Optically Trapped Fermi Gases

A few hundred thousand atoms, chilled to near absolute zero, mimic the physics of other extreme systems, including neutron stars and superconductors

John E. Thomas and Michael E. Gehm

The bowl is only a millimeter long and a tenth of a millimeter wide, no bigger than a piece of lint. Its walls are constructed of pure light, making this "optical bowl" an appropriately ethereal container for the stuff sloshing around inside: lithium atoms that have been chilled to less than a millionth of a degree above absolute zero. But you shouldn't think of the sample trapped in this vessel of light as just a cloud of lithium (any more than you'd think of a diamond as a mere lump of carbon). Its value lies not in the atoms that make it up but in the special way they are put together—in a remarkable configuration known as a degenerate Fermi gas. Such an assemblage constitutes a new state of matter and is possibly the closest that scientists will ever come to having on their desktops a neutron star or a piece of the quark matter that made up the early universe.

Although physicists had predicted the existence of degenerate Fermi gases as long ago as the 1930s, nobody had produced a fully independent one in the lab until five years ago. The closest model we had was the cloud of electrons inside an ordinary metal like copper. Even though the metal is solid, the electrons behave very much like a gas: They are free to roam around (which makes the metal conduct electricity), but they have to fit into a strict energy hierarchy—the same one found in the degenerate Fermi gases we produced.

These gases are first cousins to another strange quantum beast that appears at ultracold temperatures, called a Bose-Einstein condensate. The research group of Eric Cornell and Carl Wieman at the University of Colorado at Boulder fashioned the first such condensate in 1995. (In 2001, Cornell and Wieman shared a Nobel prize for their work with Wolfgang Ketterle of the Massachusetts Institute of Technology.)

An atomic degenerate Fermi gas is even trickier to create, because it pits two precepts of quantum mechanics against each other. On the one hand is Heisenberg's famous uncertainty principle, which says that the location of any particle becomes more ambiguous as its speed becomes less uncertain. In an ultracold gas, the speed of the atoms is known with unusual precision: It is close to zero. Therefore the atoms get smeared out into blobs that are tens of thousands of times larger than a normal room-temperature atom. This blurring is no problem for a Bose-Einstein condensate, because it is made of "sociable" atoms called bosons, which like to overlap. But degenerate Fermi gases are made from solitary atoms called fermions (like the lithium in our trap), which according to Pauli's exclusion principle cannot share space with their neighbors. As a result, making a degenerate Fermi gas is a lot like trying to pack balloons into a closet.

Recently our group was able to probe the quantum behavior of these balloons by using a form of quantum trickery known as "strong interactions" to expand the balloons greatly in size. These interactions make the atoms affect one another at a much greater distance than they ordinarily would. There are exciting indications, not yet confirmed, that the strong interactions cause the atoms to form loose alliances called Cooper pairs. Superconductivity and some forms of superfluidity are the result of Cooper pairing. But before we describe some of the remarkable properties of the resultant gas, let us take a moment to explain the significant technical hurdles our group and others had to overcome.

Chilling Out with Lasers

The possibility of creating macroscopic quantum systems, such as degenerate Fermi gases and Bose-Einstein condensates, has come about largely because of improvements in the technology of optical cooling. In most experiments with ultracold gases, magnetic forces ensnare the atoms. By contrast, optical bowls use electric forces, which have the advantage that they can corral any kind of atom, whereas magnetic traps work only for certain types.

In the simplest case, an optical bowl consists of an intense laser beam that is tightly focused into a high-vacuum region. The light draws cold atoms or molecules toward its focal point and confines them in a frictionless, heat-free environment, which is ideal for studies of fundamental phenomena.

Why would a focused beam of light attract atoms? The secret is that light is an electromagnetic wave, consisting of oscillating electric and magnetic fields. The electric field in a light beam exerts a force on charged particles, such as the electrons and protons inside an atom.

