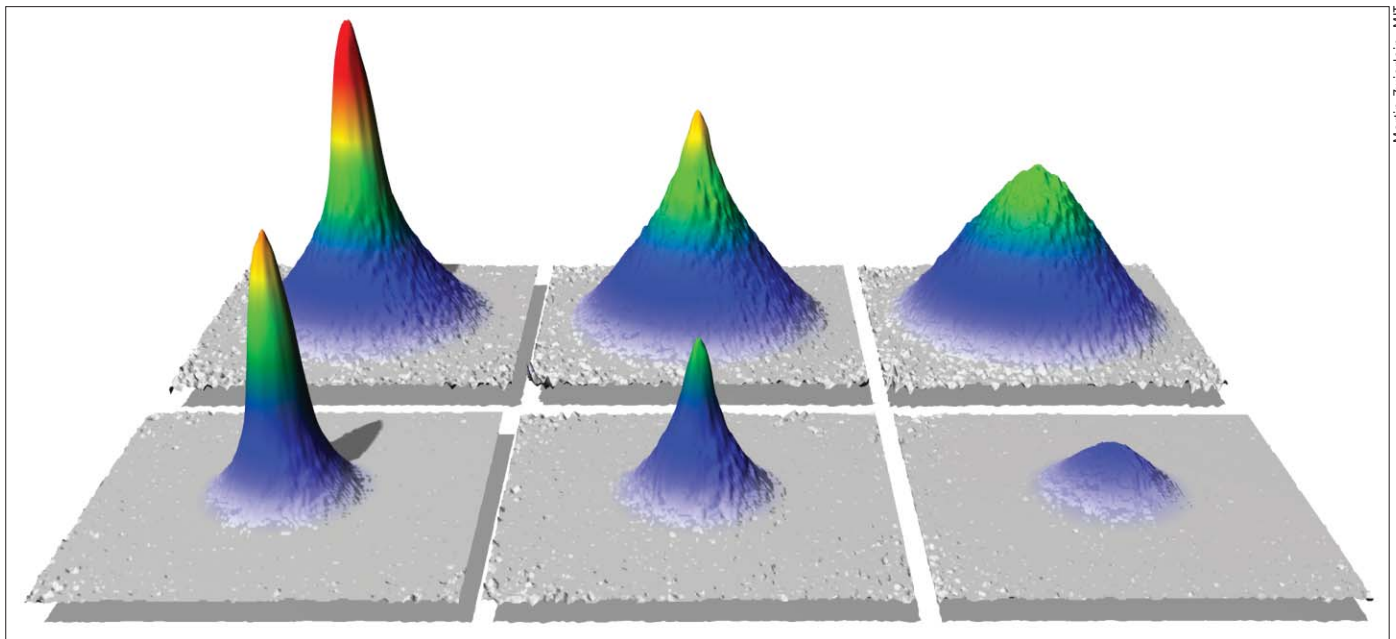


Fermi gases go with the superfluid flow

The study of superfluidity in “imbalanced” ultracold fermionic gases is helping researchers unearth the mechanisms behind superfluids and superconductors, explain **Wolfgang Ketterle** and **Yong-il Shin**



Martin Zwierlein, MIT

If asked to describe the characteristic properties of a gas, most physicists would refer immediately to its diluteness: gases such as air or the helium inside balloons are about 1000 times less dense than liquids or solids. But gases are also characterized by the random motion of their constituent atoms and molecules. This, in fact, is a direct consequence of their diluteness, since the thermal kinetic energy of the particles is much larger than their interaction energy. Such random motion can be quantified using classical statistical mechanics, which provides an extremely powerful description of the gases that we encounter under everyday conditions.

At low temperatures, however, this simple picture of a gas as a collection of randomly moving particles no longer holds. Gases usually undergo a phase transition into a liquid or a solid as they are cooled, but such transitions can be prevented at extremely low densities 100 000 times less than that of air. Here, two-particle collisions keep the gas in thermal equilibrium but the three-body collisions required to form clusters or droplets – which would then grow into a liquid or solid phase – are suppressed. When such gases are cooled to nanokelvin temperatures, they remain extremely dilute, but

quantum statistics and interactions profoundly change their properties. For example, they can even undergo a phase transition to a remarkable state of matter called a superfluid, which has no resistance to flow.

