next lowest level and so on. But, as summarized in figure 2, that's not what happens. In the two pathways the Berkeley team identified, electrons take advantage of the delocalized coupling between neighboring chlorophylls to skip between states that are close in space but not necessarily adjacent in energy. Doing so speeds the flow of energy, which is too fast for any energy-sapping phonons to respond.

Phonons and other physical features limit the efficiency of photovoltaic cells to about 20%. Could the photosynthetic pathway be exploited to make a device that converts light into electricity with *C. tepidum*'s stunning efficiency? Copying its light-harvesting system wouldn't work because the bacterium, like other photosynthesizing organisms, runs an elaborate biomolecular mechanism to mitigate and repair radiation damage. Conceivably, a bio–nano hybrid could be built. But, says Fleming, "it's a distant dream."

Charles Day

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Images of Vortices Reveal Superfluidity in a Fermi Gas

The superfluid formed in a low-density atomic gas is a clean and controllable system for exploring strong interactions among particles.

Fermionic atoms can team up in distinctly different ways. In one regime, the atoms can bind tightly together to form molecules. Such molecules, being bosons, can collapse at low enough temperature into a common ground state—a Bose–Einstein condensate (BEC). In another regime, the fermions can associate in widely spaced pairs. At low temperature, the pairs may lock in phase with one another, falling into a coherent many-body state analogous to the electronic superconductor described by the Bardeen-Cooper-Schrieffer theory. The paired state, like the BEC, would be a superfluid.

Fortuitously, experimenters can take a gas of ultracold fermionic atoms smoothly from the BEC regime to the BCS regime simply by tuning a magnetic field. More than a year ago, experimenters saw a BEC in molecules made of fermionic atoms (see Physics Today, October 2003, page 18). Soon afterward Deborah Jin's group from JILA, NIST, and the University of Colorado, all in Boulder,[1] and then Wolfgang Ketterle's group at MIT[2] observed a phase transition at low temperatures to a condensate of correlated pairs. They also saw a smooth evolution from this condensate to a molecular BEC as the interparticle force changed sign (see Physics Today, March 2004, page 21). The pair condensates were in a regime where the interatomic forces are particularly strong, unlike the weak interactions between the electrons in the Cooper pairs of a conventional superconductor.

Intrigued by this phase of correlated pairs, researchers looked for clear evidence that it is a superfluid, as expected. Recently, a number of experimental groups have reported behavior consistent with superfluidity, but they have found no direct evidence. Now, Ketterle and his coworkers have provided the smoking gun.[3] They report seeing vortices, a hallmark of superfluidity, in an ultracold fermionic gas. "It nails the case shut," remarked Randy Hulet of Rice University.

Testbed for strong interactions

One key reason for the interest in this superfluid of fermionic atoms is that it might shed light on the behavior of