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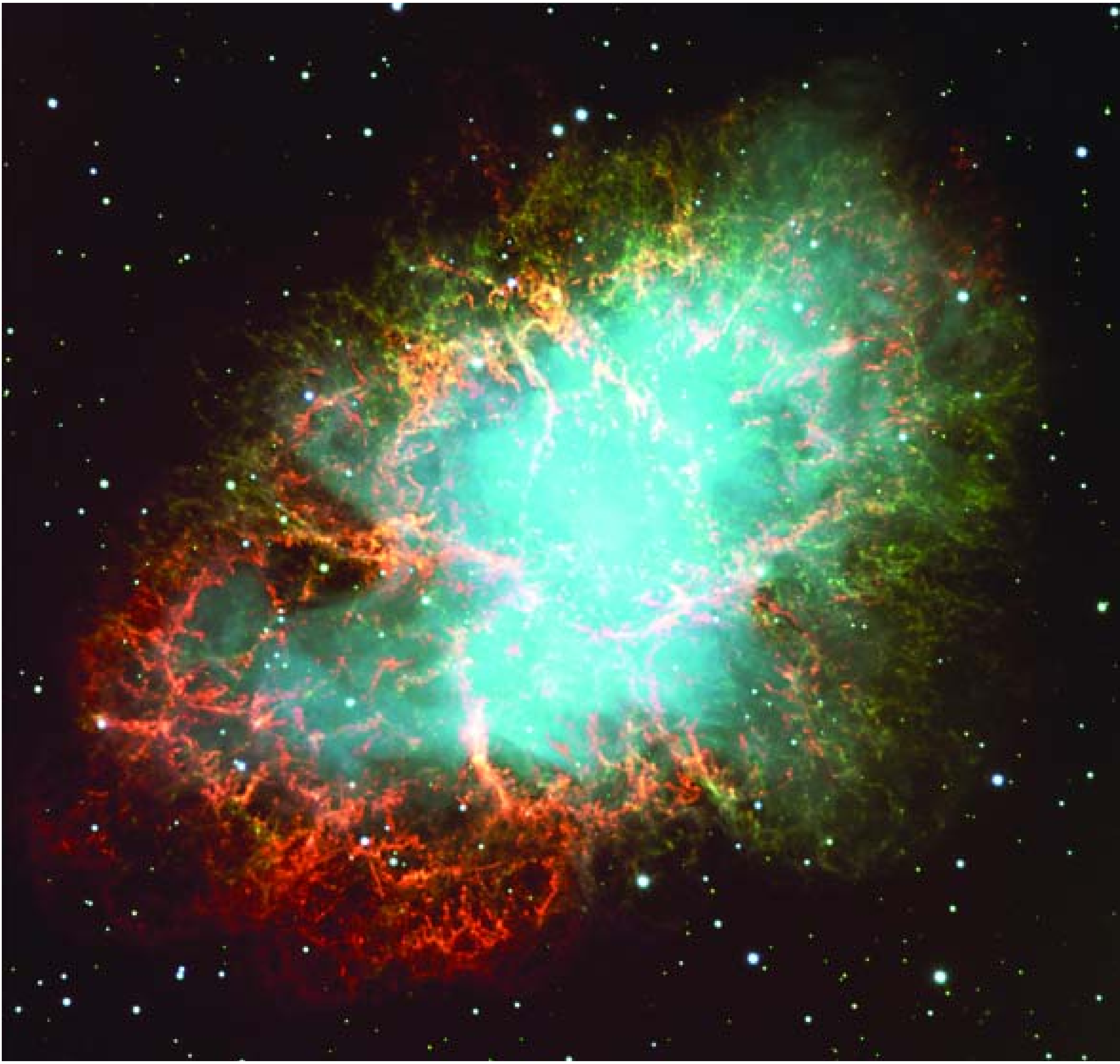

Figure 1. Experiments with ultracold Fermi gases help to illuminate the physics of various extreme systems, including the interior of neutron stars, such as the one left over from the supernova explosion that created the Crab Nebula *(above)*. Neutron stars are prevented from collapsing into black holes by virtue of "Fermi pressure," a consequence of the Pauli exclusion principle of quantum physics. (Image courtesy of the European Southern Observatory.)

An atom, however, has an equal number of electrons and protons, and thus is electrically neutral. A force nonetheless arises, for a somewhat subtle reason: the field gradient.

If, for example, the electric field points upward and toward the focus of the beam, a positively charged nucleus in an atom below the beam will be pulled upward, and the negatively charged electron cloud will be pushed downward. The nucleus, being closer to the focus of the beam where the electric field is larger, then experiences an attraction that is slightly stronger than the repulsion the electron cloud feels, and so there is a net upward force on the atom. If the situation were reversed, with the electric field pointing away from the beam, the nucleus would move farther away, and the electron

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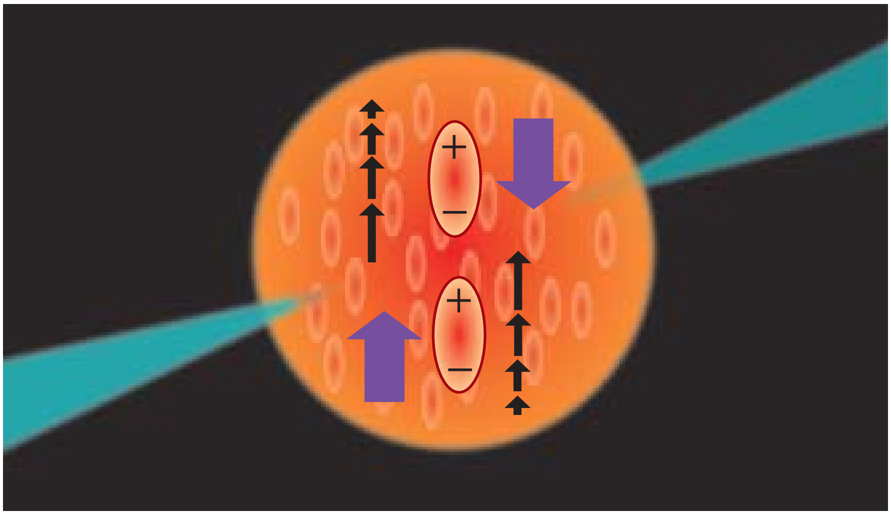

Figure 2. Trapping neutral atoms in a cold, rarefied gas *(orange cloud)* can be accomplished using an "optical bowl," an intense laser *(blue)* that draws the atoms into the focus of the beam. The oscillating electric field of the laser causes the positively charged nucleus and the negatively charged electrons of each atom to become slightly separated. Because the electric field *(black arrows)* is greatest near the focus, the force on the positive side of an atom is not completely balanced by the opposing force on the negative side. Below the beam, for example, the upward force exerted on the top of an atom slightly exceeds the downward force on the bottom. Similarly, above the beam the downward force exerted on the bottom of an atom exceeds the upward force on the top. Thus in either case a net force arises *(purple arrows)*, pulling the atoms inward.

cloud would move closer. The net force would once again be toward the focus. For reasons that are too complicated to explain here, the same phenomenon holds for atoms on the axis of the beam, but located in front of or behind the focus. Thus, whichever direction the electric field points, the atom always gets pulled gently inward.

