fermionic environment, the spin up Fermi sea. [4] A new quasi-particle was identified in this experiment, the Fermi polaron, the spin down atom dressed by a collection of fermions. The interaction between the impurity and its environment could be tuned at will via a Feshbach resonance. This enabled determining the energy of the impurity as a function of interaction strength.

To measure the binding energy, radiofrequency spectroscopy was employed, in which the impurity atom (spin down) is promoted to a new, third spin state. In the absence of interactions with the spin up bath, this transfer would cost a precisely known amount of energy (atomic clocks use such transitions to keep the standard of time). However, if the impurity atom interacted with the bath, one needed to supply additional energy—hence a higher frequency of the radio wave—to transfer the atom. The energy of the Fermi polaron could be read off directly from the resulting spectra *(Figure 2)*. For strong interactions, the impurity was found to tightly bind to one atom from the Fermi sea, forming a molecule.

The experiment is an example of a "quantum simulation," where a well-defined many-body problem ("Hamiltonian") is realized experimentally and solved by nature itself, allowing for a quantitative comparison between theory and experiment. Once the number of "impurity" particles is increased, a complicated many-fermion problem emerges where no simple theory exists to this date. However, the MIT experiment showed that the impurities do not interact strongly with each other, so that the gas can still be understood to a good approximation as a collection of non-interacting quasi-particles. At a thus far unknown transition temperature, a novel form of superfluidity is expected, where quasi-particles of the same spin state form pairs that carry non-zero angular momentum.



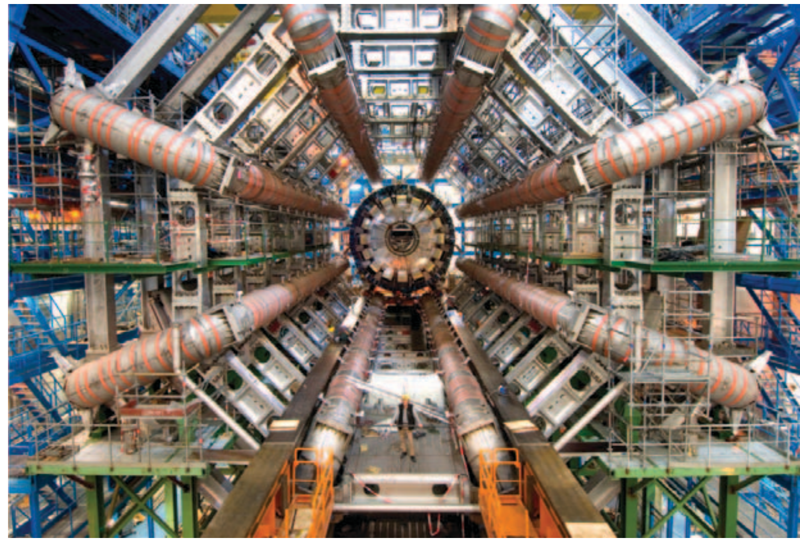


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FIGURE 3

The Little Fermi Collider and the Large Hadron Collider. *One of MIT's human-sized cold atom machines (top) with vacuum chamber, countless mirrors and optics, magnetic coils, water cooling, CCD cameras, and laser light for laser cooling of atoms. The image below shows a view of one experiment of the LHC, ATLAS, a particle collider in a tunnel 27 km in circumference. Size, staffing, and cost differ by about five orders of magnitude; energies by about 23 orders of magnitude.*

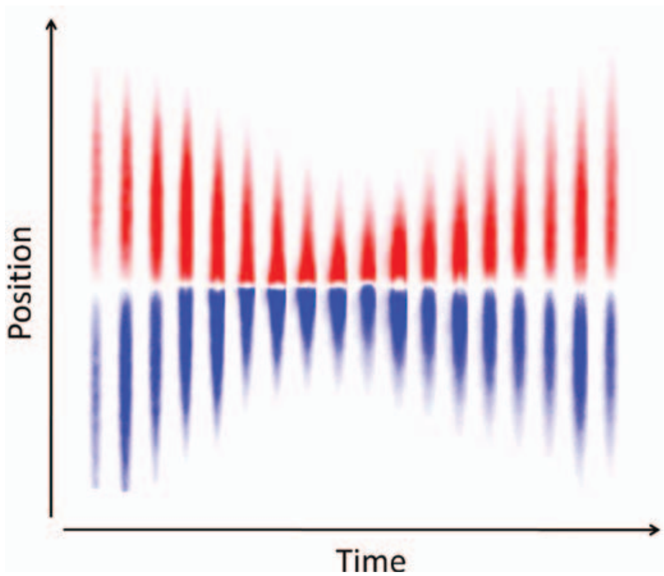

FIGURE 4

The bouncing gas. *Two clouds of opposite spin are initially separated spatially and collide in a cylindrically symmetric atom trap. Separate absorption images are taken for each hyperfine spin state at 1 ms intervals. Due to the strong interactions, the two clouds dramatically repel each other.* [5]