Ultracold gases provide a valuable tool with which to study condensed-matter phenomena because the isolated atoms can be observed and manipulated with the precision and control of atomic physics, while the forces between them are accurately known. This is crucial for comparing experimental findings with theoretical models. In particular, ultracold gases can shed light on the underlying mechanisms of superfluidity, which depend fundamentally on the quantum identity of the constituent particles of the gases – i.e. whether they are bosons or fermions.

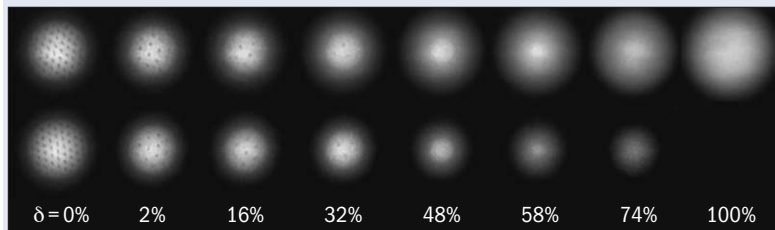
Bosons have integer values of spin angular momentum, while fermions have half-integer spins. Bosons therefore obey Bose–Einstein statistics, which places no limits on the number of identical particles that can occupy the same quantum state. A “Bose gas” at a temperature close to absolute zero can thus form an unusual phase of matter called a Bose–Einstein condensate, in which all the atoms can be described by a

Twin peaks

In a fermionic gas composed of atoms in two spin states, a pair condensate shows up as a sharp peak in both components (left). As the imbalance is increased (left to right) the pair condensate – an indirect indicator of the superfluidity – is lost.

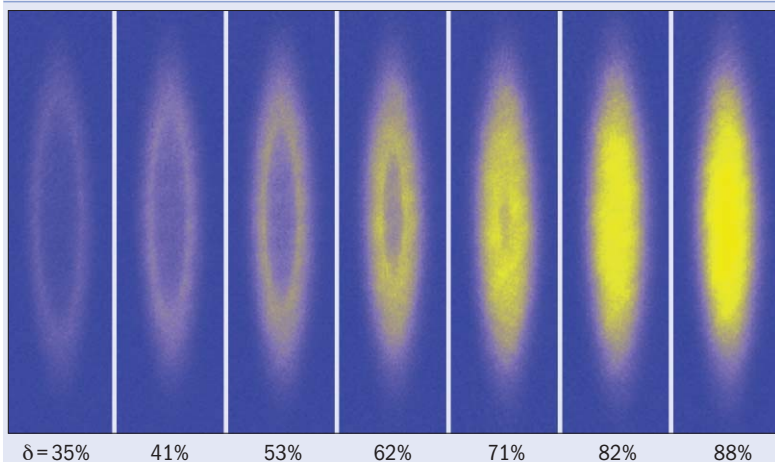
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1 Imbalanced superfluids



Last year researchers at MIT observed superfluidity in a fermionic gas made up of lithium-6 atoms prepared in two different hyperfine states, where the number of atoms in each state is not the same. The marker of the superfluid phase – in which matter flows without resistance – is a hexagonal vortex lattice, shown here for gases with different levels of “imbalance” $\delta = (N_1 - N_2)/(N_1 + N_2)$, where N_1 and N_2 are the number of atoms in state $|1\rangle$ (top) and $|2\rangle$ (bottom). Quantized vortices are apparent at imbalances of up to $\delta = 35\%$.

2 Phase separation



Using a special optical imaging technique, the MIT team recently observed the separation of a population-imbalanced ultracold fermionic system into a superfluid and a normal, non-superfluid component. In these images the optical signal is proportional to the density difference between the atoms in the two hyperfine states ($|1\rangle$ and $|2\rangle$) of lithium-6 atoms, which means that regions with equal densities are invisible. An outer shell of unequal densities surrounding a superfluid core with equal densities is clearly visible, revealing how the system maintains a superfluid state of pairs despite the overall imbalanced populations. The superfluid core disappears when the imbalance exceeds 75%, indicating the so-called Chandrasekhar–Clogston limit of superfluidity.

single macroscopic wavefunction. It is the propagation of such coherent particles, rather than their classical random motion, that leads to superfluidity.