The key word here is "gently." At room temperature, or even well below, the random thermal movements of an atom will always overcome the feeble tug of the laser. Therefore, to capture atoms in an optical bowl, one has to use a very intense laser and make the atoms very cold, so they do not move too rapidly. The carbon dioxide laser in our experiments has an intensity at its focal point of 2 million watts per square centimeter, more than enough to cut through steel. Even at this intensity, the optical bowl is only deep enough to confine an atom whose initial temperature is less than a thousandth of a degree above absolute zero. (Technically, individual atoms do not have a temperature *per se*. However, it's easy enough to convert the kinetic energy of an atom to a temperature equivalent, and this operation tells you how cold a gas must be to stay in the optical bowl.)

Because the atoms have to be very cold already for us to capture them with a laser beam, setting up the optical bowl is the second part of our three-step protocol. First, we cool several hundred million lithium atoms down to about 150 millionths of a degree above absolute zero, using a now-standard strategy called a magneto-optical trap.

This device uses six red laser beams, arranged in three orthogonal pairs. Each of the pairs of beams slows the lithium atoms in a single direction by cleverly exploiting the Doppler effect. From the perspective of a moving atom, the laser beam that propagates in the opposite direction seems to shift to a higher frequency, and the atom will see this as an increased "headwind." At the same time, the laser beam that travels in the same direction as the atom will shift to a lower frequency and create a reduced "tailwind." Because the effect increases with the velocity of the atom, one can think of the laser light as exerting a viscous force. This is why one of the inventors of the magneto-optical trap, the Nobel laureate Steven Chu of Stanford University, coined the very appropriate nickname *optical molasses*.

Without the "molasses," an atom passing into our optical bowl would shoot right out again, like a marble dropped into a teacup from a considerable height. Having a magneto-optical trap is like filling the cup with honey first—the marble comes nearly to rest at the bottom of the bowl. Thus, we should be able to turn off the molasses after loading, and retain the atoms in the optical bowl for a very long time.

Or so the theory goes. In practice, optical bowls did not work as expected until the late '90s, when our group figured out what had been vexing them. The problem was that the atoms in an optical bowl slosh back and forth at a certain characteristic frequency: in our experiments, 6,600 times per second in the short direction and 230 times per second in the long direction. (The second frequency is lower because the attraction to the center of the optical bowl is weaker in the axial direction.) The lasers then in use were not steady, and in particular they had an intensity fluctuation at twice the frequency of the atoms in the trap.

To see the problem this causes, imagine an atom oscillating from side to side, with the walls of the bowl vibrating in and out. The atom gets a push from the inward-moving side of the bowl. By the time this atom reaches the other side (after one half of its period of oscillation), it encounters the opposite wall of the bowl, which by this time is again moving inward. So the atom gets a push from that side. Over and over the sides of the bowl keep shoving the atom back and forth, pumping it right out of the bowl in a few seconds.

We overcame this problem in 1999 using a custom-built laser designed to operate without jittering so much in intensity. With it, we succeeded in trapping atoms for five minutes, hundreds of times longer than with previous optical bowls. Since then, we have replaced that laser with a more powerful and extremely stable commercial unit, and we can now keep the atoms contained for almost seven minutes.

After we confine the atoms in the bowl, they are still not cold enough for quantum effects to take over. For that, they need to be chilled even more using the third and final step, called evaporative cooling. There is nothing fancy about this stage; it is inspired by the way a hot bowl of soup cools. When two atoms collide, occasionally they can pool their energy, and one of them can gain enough oomph to escape the trap or "evaporate." The other one slows down. It then hits the other atoms in the trap, cooling them, and the process continues. Eventually the atoms get so cold that even two of them together do not have enough en-

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ergy for one of them to leave. At this point no more evaporation can take place, and the cooling stagnates. To overcome this problem, we slowly lower the intensity of the trapping laser beam—in effect, lowering the "lip" of the optical bowl—so that some of the warmer atoms can escape. We lose about two-thirds of the atoms in this way, but the remaining ones become cold enough to form a degenerate Fermi gas.

Quantum Effects

According to quantum mechanics, all matter exhibits both particle-like and wavelike properties. When a particle, such as an electron or even a whole atom, is considered as a wave, it is said to have a "de Broglie wavelength," which determines the effective "size" of the particle. The de Broglie wavelength varies inversely with momentum. Increasing the momentum, as in a particle accelerator, makes the wavelength of the particle very small. (This is why physicists use accelerators to probe very tiny features within an atom—such as its electrons, protons and neutrons.) When the momentum is very small, as in our optical trap, the atom spreads out like a balloon. At these extremely low temperatures, the balloon is about a micrometer in diam-

