# Superfluid Expansion of a Rotating Fermi Gas

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We study the expansion of a rotating, superfluid Fermi gas. The presence and absence of vortices in the rotating gas are used to distinguish the superfluid and normal parts of the expanding cloud. We find that the superfluid pairs survive during the expansion until the density decreases below a critical value. Our observation of superfluid flow in the expanding gas at $1/k_F a = 0$ extends the range where fermionic superfluidity has been studied to densities of $1.2 \times 10^{11}$ cm$^{-3}$, about an order of magnitude lower than any previous study.

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Ultracold atomic gases have been used to create novel quantum many-body systems ranging from Bose-Einstein condensates and Mott insulators in optical lattices to high-temperature superfluids of strongly interacting fermions. These systems offer a high degree of control over physical parameters including interaction strength and density. Many important features in these gases have a spatial scale too small to be resolved while the gas is trapped. A standard technique to reveal this physics is to switch off the confining potential and release the gas. A noninteracting gas expands ballistically and the expansion reveals its momentum distribution. The expansion dynamics of an interacting gas is modified by the effect of collisions. This can result in classical hydrodynamic flow and in this case the expansion serves as a (not necessarily linear) magnifying glass for the trapped state. In contrast to classical hydrodynamics, superfluid hydrodynamic flow does not rely on collisions. When a weakly interacting Bose-Einstein condensate (BEC) is released from an anisotropic trapping potential, superfluid hydrodynamics leads to an inversion of the aspect ratio, often regarded as a hallmark of Bose-Einstein condensation [1].

The expansion dynamics of strongly interacting Fermi gases have been the subject of a long-standing debate. For a weakly interacting ultracold Fermi gas anisotropic expansion has been proposed as a probe for superfluidity, analogous to the case of weakly interacting BECs [2]. Anisotropic expansion has been experimentally observed in strongly interacting Fermi gases [3–5]. In this case, however, the inversion of the aspect ratio can occur due to collisions between the expanding atoms even if they were initially at zero temperature [6,7]. So far experiments have not been able to discriminate between superfluid and collisional hydrodynamics in expansion and indeed one would expect both effects to contribute: In the BCS regime, the superfluid transition temperature $T_C$ depends exponentially on the density. Starting at $T < T_C$, the superfluid gas expands according to superfluid hydrodynamics. As the density drops, $T$ approaches $T_C$ and superfluidity cannot be maintained. From this point on, the gas should expand according to collisional hydrodynamics or enter a regime intermediate between collisional hydrodynamic and collisionless expansion.

In this Letter we study the expansion of a superfluid Fermi gas, in the regime where pairing is purely a many-body effect. We have observed superfluid flow even after 5 ms of expansion, when the cloud size had increased by more than a factor of 4 and the peak density had dropped by a factor of 17 compared to the in-trap values.

Superfluidity in Fermi gases has previously been established through the observation of vortex lattices [8,9]. To detect vortices in a rotating fermion-pair condensate the pairs are transferred into stable molecules by sweeping an external magnetic field across a Feshbach resonance shortly after the gas is released from the trap. Vortices can be observed only when the gas is still a superfluid at the moment of the magnetic field sweep [10]. At the final magnetic field (on the BEC side of the Feshbach resonance) the interactions are much weaker. Therefore the vortex core has higher contrast and is larger than near resonance. If the gas is no longer superfluid at the time of the field ramp, we expect the vortex core to fill in quickly and disappear. The observed vortex cores therefore serve as markers for the regions which are superfluid at the time of the magnetic field ramp.

Our experimental setup has been described earlier [11,12]. $^6$Li fermion-pair condensates containing $5 \times 10^6$ fermions were created in an optical dipole trap at a magnetic field of 812 G. This is on the BEC side of a Feshbach resonance at $B_0 = 834$ G. At magnetic fields below (above) $B_0$, on the BEC (BCS) side, the scattering length $a$ is positive (negative) and a nearby molecular bound state exists (does not exist). The radial and axial trapping frequencies were $\omega_r = 2\pi \times 120$ Hz and $\omega_a = 2\pi \times 23$ Hz, respectively. To observe vortices as a probe of superfluid flow, the gas was set in rotation: two blue-detuned laser beams were rotated symmetrically around the cloud for 1 s at an angular frequency of $2\pi \times 80$ Hz [8]. We allowed 500 ms of equilibration before the magnetic field was ramped (in 500 ms) to several probe fields on the BCS side of the resonance. Finally, we studied the expansion of the rotating superfluid: The gas was released