Fermions, on the other hand, obey Fermi–Dirac statistics and are prevented from occupying the same quantum state – and thus from forming a condensate – by the Pauli exclusion principle. At absolute zero, fermions have no choice but to fill up the quantum states from the ground energy level up to the Fermi energy level, forming the so-called Fermi sea. However, fermions can pair up under the influence of attractive forces and these pairs, similar to composite bosons, can then undergo condensation.

The strength of the pairing between such fermions is usually greatest when they are in two different quantum states, since the interactions between them are not suppressed by the exclusion principle. This is the case in superconductivity – which is the superfluidity of charged particles (electrons). Below a certain critical temperature, electrons in opposite spin states – i.e. “up” or “down” – form “Cooper” pairs that flow with-

out electrical resistance. In contrast to dimer molecules, Cooper pairs are very weakly bound, are spread over a large volume and are defined via the strong correlation between the two spin components in momentum space – as described by the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity (see box on page 42). As a result, fermionic superfluidity is qualitatively different from the superfluid state of a condensate of compact bosons.

Ultracold gases provide the simplest and most controlled system with which to study both bosonic and fermionic superfluidity, offering new insights into these sometimes mysterious macroscopic quantum phenomena. So far, experimentalists have found BCS-like superfluidity in systems where particles are strongly interacting, and researchers have now started to use ultracold gases to search for even more exotic forms of superfluidity.

The fermionic story so far

The first Bose–Einstein condensates (BECs) were created in 1995 by two groups in the US (including ours) by cooling Bose gases of rubidium and sodium atoms to a few hundred nanokelvin – a result that led to the award of the 2001 Nobel Prize for Physics. The realization of ultracold strongly interacting Fermi gases in 2002 and 2003 triggered a second revolution in the field of ultracold atoms. Since many properties of real-life materials are determined by the behaviour of interacting electrons, which are fermions, such systems have made the link between ultracold gases and condensed-matter and many-body physics even stronger.

The first “quantum degenerate” Fermi gases, in which the atoms were cold enough to form a Fermi sea and exhibit some quantum behaviour, were produced in 1999 by researchers at the JILA laboratory in Boulder, Colorado, by cooling a Fermi gas of potassium atoms held in a magnetic trap (*Science* **285** 1703). Three years later the JILA group, our group at the Massachusetts Institute of Technology (MIT) and another at Duke University in the US tuned the atomic interaction strength between fermions to large values using magnetic fields (*Phys. Rev. Lett.* **88** 173201, *Phys. Rev. Lett.* **89** 203201 and *Science* **298** 2179).

This tuning technique, which was first established in Bose–Einstein condensates by our group in 1998 (*Nature* **392** 151), has profoundly changed the experimental investigation of ultracold gases. At certain magnetic field strengths called Feshbach resonances two colliding atoms can interact resonantly and form stable molecules. This means that we can vary the strength of the interactions between atoms – and even change them from being attractive to repulsive – simply by varying the magnetic field across such a resonance.

The strongly interacting Fermi gases created in 2002 provided the platform from which to tackle the next major goal: to study pairing and superfluidity in Fermi gases and to establish a well-controlled system with which to simulate superconductors. In early 2003, researchers at the Ecole Normale Supérieure in Paris showed that strongly interacting fermion pairs were surprisingly long-lived (*Phys. Rev. Lett.* **91** 240401). Then in November that year, the JILA and MIT groups, and another at the University of Innsbruck in Austria

Science **311** 492

Phys. Rev. Lett. **97** 030401

achieved a major breakthrough when, independently, they created the first condensate of strongly interacting fermion pairs. This was also hailed as the first “molecular condensate”, although weak molecular binding was in fact already dominated by many-body interactions (*Nature* **426** 537, *Phys. Rev. Lett.* **91** 250401 and *Science* **302** 2101).

Until that time, the condensation of fermion pairs had been studied only for tightly bound pairs (i.e. the limit of Bose–Einstein condensation of atoms) or for extended pairs in a weak coupling regime (i.e. the limit of Cooper pairs as described by the BCS theory for superconductivity). But with the help of magnetic fields to tune the strength of the forces between the atoms, the door was finally open for a detailed study of the “BEC–BCS crossover” between these two extremes. In other words, we were in a position to study fermionic superfluidity from the strong to the weak coupling regime, thereby connecting two previously separated cases and potentially revealing new physics in the process.