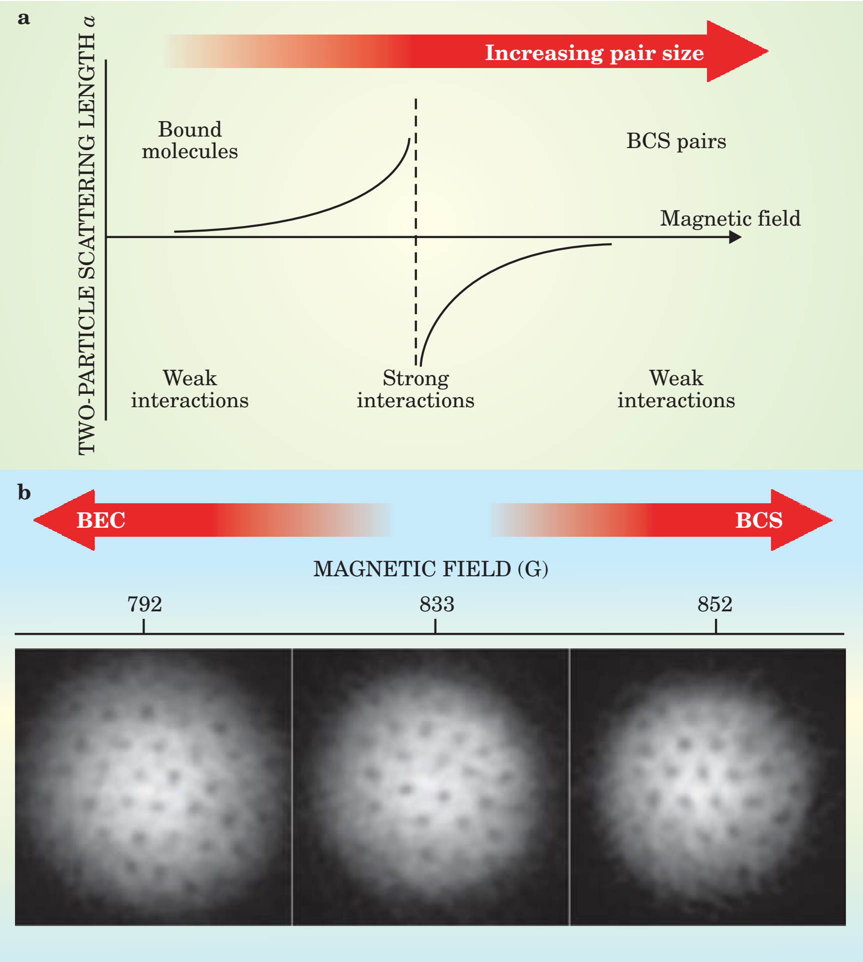

Figure 1. Pattern of vortices as seen in an ultracold Fermi gas at three different values of magnetic field. **(a)** As the magnetic field nears the Feshbach resonance (dashed line), the two-particle scattering length *a*, which determines the interaction strength, gets very large and changes sign. Near resonance, interactions are strong. To the left, fermionic atoms form bound molecules; to the right, they form Bardeen-Cooper-Schrieffer (BCS) pairs. Between those two extremes, the distance between atoms in a pair increases smoothly. **(b)** Vortices appear when the atomic cloud is just below, right at, and just above resonance. (Adapted from ref. 3.)

any strongly interacting particles. One can conduct experiments with an ultracold Fermi gas in a highly controlled way, such as dialing the magnetic field to reach a given interaction strength. When these forces are especially strong, the behavior of the atoms is expected to be universal—that is, independent of the microscopic details of the particles. The behavior should depend only on the density and temperature of the gas. Thus, the low-density gas might give interesting insight into other strongly interacting systems of fermions, such as the electrons in high-T_c superconductors or the quarks in a quark–gluon plasma.

A Fermi gas superfluid is also interesting because no other system has such a high T_c (the critical temperature below which superfluidity sets in), relative to the Fermi temperature T_F (the temperature corresponding to the Fermi energy). For fermionic atoms in the BCS regime, T_c/T_F is on the order of 0.3, compared to a value of 0.01 for a high-T_c superconductor.

The two-particle scattering length a, which determines the strength of the interaction, depends on the magnetic field in which the fermionic atoms sit. As seen in figure 1a, a changes rapidly when the magnetic field approaches the so-called Feshbach resonance. Far below this resonance, in the regime where molecules form, a is small and positive, which gives rise to weakly repulsive interactions between unpaired atoms. Far above resonance, on the BCS side, a is small and negative, and causes a weak attraction. Close to the Feshbach resonance region, where a goes from positive infinity to negative infinity, no simple theory applies. Theorists have predicted that the superfluidity of fermionic pairs near the Feshbach resonance should be observable at experimentally accessible temperatures.

The size of the pairs is expected to vary smoothly as the magnetic field increases—going from the BEC limit, where atoms are bound closely in molecules, to the BCS limit, where correlated pairs are separated by distances much larger than the interatomic spacing. In the strong-interaction region, pair size should be comparable to the separation between unpaired atoms in the gas.

A smoking gun

Ketterle and colleagues, following suggestions from theorists, looked for the formation of vortices in their condensate. If you stir a cup of coffee, you can rotate the entire fluid. But a superfluid can't rotate in the same way. Instead, the angular momentum introduced by stirring must appear as quantized vortices. In the case of atom pairs, the circulation around such vortices is quantized in units of $h/2m$, where m is the mass of a particle in the gas. (Circulation is the line integral of velocity around a closed loop.) In a vortex core, the superfluid density vanishes and only the normal component of the gas remains.