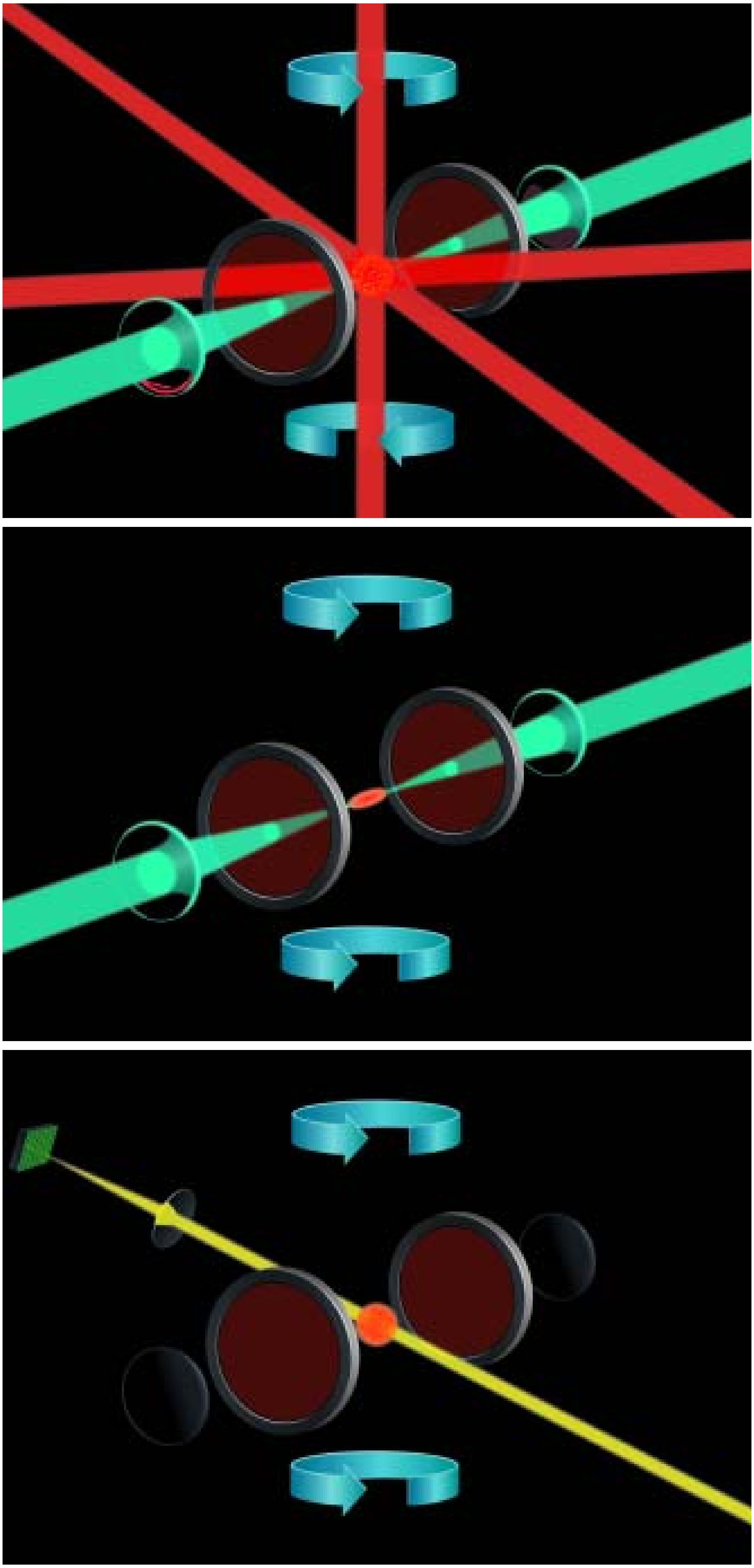

Figure 3. Formation and study of a degenerate Fermi gas begins with a cloud of lithium atoms, which are slowed by the six inward-directed laser beams of a magneto-optical trap *(red at top)*, a device that is said to create an "optical molasses." (The ringlike arrows indicate the flow of current in an adjacent pair of coils, which generates a magnetic field.) Once these atoms are cooled to 150 millionths of a degree above absolute zero, they can be confined in the "optical bowl" created by a single focused laser beam *(blue)*. Because the restoring force perpendicular to the beam is greater than along the beam, the bowl produces a cigar-shaped cloud of atoms *(center)*. Gradually decreasing the intensity of this beam allows some of the atoms to escape, cooling those that remain, which eventually reach 50 billionths of a degree above zero. At this temperature the gas becomes degenerate, a highly organized state that acts somewhat like a single "mega-atom." The authors study this phenomenon by turning off the laser that forms the optical bowl, allowing the cloud to expand. They obtain a sequence of pictures of the evolving cloud using short pulses of laser light *(yellow at bottom)*, which pass through the gas before being projected onto an imaging device *(green)*. The behavior of the cloud as it expands preserves a "memory" of its time as a degenerate Fermi gas.

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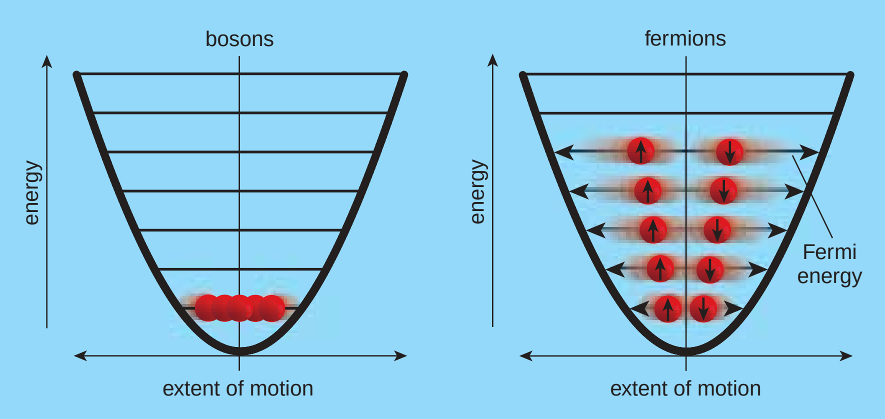

Figure 4. All atoms in a Bose-Einstein condensate attain the same energy level, the lowest one available *(left)*, whereas only two atoms (with opposite nuclear spin) can share one energy level in a degenerate Fermi gas *(right)*. As a result, the atoms in such a gas occupy a series of increasing energy levels, up to a level that corresponds to the Fermi temperature of the gas. The higher the energy level of an atom, the broader its oscillatory motion within the trap.