In 2004 researchers first at JILA and then at MIT created condensates of fermion pairs both below and above the Feshbach resonance (*Phys. Rev. Lett.* **92** 04040, *Phys. Rev. Lett.* **92** 120403). Then during 2004 and early 2005, researchers at JILA, MIT, Innsbruck, Duke, Paris and at Rice University in the US characterized the BEC–BCS crossover by studying collective excitations of the condensate, its energy, the dynamics of its formation and the nature of the pairing. But these results could not directly address superfluidity.

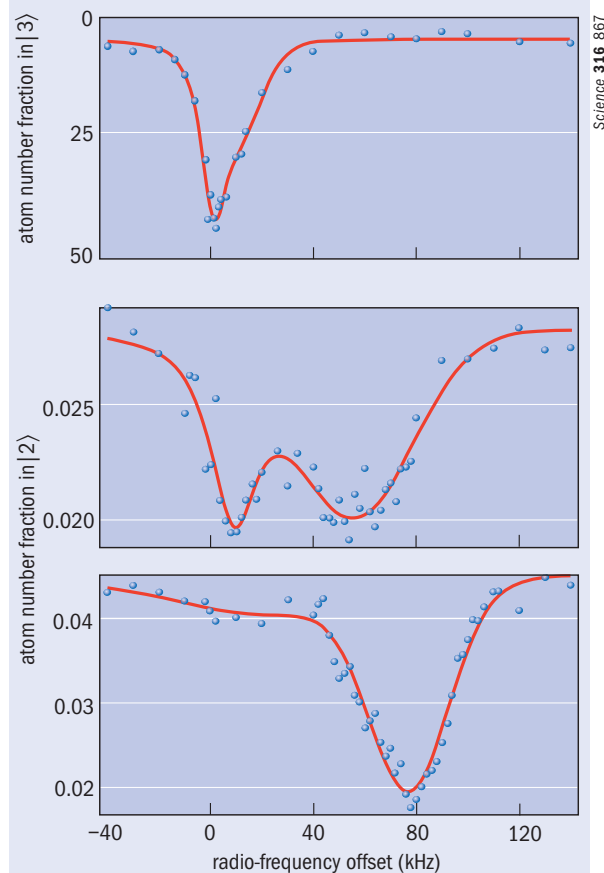
This step was taken in 2005 when our group at MIT obtained direct evidence for fermionic superfluidity in the form of quantized vortices in a rotating system of ultracold lithium-6 atoms (*Nature* **435** 1047). In fact, this finding established a novel form of high-temperature superfluidity: if we extrapolate the observed transition temperature in the dilute Fermi gases to the density of electrons in a solid, then it would be much higher than room temperature. Since then, we and other groups have realized fermionic superfluidity in new systems and in new geometries, such as fermionic gases with imbalanced spin populations or in periodic potentials.

Fermionic superfluid dance

Some of the most important results in the study of ultracold Fermi gases in the last two years have come from looking at superfluidity in systems that contain unequal populations of atoms in the two different spin states. By observing the breakdown of superfluidity in such a population-imbalanced system we gain insight into the pairing mechanism that is responsible for superfluidity. For example, if not every fermionic atom can find a partner, then how (if at all) can the system find a way to become superfluid?

Another way to put this is to imagine fermionic superfluidity as a dance of couples in which women and men pair up to perform a “superfluid dance”, and then to ask what happens if there are more men than women on the dance floor. For example, the dance may stop (indicating the breakdown of superfluidity) or it could continue with the extra men and possibly some women standing off the dance floor (indicating that the system has separated into a superfluid phase and a normal fluid phase). Another possibility is that a more exotic

3 Pairing without superfluidity



The MIT group has recently used radio-frequency spectroscopy to study pairing in the normal and superfluid phases of a strongly interacting Fermi gas with highly imbalanced spin populations ($\delta = 90\%$) that were tuned beyond the Chandrasekhar–Clogston limit of superfluidity. At high temperatures (top) only a single atomic “peak” is present, indicating that no pairing has taken place. As the temperature is lowered (middle) a second peak emerges, reflecting the existence of pairs that require additional excitation energy. At sufficiently low temperatures (bottom) only the pairing peak remains, demonstrating that full pairing develops in the absence of superfluidity.

dance (in which the numbers of men and women are not matched) begins, as suggested in long-predicted forms of superconductivity such as the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) state in which either the density or the phase of the superfluid has a spatial periodic modulation.