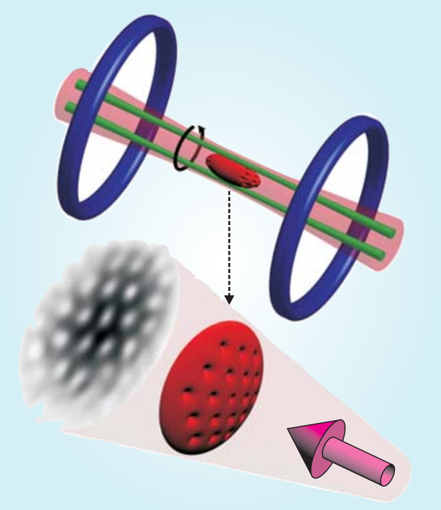

Figure 2. Experimental setup. A condensate of fermionic pairs (red) is trapped in the waist of a focused laser beam (pink). Two additional laser beams (green) rotate around the edges to stir the condensate. Blue coils create a magnetic field. After the cloud has ballistically expanded, yet another laser beam (pink arrow) projects the vortices onto an absorption image. (Courtesy of Andre Schirotzek, MIT.)

Forming such vortices in a Fermi gas was far more difficult than Ketterle had anticipated. He said it took his best people 10 months to get the vortices, despite his group's prior experience with vortices in BECs.

For the experiment, sketched in figure 2, the MIT team confined and cooled a gas of fermionic lithium-6 atoms in an optical trap. The gas formed a cigar-shaped cloud around a symmetry axis. Once the gas was optically trapped in a focused laser beam, the researchers applied a magnetic field parallel to the cigar's long axis to tune the strength of the interactions. Finally, team members Martin Zwierlein, Jamil Rashid Abo-Shaeer, Andre Schirotzek, and Christian Schunck stirred the cloud by shining laser beams parallel to the same axis but on opposite sides of the condensate. The beams were moved around the periphery of the cloud at a fixed rotational frequency to add angular momentum. An additional laser beam was used to make absorption images of the vortices.

A critical factor in this experiment was to align the magnetic field, the trapping laser beam, and the imaging laser beam very precisely, commented John Thomas of Duke University. To help with that alignment, the MIT researchers practiced by forming vortices in a sodium BEC—a much easier task. Doing so helped optimize the setup for the more finicky lithium gas.

Imaging the vortices was another problem. The vortices on the BCS side of resonance are not expected to have enough contrast to show up in an absorption image. Furthermore, the experimenters had to expand the cloud before imaging it, to magnify the vortices. During expansion, the weakly bound Fermi pairs started to break up. So Ketterle and his colleagues resorted to a trick.[1] They brought the cloud back to the BEC side, forcing the loosely bound pairs to collapse into more stable molecules, before expanding the cloud and imaging it.

That procedure, of course, raised concerns that vortices might be formed in the process of ramping down the field. The MIT researchers think they excluded this possibility by ramping the system back to the BEC side only when the cloud was already expanding. The ramping time was much shorter than the time to form an ordered pattern of vortices.

The images seen in figure 1b are the vortices formed at three different values of magnetic field: just below, at, and just above the Feshbach resonance. The vortices are arranged in a regular lattice, as expected by theory. To enhance the contrast for these particular images, the cloud was stirred at a lower field before being ramped up to the field indicated. This procedure results in a larger number of vortices than if the stirring had been done at the final field.

Previous hints of superfluidity

Before the MIT group found vortices, researchers had detected a variety of behaviors consistent with superfluidity. Two experiments measured the anisotropic hydrodynamic expansion of an atomic cloud after it was released from its trap.[4,5] Two other experiments found damped oscillations in an excited atomic cloud, which resembled the jiggling of a disturbed dish of jelly.[6,7]

Rudolf Grimm and his colleagues from the University of Innsbruck measured the energy gap, or binding energy, of the pairs above and below the temperature predicted for the onset of superfluidity.[8] The researchers found that the gap increased as the temperature fell. Furthermore, they noted that the energy gap opened well above the predicted temperature; they cited that behavior as evidence that the pairs were correlated at higher temperature but became coherent only below T_c.

