Measurement of Positive and Negative Scattering Lengths in a Fermi Gas of Atoms

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We report on progress toward realizing a predicted superfluid phase in a Fermi gas of atoms. We present measurements of both large positive and large negative scattering lengths in a quantum degenerate Fermi gas of atoms near a magnetic-field Feshbach resonance. We employ an rf spectroscopy technique to directly measure the mean-field interaction energy, which is proportional to the s-wave scattering length. Near the peak of the resonance we observe a saturation of the interaction energy; it is in this strongly interacting regime that superfluidity is predicted to occur. We have also observed anisotropic expansion of the gas, which has recently been suggested as a signature of superfluidity. However, we find that this can be attributed to a purely collisional effect.

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The possibility of superfluidity in an atomic Fermi gas has been studied theoretically [1–5]. Analogous to superconductivity in metals and superfluidity in liquid ^{3}He, this fermionic superfluid phase requires effectively attractive interactions in the gas. In addition, these interactions need to be relatively strong if the phase transition is to occur at a temperature T_c that can be realized with current experimental techniques. Magnetic-field tunable Feshbach scattering resonances provide a unique tool that could create these conditions in an ultracold atomic Fermi gas. These resonances arise when the collision energy of two free atoms coincides with that of a quasibound molecular state [6,7]. By varying the strength of the external magnetic field the experimenter can tune relative energies through the Zeeman effect and thus control the strength of the interactions as well as whether they are effectively repulsive or attractive.

A novel superfluid phase, termed "resonance superfluidity," is predicted for a Fermi gas near a Feshbach resonance [2,3]. Unique properties of this phase include a T_c that is a large fraction of the Fermi temperature T_F. With a predicted T_c/T_F as high as 0.26, resonance superfluidity would exist in a crossover regime between the physics of Bose-Einstein condensation, which occurs for composite bosons made up of tightly bound fermions, and BCS-type superconductivity, which occurs for pairs of fermions that are loosely correlated in momentum space (Cooper pairs). The experimental investigation of resonance superfluidity, and its dependence on magnetic-field detuning from the Feshbach resonance, could provide new insight into these two types of quantum fluids.

Interactions in ultracold gases arise predominantly from binary s-wave collisions whose strength can be characterized by a single parameter, the s-wave scattering length a. Across a Feshbach resonance a can in principle be varied from $-\infty$ to $+\infty$, where $a < 0$ ($a > 0$) corresponds to effectively attractive (repulsive) interactions. In atomic Fermi gases Feshbach resonances have been seen in their enhancement of elastic [8–10] and inelastic [9–12] collision rates. However collision cross sections depend on a^2 and are not sensitive to whether the interactions are attractive or repulsive. The mean-field energy, on the other hand, is a quantum mechanical, many-body effect that is proportional to na, where n is the number density. For Bose-Einstein condensates with repulsive interactions the mean-field energy can be determined from the size of the trapped condensate [13,14], while attractive interactions cause large condensates to become mechanically unstable [15,16]. For an atomic Fermi gas, where the atoms occupy higher energy states of the external trapping potential, the mean-field interaction energy has a much smaller impact on the thermodynamics [17]. In this work we introduce an rf spectroscopy technique that measures the mean-field energy directly. With this technique we have measured both positive and negative scattering lengths in a Fermi gas of atoms near the peak of a Feshbach resonance.

The experiments reported here employ previously developed techniques for cooling and spin state manipulation of ^{40}K [8,18]. Because of the quantum statistics of fermions a mixture of two components, for example, atoms in different internal spin states, is required to have s-wave interactions in the ultracold gas [19]. With a total atomic spin $f = 9/2$ in its lowest hyperfine ground state, ^{40}K has ten available Zeeman spin states $|f, m_f\rangle$. Atoms in a 90/10 mixture of the $m_f = 9/2$ and $m_f = 7/2$ states are held in a magnetic trap and cooled by forced evaporation [18]. The gas is then loaded into a far-off resonance optical dipole trap where rf transitions are used to obtain the desired spin composition [8]. First, the gas is completely transferred to the $m_f = -9/2$ and $m_f = -7/2$ states using adiabatic rapid passage. We apply a 15 ms rf frequency sweep across all ten spin states at a field of 20 G. We then move to a higher field, 240 G, where the Zeeman transitions are no longer degenerate and apply an rf $\pi/2$ pulse on the $m_f = -9/2$ to a $m_f = -7/2$

transition. After the coherence is lost (which takes <100 ms) we are left with a mixture of two components, whose relative population is controlled with the rf pulse duration.