The breakdown of superfluidity by such population imbalance can be understood by realizing that deep in the Fermi sea, particles cannot form a pair or even scatter off one another because their motion is “frozen” by the exclusion principle. Pairing requires partially empty energy states that are found only near the Fermi surface. But if the populations of the two different spin components are different, the two Fermi surfaces no longer match up in momentum space – i.e. there are no partially occupied states in which both atoms have the opposite momentum and can form a zero-momentum pair. This makes pairing energetically less favourable and eventually causes superfluidity to break down. More technically, superconductivity is lost when the energy difference be-

By observing the breakdown of superfluidity in a fermionic gas made up of atoms in different spin states, we gain insight into the pairing mechanism responsible for superfluidity

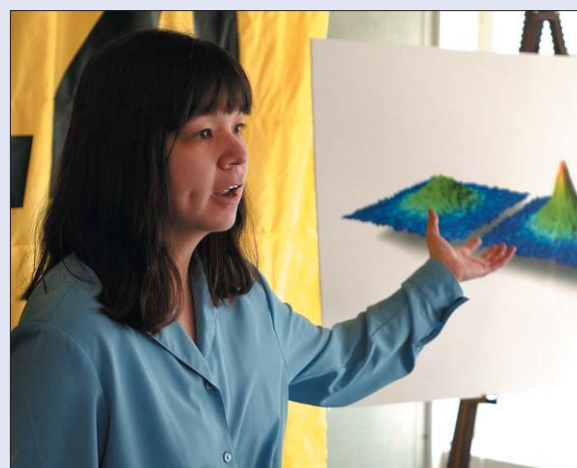
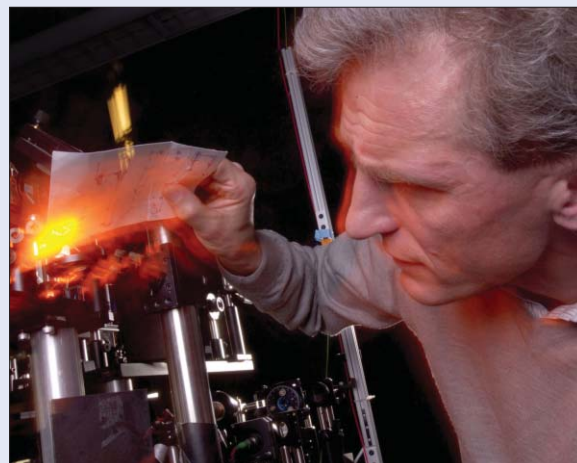
Timeline of success

Milestones in superfluidity and superconductivity

- 1911 Superconductivity discovered in metals at low temperatures (1913 Nobel Prize for Physics awarded to Heike Kamerlingh Onnes)
- 1924/5 Satyendra Nath Bose and Albert Einstein formulate Bose–Einstein statistics
- 1933 Walther Meissner and Robert Ochsenfeld discovered the Meissner effect
- 1938 Superfluidity discovered in liquid helium-4 (a bosonic system) below 2 K (1978 Nobel Prize for Physics shared by Pjotr Kapitsa)
- 1938 Fritz London linked superfluidity with Bose–Einstein condensation and Lazlo Tisza developed a two-fluid model
- 1941 Quantum hydrodynamics for superfluid helium-4 (1962 Nobel Prize for Physics awarded to Lev Landau)
- 1957 BCS theory of low-temperature superconductivity (1972 Nobel Prize for Physics awarded to John Bardeen, Leon Cooper and John Schrieffer)
- 1962 Prediction of the flow of supercurrent through a tunnelling barrier (1973 Nobel Prize for Physics shared by Brian Josephson)
- 1972 Superfluidity discovered in liquid helium-3 (a fermionic system) at 0.002 K (1996 Nobel Prize for Physics awarded to David Lee, Douglas Osheroff and Robert Richardson)
- 1986 Discovery of high-temperature superconductivity (1987 Nobel Prize for Physics awarded to Georg Bednorz and Alexander Müller)
- 1995 Bose–Einstein condensation in a gas (2001 Nobel Prize for Physics awarded to Eric Cornell, Carl Wieman (JILA) and Wolfgang Ketterle (MIT))
- 2003 Nobel Prize for Physics awarded to Alexei Abrikosov, Vitaly Ginzburg, and Anthony Leggett for contributions to the theory of superconductors and superfluids