Earlier this year, Thomas and his group at Duke teamed with Kathryn Levin and her coworkers from the University of Chicago to undertake a thermodynamic measurement of a fermion cloud.[9] The collaborators determined the heat capacity of the Fermi gas in the strong-interaction region and reported an abrupt change in slope, which they attributed to the formation of a superfluid. The transition temperature is close to the predicted onset of superfluidity. The collaborators had to devise a model-dependent calibration of the temperature in the strong-interaction region, where the well-understood relation between the shape of the atomic cloud and its temperature breaks down.

More recently, the Duke experimenters have reported that the rate of damping of a radial oscillation in a trapped cloud of gas slows near the same temperature at which they saw the change in heat capacity.[10]

Grimm recognizes that his group's experiment,[8] as well as that of the Duke–Chicago team, "needs some theoretical support for a conclusion on superfluidity," though, he adds, such support is available in both cases.

In a forthcoming paper, Hulet and his Rice University coworkers have studied further the nature of fermionic pairs.[11] They have measured the pair correlation as the interaction strength increases through the Feshbach resonance and, for the first time, into the weakly interacting BCS regime. They find that the pair correlation varies smoothly across this region, growing smaller as the size of the pairs grows. The data show a deviation from two-body physics in the resonance region and imply that many-body physics must be invoked there.

Still more horizons

Theorist Jason Ho of Ohio State University is very excited about exploiting the atomic systems to learn more about unusual many-body phenomena similar to those in high-T_c superconductors. In high-T_c materials, he says, the normal state is not the usual Fermi liquid, but instead "is very weird." One might be able to study the normal state of the superfluid atomic system by putting in so much angular momentum that the superfluidity will go away and reveal the normal state. It will also be interesting to measure many other properties of the superfluid system, but doing so will require model-independent methods of thermometry.

Ketterle sees the vortices as a way to map out superfluidity in a broader range of interaction strengths. There are new questions to answer, and theoretical predictions are already emerging about such things as the structure of vortex lines and the density depletion in the cores.

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Single, Physics-Based Model Accounts for the Mechanical Properties of Diverse Biopolymer Gels

Despite their variety of composition, stiffness, and strength, the protein-based filaments that support and connect cells behave in the same, predictable way when strained.

During each heartbeat, the aorta's walls expand to hold the pulse of blood, then rebound elastically to propel the blood downstream. At rest, a healthy human heart has a systolic blood pressure of about 16 kilopascals. But for strenuous, impulsive effort, like dashing upstairs or hoisting a sack of mulch, the systolic pressure can double, even triple.

If the aorta's walls responded linearly to such increases, they'd balloon and most likely burst. Fortunately, Nature has endowed the aorta with a nonlinear property called strain stiffening. As stress increases so too does the ratio of stress to strain, the elastic modulus.

The aorta's strain stiffening arises from its structure, a complex set of concentric, alternating layers of rubbery and stiff tissues. It's surprising, therefore, to find strain stiffening in the far simpler gels that form the support structures within and between cells (see figure 1).

Those gels consist of weblike filamentary networks of biopolymer embedded in the ambient extracellular or intracellular solution. They perform different functions and bear different stresses and strains. Yet remarkably, despite the variety of composition, strength, and flexibility, the gels' stress–strain curves follow the same basic shape.

Physicists, when they encounter such similar behavior, look for a universal equation or model. And that's what Cornelis Storm of the University of Leiden and his collaborators have now found. According to their analysis, a biopolymer gel's nonlinear response to strain depends principally on the stiffness of its constituent filaments and the density of the links between them.[1] The work suggests that human attempts to mimic certain biomaterials might turn out to be easier than expected.

Storm's paper builds largely on the earlier work of two of his coauthors, theorist Fred MacKintosh of the Free University of Amsterdam, and experimenter Paul Janmey of the University of Pennsylvania. The other coauthors are also from the University of Pennsylvania: Tom Lubensky, who helped out with the theory, and Jennifer Pastore, who made the measurements the model sought to explain.