With this spin mixture we further evaporatively cool the gas by lowering the optical trap depth. The optical power is ramped from 900 to 8 mW in 2.9 s. During this evaporation, the radial frequency of the optical trap ν_r varies from 2800 to 270 Hz and the trap aspect ratio $\lambda = \nu_z/\nu_r$ remains constant at 0.016 [20]. Starting with 2×10^7 atoms at $T/T_F \approx 4$ our evaporation reaches $T/T_F \approx 0.10$ with 10^5 atoms remaining. To measure the quantum degeneracy of the cooled gas we take resonant absorption images of the cloud after expansion from the optical trap. These images reflect the momentum distribution of the ultracold gas and are surface fit to a Thomas-Fermi profile [21]. In the fits the fugacity z is left as a free parameter that measures the amount of distortion from a Gaussian shape. The value of z obtained from the fit can then be compared to T/T_F obtained from the measured temperature T and calculated Fermi temperature $T_F = h\nu_r(6\lambda N_9)^{1/3}$, where N_9 is the total number of $m_f = -9/2$ atoms and h is Planck's constant. This analysis verifies that the gas is cooled well into the quantum degenerate regime (Fig. 1).

To control the interactions in the two-component Fermi gas we access a magnetic-field Feshbach resonance in the collisions between atoms in the $|9/2, -9/2\rangle$ and $|9/2, -5/2\rangle$ spin states [22]. At magnetic fields B near the resonance peak, the mean-field energy in the Fermi gas was measured using rf spectroscopy [Fig. 2(a)]. First, optically trapped atoms were evaporatively cooled in a 72/28 mixture of the $m_f = -9/2$ and $m_f = -7/2$ spin states. After the evaporation the optical trap was recompressed to either $\nu_r = 1390$ Hz or $\nu_r = 2770$ Hz. In addition the magnetic field was ramped to the desired value near the resonance. We then quickly turned on the resonant interaction by transferring atoms from the $m_f = -7/2$ to the $m_f = -5/2$ state with a 73 μs rf π pulse. The fraction of $m_f = -7/2$ atoms remaining after the pulse was measured as a function of the rf frequency.

The number of $m_f = -7/2$ atoms was obtained from a resonant absorption image of the gas taken after 1 ms of expansion from the optical trap. Atoms in the $m_f = -7/2$ state were probed selectively by leaving the magnetic field high and taking advantage of nonlinear Zeeman shifts. Sample rf absorption spectra, taken in the $\nu_r = 1390$ Hz trap, are shown in Fig. 2(b). At magnetic fields well away from the Feshbach resonance we transfer all of the $m_f = -7/2$ atoms to the $m_f = -5/2$ state and the rf line shape has a width limited by the pulse duration. The rf frequency for maximum transfer depends predictably on the current in the magnetic-field coils and provides a calibration of B. The values of B reported here have a systematic uncertainty of ± 0.05 G. At the Feshbach resonance we observe two changes to the rf spectra. First, the frequency for maximum transfer is shifted relative to the expected value from the magnetic-field calibration. Second, the

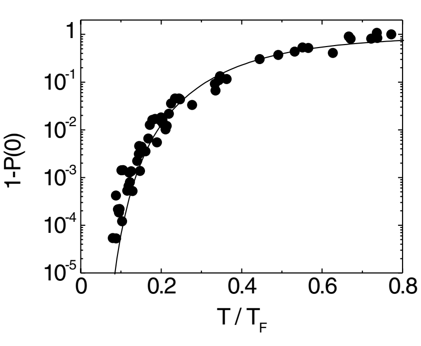

FIG. 1. Quantum degeneracy seen in the thermodynamics of a two-component Fermi gas. Images of the gas, taken after varying amounts of evaporative cooling, are fit to a Thomas-Fermi profile with the fugacity z left as a free fitting parameter. We plot $1 - P(0) = 1/(1 + z)$, where $P(0)$ is the occupancy of the lowest energy state of the trap. The agreement of the data with the expected curve for an ideal Fermi gas (solid line) confirms that the gas can be cooled to $T/T_F \approx 0.10$. This agreement is well within the estimated 18% systematic uncertainty in T/T_F from the determinations of N and ν_z. The data shown here were taken with an equal mixture of atoms in the $m_f = -9/2$ and $m_f = -7/2$ Zeeman states at $B = 240$ G.