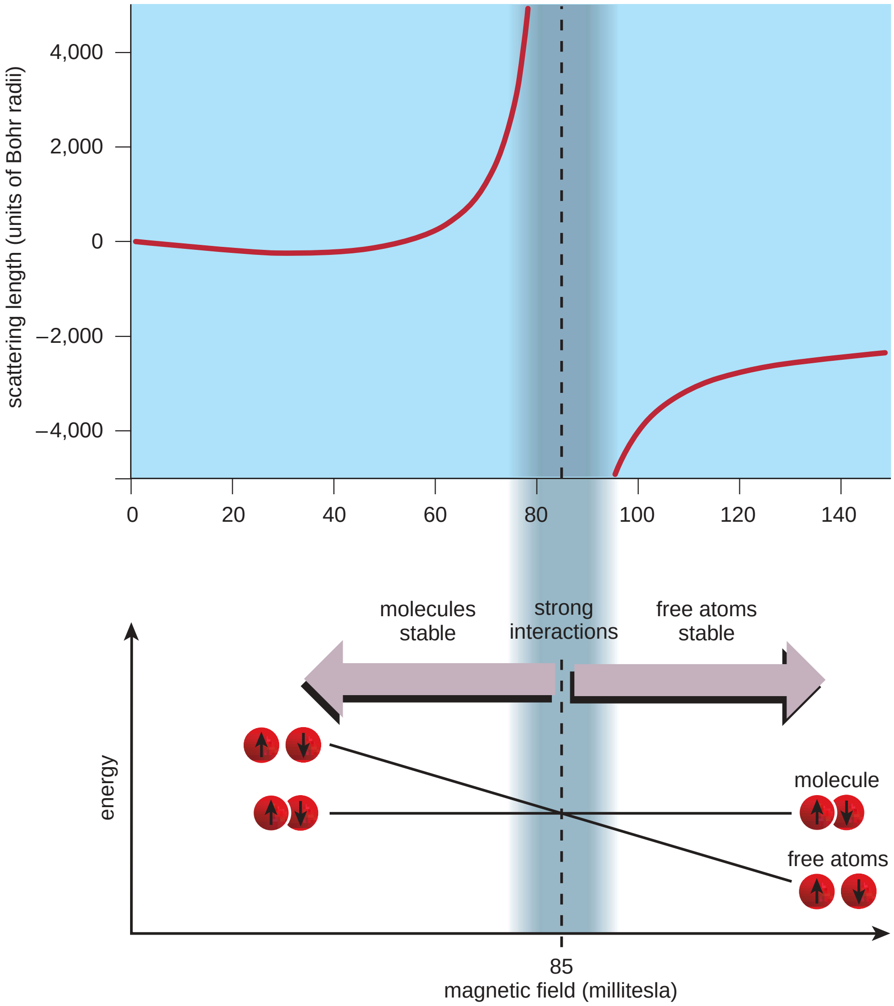

Figure 5. Feshbach resonance changes the behavior of a degenerate Fermi gas. This phenomenon causes the distance at which the atoms influence one another—their "scattering length"—to increase dramatically when a magnetic field of a particular strength is applied *(top)*. (A positive scattering length corresponds to repulsion; negative to attraction.) In the case of ^{6}Li atoms, Feshbach resonance takes place at 85 millitesla. In a weaker magnetic field, a molecule has a lower energy than a pair of free atoms. In a stronger field, free atoms are energetically favored *(bottom)*. Near resonance, free atoms and those bound in a molecule act similarly, which accounts for the substantially increased scattering length, or what physicists call "strong interactions."

eter—a length that is large enough to resolve with a good microscope.

When the de Broglie wavelength gets large enough, the balloons start to touch one another and then try to overlap. At that point, the gas is called "degenerate," and its behavior starts to be governed by quantum rules rather than the rules of classical physics.

Yin and Yang

Since the 1930s, physicists have realized that quantum particles fall into two categories: bosons and fermions. Identical bosons are gregarious particles, preferring to occupy the same energy states as their neighbors. Photons (particles of light) behave this way, for example in lasers, where photons of a certain energy stimulate atoms to release more photons of the same energy.

The particles that make up ordinary matter—protons, neutrons and electrons—are fermions, and they behave quite differently. As the physicists Enrico Fermi and P. A. M. Dirac discovered, these particles are introverts. Two fermions with the same "spin" cannot be at the same energy level and occupy the same region of space. (The spin of a particle has to do with the way it lines up in a magnetic field. It comes in two varieties: spin up and spin down.) This behavior, too, has major consequences in everyday life. It explains the periodic table. The second row of the periodic table, for instance, has eight elements because the second electron shell has slots for eight electrons. Two electrons can never share the same slot, because they are fermions.

Larger composite particles, such as atoms or molecules, act like fermions if they are made of an odd number of fermions, and like bosons if they are made up of an even number. Thus lithium-6, with 3 protons, 3 neutrons and 3 electrons, is a composite fermion, whereas lithium-7, with one more neutron, is a composite boson. At ordinary temperatures the two isotopes have identical chemical properties, but at supercold temperatures, their different quantum personalities emerge.