Recent experimental breakthroughs in superfluid Fermi gases

- 1999 Quantum-degenerate fermion gases (JILA)
- 2002 Feshbach resonances in ultracold Fermi gases (JILA/MIT/Duke)
- 2003 Condensates of strongly interacting fermion pairs (JILA/MIT/Innsbruck)
- 2004 Phase diagram across the BEC–BCS crossover (JILA)
- 2004 Studies of the BEC–BCS crossover (JILA/MIT/Innsbruck/Duke/Paris/Rice)
- 2005 Observation of superfluidity in fermionic gases (MIT)
- 2006 Superfluidity (MIT) and spatial structure (MIT/Rice) of imbalanced fermion mixtures



Fermionic pioneers Wolfgang Ketterle (top) in the lab at MIT and Deborah Jin of JILA presenting fermionic pair condensates in 2004.

tween the two Fermi surfaces exceeds the energy gained from pairing – the so-called Chandrasekhar–Clogston (CC) limit of superconductivity.

The issue of pairing and fermionic superfluidity in an imbalanced Fermi mixture has intrigued physicists for many decades. Although a population imbalance can be created in electron gases by applying magnetic fields, this method is no good for common superconductors because the field is shielded by the Meissner effect. Until now the CC limit could therefore only be studied in heavy-fermion and layered superconductors in which the Meissner effect is suppressed. Using cold atomic gases, on the other hand, we can prepare an arbitrary ratio of fermions in two different hyperfine (i.e. spin) states using radio-frequency fields to transfer populations.

Last year our group reported superfluidity in a wide range of such imbalanced mixtures by observing quantized vortices in the systems when they were rotated (*Science* **311** 492) (see figure 1). A more quantitative analysis, in which we used the appearance of pair condensates as an indirect indicator of superfluidity, enabled us to map out the phase diagram of the imbalanced mixture. This showed that the stronger the coupling, the larger was the imbalance in the spin populations that would destroy superfluidity. When the two

components are interacting at a Feshbach resonance in the BEC–BCS crossover region, the CC limit is reached when the ratio of the two spin populations is about seven. These results showed that the superfluid dance continues even with an imbalanced population. But what is the dance like? Returning to the superfluid–dance metaphor, are the single men merged with the dancing couples or do they stay off the dance floor?

We addressed this question last year using phase-contrast imaging, in which the two different spin components contribute opposite signs and therefore cancel out to reveal only unpaired men and not couples (*Phys. Rev. Lett.* **97** 030401). At low temperatures we found that with the onset of superfluidity the core region of the gas abruptly assumed equal densities of the two components, while the region outside mostly contained just one spin component (see figure 2).

One conclusion of this experiment is that the nature of the superfluidity in the core region of an imbalanced mixture is the same as it is in a balanced mixture. The system avoids creating a superfluid with imbalanced populations by phase separating into two regions: a superfluid region with equal densities of each component and a normal region with unequal densities. A new exotic dance has so far not been found, but we cannot rule out that one exists at the interface between

the superfluid and normal region. Meanwhile, researchers at Rice University have studied the spatial distortions of imbalanced Fermi clouds. However, the interpretation of these results is not yet clear because neither pair condensates nor superfluidity have been observed; and in very small samples, surface energies play a major role (*Science* **311** 503 and *Phys. Rev. Lett.* **97** 190407).

The present authors at MIT also recently addressed the question of what happens to the couples when the superfluid dance has stopped, by increasing the population imbalance until the CC limit was exceeded. To do this we used radio-frequency spectroscopy to measure the excitation spectrum of a strongly imbalanced mixture of lithium-6 atoms (see figure 3). Isolated atoms show a narrow peak, while those that are bound in pairs produce a second peak at a higher frequency due to the extra energy required to break the bond (this frequency shift is often referred to as the pairing gap).