 

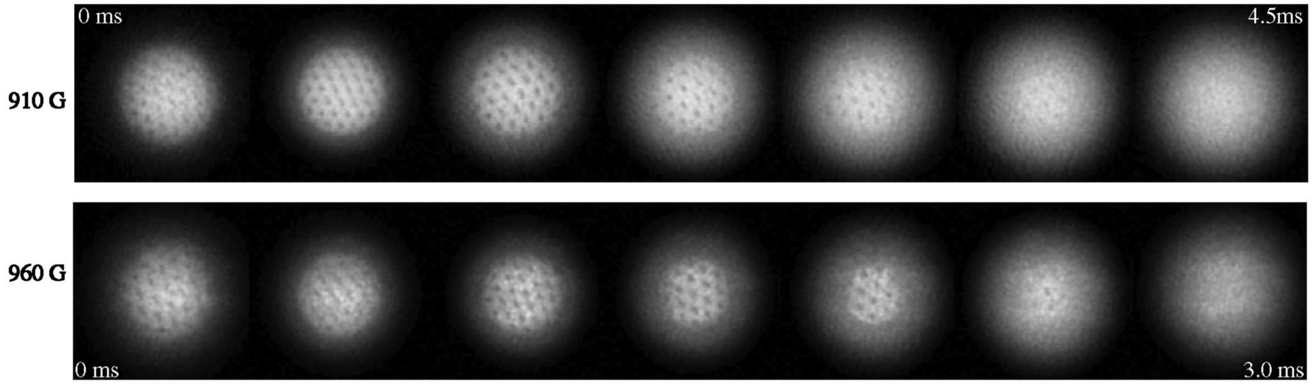


FIG. 1. Superfluid expansion of a strongly interacting rotating Fermi gas. Shown are absorption images for different expansion times on the BCS side of the Feshbach resonance at 910 G (0.0, 1.0, 2.0, 3.0, 3.5, 4.0, and 4.5 ms) and 960 G (0.0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3 ms), before the magnetic field was ramped to the BEC side for further expansion. The vortices served as markers for the superfluid parts of the cloud. Superfluidity survived the expansion for several milliseconds and was gradually lost from the low density edges of the cloud towards its center. Compared to 910 G ($a = -7200a_0$), superfluidity decayed faster at 960 G ($a = -5000a_0$) due to the reduced interaction strength. The total expansion time remained constant [14]. The field of view of each image is 1.2 mm × 1.2 mm.

from the optical trap and expanded at the probe field for a variable "BCS-expansion" time $t_{BCS}$, that was increased in 500 $\mu$s steps. To transfer the remaining fermion pairs into stable molecules the magnetic field was then lowered in 400 $\mu$s to 680 G [13]. Here, the cloud was given several milliseconds of "BEC expansion." For absorption imaging the magnetic field was raised to 730 G in 500 $\mu$s before the last 2 ms of time of flight. For most of the data the total time of flight was chosen to be 11 ms [14]. An absorption image of the gas was obtained separately at $t_{BCS}$ to determine the peak density and the peak Fermi momenta $k_F$ before the magnetic field sweep.

Figure 1 shows absorption images taken as outlined above for seven different BCS-expansion times at both 910 and 960 G. The presence of vortices proves that superfluid fermion pairs survived in the expanding gas. As the density of the gas dropped during the BCS expansion the vortices were gradually lost from the low density edges of the cloud towards its center. After 4.5 ms time of flight at 910 G and 3 ms at 960 G all of the vortices had decayed. If we regard the number of vortices as an indicator of the superfluid fraction of the gas, we can draw the "phase diagram" of Fig. 2. Here the number of vortices is shown as a function of the inverse scattering length $1/a$ and the inverse peak Fermi momentum $1/k_F$. As $1/k_F$ increases at a given magnetic field, corresponding to the decrease in density during time of flight, vortices are lost. The reduction in the number of vortices for decreasing $|a|$ reflects the decrease of the superfluid fraction for smaller attractive interactions at a given temperature. In addition, the increase in the normal fraction leads to higher damping of the remaining vortex number [8]. Most importantly, however, we see that vortices are lost earlier in time of flight as the interactions are reduced.