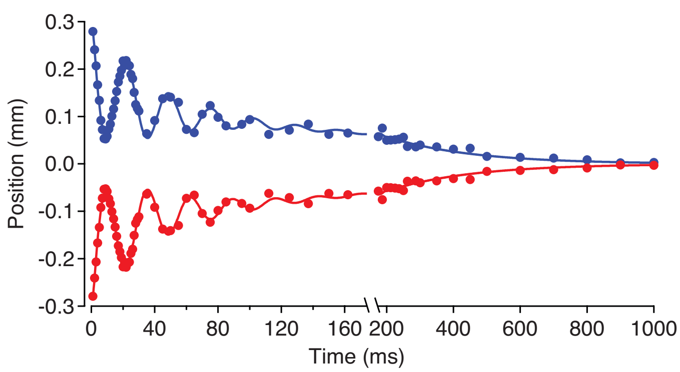

FIGURE 5

The center of mass position *of the spin up and spin down cloud as a function of time. After several initial bounces, the clouds slowly penetrate into each other through quantum limited diffusion.* [5]

The Bouncing Gas

A central topic in many fields of physics concerns the transport of fermions. Electron transport runs modern technology and defines states of matter such as superconductors and insulators. Neutrino transport energizes supernova explosions following the collapse of a dying star. At the Large Hadron Collider (LHC) at CERN and the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory, heavy nuclei are smashed into each other at ultra-relativistic energies to recreate the quark-gluon plasma. This primordial "soup" of strongly interacting particles existed a split second after the Big Bang and the transport of fermions through this extreme form of matter governed the expansion of the early universe.

On a much smaller scale *(Figure 3)*, in an experiment one might call the "Little Fermi Collider" (LFC), the Zwierlein group recently studied the collision of two atom clouds of opposite spin, but with interactions as strong as quantum mechanics allowed. [5, 6] From the previous discussion, one might expect that these atoms could quickly team up in pairs and form a superfluid. On the contrary, it was observed that initially the two spin clouds almost completely repel each other, much like oppositely oriented magnets *(Figure 4)*. The experiment thus demonstrated that interactions could be strong enough to reverse spin currents. After several bounces, the two gases very slowly diffused into each other, in a process that took over one entire second *(Figure 5)*. In that same time about one hundred thousand collisions between atoms occurred. The diffusivity D of this gas approached a fundamental limit set by quantum mechanics, $D \sim \hbar/m$, Planck's quantum divided by the atomic mass. For a gas of ^{6}Li, this quantum limit is given by $(100\ \mu m)^2/1$ s, *i.e.*, it will take about one second for two clouds of opposite spin and a typical size of 100 µm to penetrate each other—just what is observed in experiments.

For the quark-gluon plasma created at particle accelerators such as RHIC and the LHC, the diffusivity is predicted to be $D \sim \hbar c^2/k_B T$, Planck's quantum times the square of the speed of light divided by the plasma temperature. [7] The formulas for this ultra-relativistic result and that found for non-relativistic cold atoms are in fact related: while at ultra-relativistic energies, the total energy of the gas is dominated by kinetic energy $k_B T$; in a non-relativistic gas the expression would get replaced by the rest energy of particles, mc^2, giving a diffusivity of $D \sim \hbar /m$, as observed in our experiment. It is fascinating to see how the physics at vastly different energy scales is intricately linked.

Conclusion and Outlook

This article described several experiments undertaken at MIT to make, probe, and understand strongly interacting fermionic matter. These experiments allow direct connections to other fields of physics. For example, imbalanced Fermi gases are encountered in atomic nuclei, where protons and neutrons typically occur with unequal numbers. Neutron matter at high densities should form a superfluid of quarks (a so-called "color superfluid"), as studied by MIT's Frank Wilczek, Krishna Rajagopal, and others. Charge neutrality of this extreme form of matter requires the various types of quarks to occur at different densities. And in certain heavy-fermion superconductors, strong magnetic fields can enter the superconducting state, breaking pairs and leaving behind an imbalanced electron liquid. Decades ago, an exotic form of superfluidity was proposed in such imbalanced systems, where superfluid pairs and unpaired atoms can coexist, the Fulde-Ferrell-Larkin-Ovchinnikov-state of moving Cooper pairs. Cold atom experiments, especially in lower dimensions, might be in an excellent position to uncover this novel state of matter.

On the theoretical side, an exciting development is the application of string theoretical methods to the description of strongly interacting Fermi systems, as studied by MIT's Allan Adams and John McGreevy. To quantitatively test and benchmark such novel theoretical methods will be one central theme in future experiments on Fermi gases.

Another direction is to create systems with novel properties, such as fermionic superfluids of unequal fermions, where the pairing partners are not related to each other via time reversal symmetry, such as ^{6}Li bound to ^{40}K. Furthermore, fermions in confined geometries—especially in two dimensions—are a paradigm of condensed matter physics and of high practical importance: many modern materials feature a layered structure, for example the Copper-Oxide planes of cuprate superconductors that should play an important role in the system's properties such as the critical temperature for superconductivity. A dream would be the creation of quantum Hall states that might allow topologically protected quantum computing.

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