When a gas of composite bosons, say one made up of lithium-7, is chilled in an optical bowl, a sudden transition occurs at the onset of degeneracy (the "transition temperature"). Suddenly the gas changes from a classical one, with the atoms in various energy states, to one in which they all have the same energy—the least that the container al-

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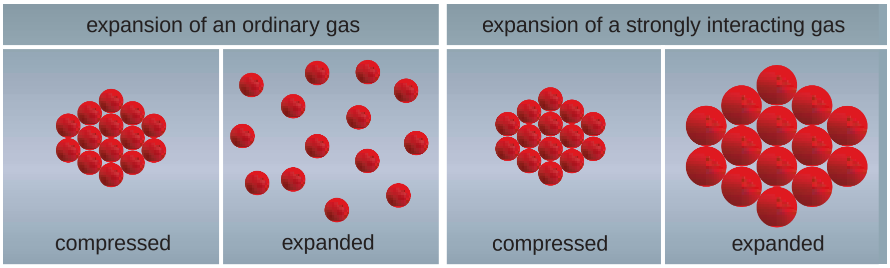

Figure 6. Strongly interacting Fermi gases behave very differently from normal gases when they expand. In an ordinary gas, the atoms interact very rarely after they are released from a compressed state. In the Fermi gas, the atoms oscillate inside "quantum balloons," which expand along with the atomic spacing. Therefore the atoms continue to exert Fermi pressure on one another, an interaction that operates over comparatively large distances.

lows. That is, all of the atoms oscillate with the lowest energy and the longest wavelength possible. They vibrate in unison, like a single mega-atom. This is a Bose-Einstein condensate.

When a gas of composite fermions, say one made up of lithium-6, is cooled to the transition temperature (called the "Fermi temperature" for fermions), a different transition takes place: The atoms begin to arrange themselves in an orderly fashion, two in the lowest energy state allowed, two in the next lowest, and so on—just as the electrons in a regular atom do. The result is a degenerate Fermi gas, which might be thought of as a different kind of mega-atom.

Soon after Cornell and Wieman created the first Bose-Einstein condensate, investigators began trying to produce the first degenerate Fermi gas of atoms. (Recall that degenerate Fermi gases made of electrons already existed, in any metallic conductor.) In 1999, Deborah Jin of the University of Colorado succeeded with potassium-40, using a modified version of Cornell and Wieman's magnetic trapping techniques. Unfortunately, Jin's method does not apply to all atoms, and it took other groups a longer time to develop more general techniques. In 2001 Randy Hulet's group at Rice University, Christophe Salomon's at École normale supérieure, and Ketterle's at MIT achieved success using magnetically trapped bosons to cool fermions contained in the same trap. Hulet and Salomon showed that fermionic lithium-6 gas occupies a much larger volume than bosonic lithium-7. This difference makes sense, because the fermions are forced to adopt many different energy levels—and some thus must move in orbits of large radius, whereas the bosons all crowd into the lowest energy state and have a small radius of motion.

At the same time, our group at Duke also managed to produce degenerate Fermi gases colder than one-tenth of the Fermi temperature, using all-optical cooling methods. These highly degenerate Fermi gases are quite stable, and they exhibit spectacular properties when we introduce the "strong interactions" that we mentioned in the introduction.

The Magic of Strong Interactions

In an ordinary gas, collisions between atoms are quite rare and short-lived, and hence any particular atom is not affected very much by its neighbors. This is not the case in a strongly interacting degenerate Fermi gas, where the atoms jostle against one another and exist in a more or less constant state of collision.

"Collision" is perhaps too violent a word for this kind of behavior, so quantum physicists usually employ the more neutral term "interaction." But one should not confuse these very long-distance interactions with classical forces. An interaction arises when two particles literally try to share the same real estate and either do it amicably (as in the case of bosons) or fight over it (as in the case of fermions). The distance at which the particles first start to "notice" one another is called the scattering length, and an interaction is said to be *strong* if it has a large scattering length. In recent years, several groups have demonstrated the possibility of changing the scattering length—making it as large as desired, and even changing it from attractive to repulsive—by applying a magnetic field.

Why does this work? To begin with, we should explain that our degenerate Fermi gas really contains two populations of fermions, some with spin up and others with spin down. The prohibition on sharing the same space does not apply to two fermions with opposite spin. Normally lithium-6 atoms with opposite spin barely notice each other, and so their scattering length is near zero.

When we turn on a magnetic field, it changes the internal magnetic energy of an atom, which behaves like a bar magnet. When the total energy of an opposite-spin pair of atoms matches that of a two-atom molecule, they can interact very strongly. In a sense, the magnetic field fools the atoms into thinking they are in a molecule. The phenomenon is called a "Feshbach resonance," after the late MIT physicist Herman Feshbach, who first predicted it. When the magnetic field is tuned correctly, the atoms can notice each other at what is, in atomic terms, an incredibly long distance.

How long, exactly? One limitation is the de Broglie wavelength; if two atoms are farther apart than the de Broglie wavelength, they will be obliv-

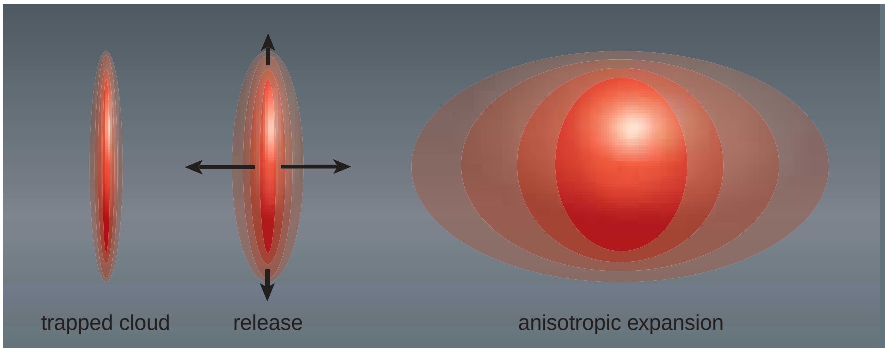

Figure 7. Theory predicts that strongly interacting Fermi gases should expand anisotropically after release from an optical trap. Because pressure falls off most abruptly radially outward from the axis of the elongate cloud, the gas expands more rapidly in this direction than along the axis *(black arrows)*. The gas thus changes shape over time, shifting from cigar *(left)* to bulging pumpkin *(right)*. The presence or absence of such shape-changing expansion can serve as a litmus test for strong interactions—and perhaps for superfluidity.