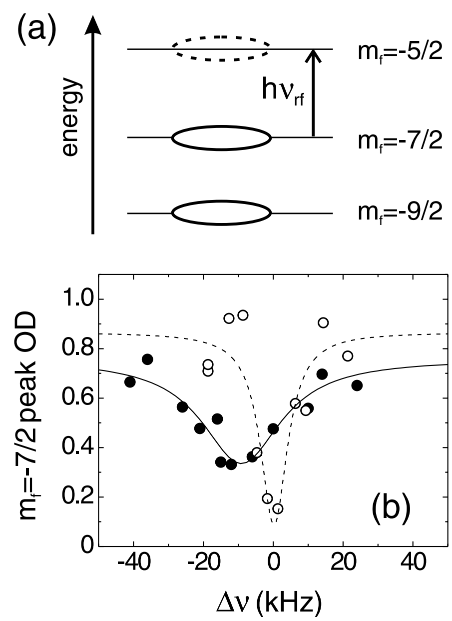

FIG. 2. Schematic of the rf spectroscopy measurement (a) and example rf line shapes (b). With atoms originally in the $m_f = -9/2$ and $m_f = -7/2$ Zeeman states, we apply an rf pulse to transfer atoms from $m_f = -7/2$ to $m_f = -5/2$. In (b) we plot the peak optical depth (OD) of the remaining $m_f = -7/2$ gas, measured after expansion, versus rf frequency $\Delta\nu \equiv \nu_{rf} - \nu(B)$, where $\nu(B) \sim 50$ MHz is the expected resonance frequency for a given B. The rf line shape near the Feshbach resonance ($B = 224.36$ G) (solid circles) is shifted and broadened compared to the line shape taken farther from the resonance ($B = 215.45$ G) (open circles).

maximum transfer is reduced and the measured line shape is wider.

Both of these effects arise from the mean-field energy due to strong interactions between $|9/2, -9/2\rangle$ and $|9/2, -5/2\rangle$ atoms at the Feshbach resonance. The mean-field energy produces a density-dependent frequency shift given by

$$\Delta\nu = \frac{2\hbar}{m} n_9 (a_{59} - a_{79}), \tag{1}$$

where m is the atom mass, $\hbar = h/2\pi$, n_9 is the number density of atoms in the $m_f = -9/2$ state, and a_{59} (a_{79}) is the scattering length for collisions between atoms in the $m_f = -9/2$ and $m_f = -5/2$ ($m_f = -7/2$) states. Here we have ignored a nonresonant interaction term proportional to the population difference between the $m_f = -7/2$ and $m_f = -5/2$ states; this term is 0 for a perfect π pulse. For our spatially inhomogeneous trapped gas, the density dependence broadens the line shape and lowers the maximum transfer on both sides of the Feshbach resonance peak. In contrast, the frequency shift for maximum transfer reflects the scattering length and changes sign across the resonance.

We have measured the mean-field shift $\Delta\nu$ as a function of B near the Feshbach resonance peak. The rf frequency for maximum transfer was obtained from Lorentzian fits to spectra similar to those shown in Fig. 2(b). The expected resonance frequency was then subtracted to yield $\Delta\nu$. The scattering length a_{59} was obtained using Eq. (1) with $n_9 = 0.5 n_p$ and $a_{79} = 174 a_0$ where a_0 is the Bohr radius [8]. The peak density of the trapped $m_f = -9/2$ gas n_p was obtained from Gaussian fits to absorption images. The numerical factor 0.5 multiplying n_p was determined by modeling the transfer with a pulse-width limited Lorentzian integrated over a Gaussian density profile in the two radial directions.

The measured scattering length as a function of B is shown in Fig. 3. This plot, which combines data taken for two different trap strengths and gas densities, shows that we are able to realize both large positive and large negative values of a_{59} near the Feshbach resonance peak. The solid line in Fig. 3 shows a fit to the expected form for a Feshbach resonance $a = a_{bg}\{1 - [w/(B - B_{pk})]\}$. Data within ± 0.5 G of the peak were excluded from the fit. With $a_{bg} = 174 a_0$ we find that $B_{pk} = 224.21 \pm 0.05$ G and $w = 9.7 \pm 0.6$ G.

When B is tuned very close to the Feshbach resonance peak we expect the measured $|a_{59}|$ to have a maximum value of $\sim 1/k_F$ due to the unitarity limit. Here $\hbar k_F$ is the Fermi momentum for the $m_f = -9/2$ gas. This saturation can be seen in the data shown in Fig. 3. Two points that were taken within ± 0.5 G of the Feshbach resonance peak, one on either side of the resonance, clearly lie away from the fit curve. Observation of this saturation demonstrates that we can access the strongly interacting regime when $a_{59} k_F$ is greater than 1. It is in this regime that resonance superfluidity is predicted to occur. Using the fit discussed above, we find that the unitarity-limited point on the attractive interaction side of the resonance (higher B) corresponds to a gas that actually has $a_{59} k_F \approx 11$.

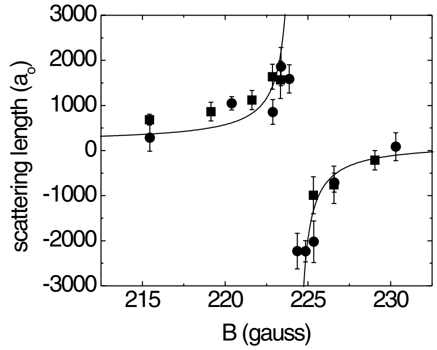

FIG. 3. Scattering length versus magnetic field near the Feshbach resonance peak. The scattering length a_{59} was obtained from measurements of the mean-field energy taken for $T/T_F = 0.4$ and two different densities: $n_p = 1.8 \times 10^{14}$ cm^{-3} (circles) and $n_p = 5.8 \times 10^{13}$ cm^{-3} (squares). We estimate a systematic uncertainty in a_{59} of $\pm 50\%$ due to uncertainty in our measurement of the trapped gas density.