At all magnetic fields the peak interaction strength at the point where all vortices were lost is about constant, $k_F a \sim -0.8$ (Fig. 3). As shown in Fig. 1 the loss of vortices occurred gradually and the surviving vortices were located within a circle of decreasing radius. We assume that the critical value of $k_F a$ for which superfluidity was lost, was first reached at the edge of the cloud and subsequently further inward. However, we were not able to confirm this

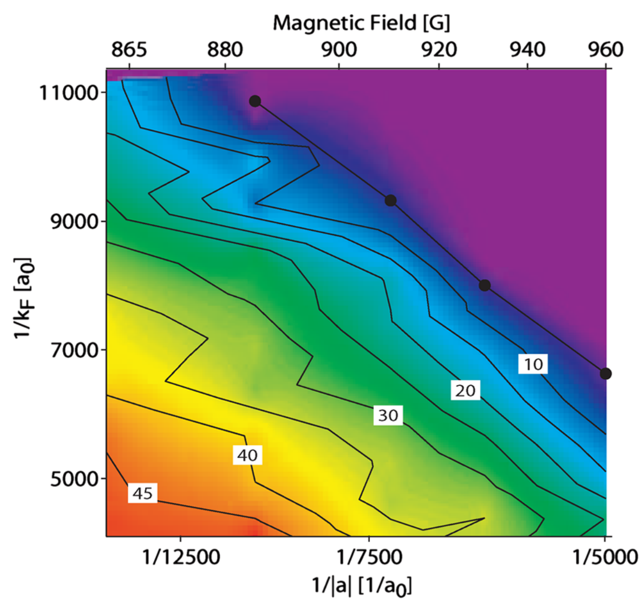


FIG. 2 (color online). "Phase diagram" of an expanding, rotating Fermi gas: At a given magnetic field the number of vortices served as a measure for the size of the superfluid region in the gas. The number of vortices is plotted versus $1/k_F$ and $1/|a|$. The contour plot was created from a total of 53 data points. In this diagram lines of constant $k_F a$ correspond to hyperbolas. The vortices decayed when the density (increasing $1/k_F$) or the scattering length (increasing $1/|a|$) was reduced. For weaker interactions, at smaller scattering lengths $|a|$, vortices were lost already at higher densities. The four data points shown mark the breakdown of superfluidity and are the same as the squares in Fig. 3.

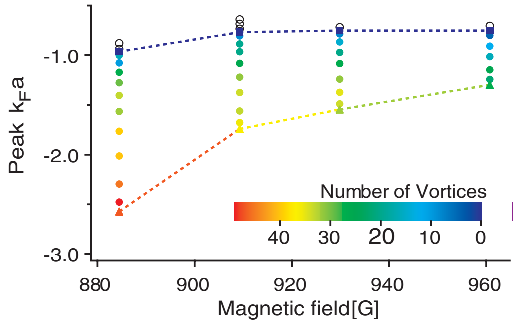


FIG. 3 (color online). The peak interaction strength during superfluid expansion. Starting at a peak $k_F a$ in the optical trap (triangles) vortices survived up to a critical peak $k_F a$ of $-0.8 \pm 0.1$ (squares), almost independent of the magnetic field (scattering length). Solid circles correspond to partially superfluid, open circles to normal clouds. The observed number of vortices is color coded. The critical $k_F a$ was obtained for each magnetic field separately by taking the average of the peak $k_F$ of the last partially superfluid and the first completely normal cloud. The error in $k_F a$ is about 10% and dominated by the systematic error in the atom number.

picture quantitatively without a model that describes how the shape of the cloud and the bimodality develop during and after the magnetic field sweep.