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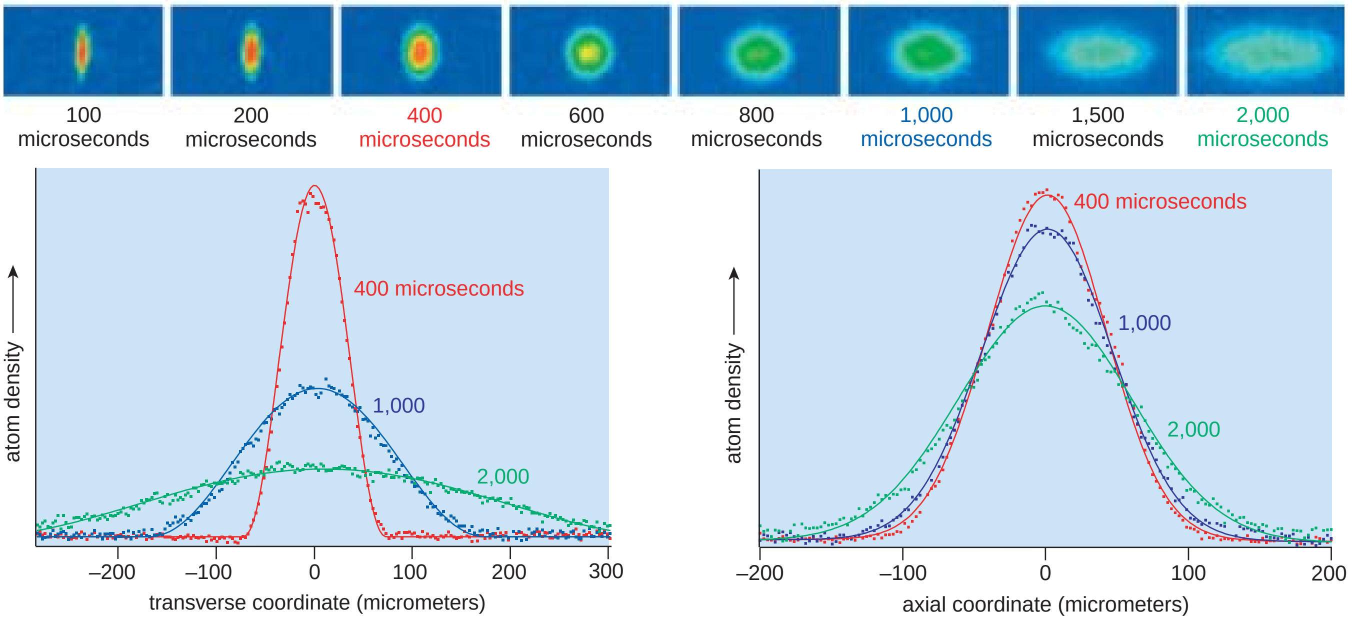

Figure 8. Experimental data confirm the anisotropic expansion of a cloud of ^{6}Li atoms. Sequential images capture the change in shape and density of the gas cloud as it warms. The gas remains degenerate, and strongly interacting, for about 400 microseconds after release (shown in the first three frames). After 400 microseconds, the high initial velocity of the atoms causes the cloud to continue changing shape in the same manner, although the atoms are no longer strongly interacting. Quantitative measurements derived from these images show that the atoms spread out much more rapidly transverse to the axis of the cloud *(left graph)* than along it *(right graph).*

ious of each other for sure, like two balloons that pass by each other. So in any Fermi gas, the scattering length can be no larger than the de Broglie wavelength, which in turn can be no bigger than the spacing between particles (because otherwise some of the same-spin fermions would overlap).

But at supercold temperatures, the de Broglie wavelength grows until it matches the spacing between atoms. Also, when the magnetic field is suitably arranged, the Feshbach resonance makes the scattering length increase to its maximum possible value: the deBroglie wavelength. So when we combine cold temperature with a precisely tuned magnetic field, the scattering length, the de Broglie wavelength and the interparticle spacing are all the same.

Our group was the first to observe a remarkable thing that happens when you prepare such a gas and then remove the container by turning off the optical bowl. Initially, the trapped atomic gas has the shape of the optical bowl—a long, narrow cigar. When the atoms are released, the atomic gas expands rapidly in the narrow (radial) direction of the cigar, while standing nearly still in the long (axial) direction! This is a consequence of the pressure forces on the gas: Each small part of the gas is pushed out by the pressure behind it and inward by the pressure in front of it. That is, the pressure gradient determines the outward force, which is largest in the narrow directions of the cigar. In an ordinary gas, the atoms would soon stop pressing against one another as they escaped. But in our strongly interacting Fermi gas, the atoms themselves (really their quantum "balloons") keep expanding to match the spacing between them, and the pressure gradient does not go away for a long time. The metamorphosis continues even after the gas stops interacting, because the radial velocity of the atoms continues to be greater than the axial velocity as the atoms coast freely. Then, the cloud continues to expand much more rapidly in the radial direction than it does lengthwise, so it visibly changes shape, from a "cigar" to a "pancake."