Anisotropic expansion has been put forth as a possible signature of superfluidity [23] and has recently been observed in a ^{6}Li Fermi gas [24]. However, a normal gas in the hydrodynamic regime, where the collision rate is large compared to the trap oscillator frequencies, is expected to exhibit the same anisotropy in expansion [23,25]. In this case, collisions during the expansion transfer kinetic energy from the elongated axial cloud dimension into the radial direction. A large magnitude scattering length, such as is required for resonance superfluidity, enhances the collision rate in the gas and could cause the normal gas to approach the hydrodynamic regime.

We have utilized our ability to tune a_{59} with the magnetic-field Feshbach resonance to investigate these effects. After evaporatively cooling atoms in a 45/55 mixture of the $m_f = -9/2$ and $m_f = -7/2$ spin states, the optical trap power was recompressed to $\nu_r = 1230$ Hz and B was ramped to the desired value near the resonance. We then transferred atoms from the $m_f = -7/2$ state to the $m_f = -5/2$ state with a 29 μs rf π pulse [26]. Expansion was initiated by turning off the optical trapping beam with an acousto-optic modulator 0.3 ms after the rf pulse. The magnetic field remained high for 5 ms of expansion and a resonant absorption image was taken after a total expansion time of 20 ms.

We find that the ratio of the axial and transverse widths of the expanded cloud, σ_z/σ_y, decreases at the peak of the Feshbach resonance (Fig. 4). This effect depends on having strong interactions during the expansion; we do not see any change in σ_z/σ_y if the magnetic field, and consequently the resonant interactions, are switched off at the same time as the optical trap. The anisotropic expansion is seen on both sides of the peak of the

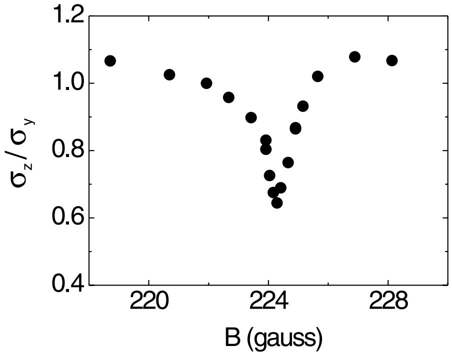

FIG. 4. Anisotropic expansion at the Feshbach resonance peak. The aspect ratio σ_z/σ_y of the expanded cloud decreases at the Feshbach resonance because of an enhanced elastic collision rate. Note that σ_z/σ_y, measured after 20 ms of expansion, drops below 1, indicating that the initially smaller radial size has grown larger than the axial size. The data were taken for $N = 2.8 \times 10^5$ atoms at $T/T_F = 0.34$.

resonance and thus is not sensitive to the sign of the interactions (repulsive or attractive).

To see if hydrodynamic expansion of the normal gas is expected we can calculate the elastic collision rate Γ [27]. For this calculation T and N are obtained from fits to absorption images of clouds away from the Feshbach resonance where we find that $T/T_F = 0.34$. Using an elastic collision cross section given by $\sigma = 4\pi a_{59}^2$ and $|a_{59}| = 2000a_0$ (as measured near the resonance peak), we find $\Gamma = 31$ kHz. With $\Gamma/\nu_r = 25$ and $\Gamma/\nu_z = 1600$ it is not surprising that we observe anisotropic expansion. For a fully hydrodynamic gas, with $\Gamma \gg \nu_r, \nu_z$, we would expect our measured aspect ratio to reach 0.4 [23,25]. Given the strong collisional effects seen here, normal fluid hydrodynamics are an alternative explanation for the results reported in Ref. [24].

In conclusion, we have measured the mean-field energy in a Fermi gas of atoms for both strong attractive and strong repulsive interactions. The rf spectroscopy technique demonstrated here allows one to measure both the sign and the strength of the interactions. In addition to the ability to create strong attractive interactions in the gas, we have demonstrated two other ingredients that are key to the goal of realizing Cooper pairing in a gas of atoms. We are able to cool the optically trapped gas to $T/T_F \approx 0.10$ and precisely control the spin composition. In addition the rf spectroscopy demonstrated here could provide a method for detecting resonance superfluidity by measuring the binding energy of Cooper pairs [28–30]. Finally, we have observed anisotropic expansion of the strongly interacting Fermi gas, and find that this can be a purely collisional effect.

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