When we cooled the imbalanced mixture and monitored the minority atoms for pairing effects using radio-frequency spectroscopy, we found complete pairing of the minority atoms at the lowest temperatures (*Science* **316** 867). In other words, pairing can occur without superfluidity. Since the system is beyond the CC limit, this normal state consists of fermion pairs that do not undergo Bose–Einstein condensation even at zero temperature due to their interactions.

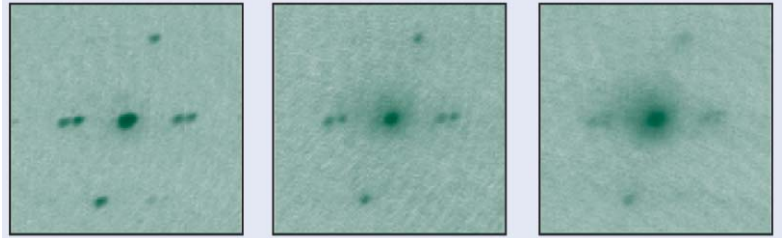
This finding allows us to test theories of superfluidity that extend standard BCS theory into the regime of strong interactions, a region not accessible in condensed-matter experiments. We found almost identical spectra when we varied the population imbalance and compared the normal to the superfluid state, suggesting that radio-frequency spectroscopy cannot distinguish between the two phases. This is in contrast to previous interpretations that spectra with a pairing gap provide strong evidence for superfluidity (*Science* **305** 1128).

Populating the lattice

Although the basic properties of superfluidity in imbalanced systems have now been mapped out, several questions remain about the phase diagram. For example, for what imbalances and temperatures is the superfluid transition first order or second order, and are there small regions with other more-exotic forms of superfluidity?

With a flurry of theoretical papers predicting new aspects of superfluidity, it seems certain that we have exciting years ahead of us

4 Fermions in the lattice



Nature 443 961

By imaging the high-contrast interference of fermion pairs released from the periodic potential of an optical lattice below (left), at (middle) and above (right) the Feshbach resonance, last year the MIT group indirectly observed superfluidity of fermions in an optical lattice.

Another important direction is the study of fermionic superfluidity in a periodic potential. This is motivated by the crystalline structure of many superconductors, but also by many theoretical treatments that are formulated on a lattice. Last year our group took a first step in this direction by transferring superfluid fermions into an optical lattice, a periodic potential created by optical standing waves (*Nature* **443** 961). For small lattices, superfluidity was maintained, as revealed by a coherent diffraction pattern of the atoms in the lattice produced by long-range coherence in the system (figure 4). For deeper lattices, the coherence disappeared, most probably due to the atoms becoming more localized in one lattice site, as they do in the so-called Mott insulating phase.

A major goal now is to see what happens when the interatomic interactions are switched from attractive to repulsive by tuning the magnetic field to the other side of a Feshbach resonance. In 2002 researchers at Harvard University in the US and collaborators predicted that, depending on the number of atoms per lattice site, the atoms will undergo a phase transition to antiferromagnetic order or that they will show “d-wave” superfluidity, where the fermion pairs have two units of angular momentum (*Phys. Rev. Lett.* **89** 220407). This is more closely related to high-temperature superconductivity, where fermion pairs have d-wave character.

Meanwhile, the JILA group has studied molecules with “p-wave” characteristics, with the aim of studying more complex p-wave superfluidity. And the Innsbruck and MIT groups, plus those at the universities of Munich and Amsterdam, are striving to make mixtures of potassium and lithium atoms to study superfluid pairs made from fermions with different masses. With all these new systems on the drawing board or already in preparation, and with a flurry of theoretical papers predicting new aspects of superfluidity, it seems certain that we have exciting years ahead of us. Our next goal is to use the toolbox of ultracold atoms to realize a model system for high-temperature superconductors where parameters can be controlled and varied at will.

Although the density of ultracold atoms is very different from that of superconductors, the underlying physics is the same. It is like looking at the superfluid state with a huge magnifying glass that may help to resolve some of the mysteries of superconductivity, which, more than 90 years after its discovery, are still not fully understood. ■