With the strong interactions, degenerate Fermi gases also exhibit what physicists call *universal behavior*, becoming a model for many other natural physical systems. In other words, any strongly interacting Fermi system (any system in which scattering length equals interparticle spacing) should act in like ways. It does not matter whether the fermions are atoms, electrons, quarks or something else. The way these systems interact in bulk will always be similar. That is why the degenerate Fermi gas in our laboratory can become a table-top tool to test the latest theories of quark matter or neutron stars. Indeed, the remarkable shape-shifting behavior we observe is similar to the dynamical behavior predicted recently for a quark-gluon plasma.

As another example, we have done experiments to determine the "net interaction energy" in a strongly interacting Fermi gas, which is simply the total energy of attraction or repulsion of a given particle to all other particles near enough to interact with it. In a universal system, one can show that this quantity is proportional to the average kinetic energy of the constituent particles.

The constant of proportionality, denoted beta, has important consequences for the mechanical stability of such a system. The kinetic energy gives rise to an effective repulsion between the interacting fermions, which is known as the Fermi pressure. This pressure tends to keep fermions apart and is responsible for the stability of neutron stars against gravitational collapse and for the mechanical stability of our trapped gas. However, the net interaction energy also provides a pressure, which can be inward or outward, depending on the sign of the proportionality constant. If beta were less than –1, the inward pressure due to the interaction energy would exceed the outward Fermi pressure, and the system would collapse.

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Nuclear physicists have struggled for thirty years to compute beta. That task is extremely difficult because the required calculations involve the interaction of many particles. The best estimate obtained from theory is about –0.5. That is, the net interaction energy should exert an inward force that is only half the strength of the outward Fermi pressure, which is consistent with the obvious fact that neutron stars are stable. Needless to say, one can't just grab of piece of a neutron star and check out whether this value is exactly –0.5. But now we have measured beta in our laboratory, and Salomon and Rudolf Grimm of the University of Innsbruck have since made similar measurements.

From our first experiments, we have estimated that beta is about –0.26. Recently, Salomon obtained –0.3 at a somewhat higher temperature, and Grimm obtained values closer to –0.5. It is too early to pronounce a definite verdict, as both the experimental and theoretical estimates may still have systematic errors. What is encouraging is that the values are reasonably close—close enough anyway that experimentalists and theorists will have something to talk about over the next few years.

The Quest for Superfluidity

Sandro Stringari, a theorist at the University of Trento in Italy, first predicted the "shape-changing" behavior in 2002, before anyone had managed to produce a strongly interacting degenerate Fermi gas. He argued, further, that the shape-changing was a possible signature of superfluidity.

Superfluids, which were first discovered in the 1930s, are substances that flow without friction. The atoms in superfluids act like the electrons in superconductive materials, which flow with zero resistance. In principle, superconducting wires can be harnessed for all sorts of useful purposes, for example, to transmit electricity long distances without any energy loss. In practice, though, ordinary superconductors only operate at temperatures a few degrees above absolute zero. Even the so-called "high-temperature" superconductors, discovered since the 1980s, have to be chilled to liquid-nitrogen temperatures. It is no exaggeration to say that the search for a room-temperature superconductor is a holy grail of condensed-matter physics.

To the extent that the atoms in a superfluid imitate the electrons in a superconductor, degenerate Fermi gases may help in that quest. Physicists have known since the 1950s that conductors become superconducting when opposite-spin electrons pair up and start flowing together through the atomic lattice. Similarly, a fermionic liquid, such as helium-3, becomes a superfluid when its atoms pair up in the same way. These loose associations, which are not as permanent as molecular bonds, are known as Cooper pairs.

For all known superconductors, Cooper pairs become stable only at a temperature vastly below the Fermi temperature—roughly 10 to 100 degrees above absolute zero, or one-hundredth to one-thousandth of the Fermi temperature. (The Fermi temperature of a metal—construed as a degenerate Fermi gas—is extremely high because it contains so many electrons, or fermions. Thus every energy level is occupied up to a very high energy. The most energetic electrons, the ones in the conduction band, have an equivalent temperature of 10,000 degrees.)

Recently, three theoretical groups have predicted that strongly interacting Fermi gases can become superfluids at temperatures up to half of the Fermi temperature. If the theory is correct, such systems will produce the highest-temperature Cooper pairs known to physics (highest temperature as a fraction of the Fermi temperature, that is). Several groups, including ours, have now produced such gases at temperatures well below one-tenth of the Fermi temperature, so a high-temperature superfluid may already have been created. However, unambiguous proof of its existence has so far eluded all experiments.

Perhaps it seems like cheating to call a gas a "high-temperature" superfluid when its actual temperature is less than a millionth of a degree above absolute zero. To understand why not, consider this analogy. The development of a new airplane proceeds from sketches on paper to scale models to a working prototype. In our case, the "paper sketch" is the concept of a universal Fermi system. The "scale model" is a strongly interacting degenerate Fermi gas. It is scaled down both in physical size and in temperature. The universality principle means that this scaling should not fundamentally change the properties of the system. If the scale model did not work, we would have reason to suspect that Cooper pairs cannot form at temperatures comparable to the Fermi temperature. But if the scale model does work—if Cooper pairs can exist at a large fraction of the Fermi temperature—then the same thing might be possible in a conductor: It is conceivable that scientists might one day fashion materials that superconduct all the way up to 2,000 degrees or more—not just room temperature but a good deal warmer.

It may be too much to dream of such an ultrahigh-temperature superconductor happening anytime soon. But we can hope at least that the insights gleaned from recent work on degenerate Fermi gases will lead to an era of new super-high-temperature superconducting materials.

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