It is remarkable that the observation of superfluidity and fermion-pair condensation for *trapped* gases has also been limited to values of $k_F|a|$ larger than 1 on the BCS side [8,12,15]. This suggests that the underlying reason for this limitation is the same for a trapped and an expanding gas. One obvious scenario for the decay of the vortex lattice during expansion is the breakdown of superfluidity due to finite temperature when a critical interaction strength is reached. As the density decreases, $T_C/T_F$ drops while $T/T_F$ remains constant (since the phase space density $n \times T^{-3/2}$ is invariant during expansion). Therefore $T_C$ eventually becomes smaller than $T$ everywhere in the cloud. The critical interaction strength can be estimated by equating $1 \equiv T/T_C = (T/T_F)(T_F/T_C) = 1.76(T/T_F)(E_F/\Delta)$. Here $\Delta = (2/e)^{7/3} E_F \exp(-\pi/2k_F|a|)$ is the pairing gap in the BCS limit (valid for $k_F|a| \lesssim 1$) [16], where the peak Fermi energy $E_F = \hbar^2 k_F^2/2m$ and $k_F$ are density dependent. For an estimate of our lowest temperatures of $T/T_F = 0.05$ [17] this gives $k_F a = -0.9$ close to the observed value. This finite-temperature scenario implies that the superfluid state evolves adiabatically during expansion, which is plausible: Even when the critical $k_F a$ is reached, the pair binding energy changes at a slower rate, $\dot{\Delta}/\Delta$, than the rate at which the pairs can respond to this change, $\Delta/\hbar$ [18]. For weakly interacting BECs, the decay of vortex lattices at finite temperature was studied theoretically [19], and similar structures are found.

In analogy to the critical magnetic field $H_{c2}$ in type-II superconductors, superfluidity can also break down in response to rapid rotation [20,21]. However, Ref. [21] predicts that superfluidity is stable in the strongly interacting regime ($k_F|a| > 1.029$) at all rotation frequencies up to the trap frequency. Since our estimated rotation frequencies are much smaller [22] we believe that the observed breakdown of superfluidity at $k_F|a| = 0.8$ is mainly due to finite temperature, and only weakly affected by rotation. This is consistent with the observation that vortices disappear in rotating clouds at approximately the same $k_F a$ at which fermion-pair condensates disappeared in experiments with nonrotating clouds.

Another explanation for the loss of vortices is a failure of the transfer of correlated fermion pairs into molecules since the size of the fermion pairs increases with decreasing density. When the fermion-pair size becomes larger than the interparticle spacing, molecules might be formed out of uncorrelated nearest neighbors rather than out of correlated pairs. The magnetic field sweep then destroys the coherent many-body wave function.

Vortices [8,9] and bimodal density distributions [12,15] are indicators for superfluidity and pair condensation, respectively. If a fermion-pair condensate is transferred to the BEC side before its interaction energy has been converted into kinetic energy, it continues to expand with the drastically reduced mean-field energy of a molecular BEC at 680 G. This results in a clear separation of condensate and thermal cloud after further BEC expansion. If the transfer of fermion pairs into molecules is delayed after releasing the gas from the trap, the fermion-pair condensate initially expands just like the normal part of the cloud. This eventually leads to a loss of bimodality in the density profiles after the transfer. We can now study how the two indicators, vortices and bimodality, are related in this experiment. For short BCS expansion $t_{BCS}$ our data showed bimodality as well as vortices. However, bimodality was gradually lost and could not be discerned after longer BCS

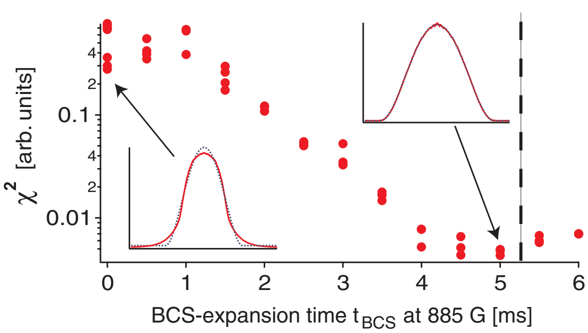


FIG. 4 (color online). Disappearance of bimodality. Zero temperature Thomas-Fermi profiles (dotted) were fit to density profiles (solid) obtained after BCS expansion at 885 G and subsequent BEC expansion at 680 G. The $\chi^2$ of the fit was monitored as a function of the BCS-expansion time $t_{BCS}$. A high $\chi^2$ indicates a bimodal density distribution. Vortices were still observed after 5 ms of expansion (indicated by the dashed line in the figure) while bimodality had already disappeared (for $\chi^2$ values smaller than 0.01 bimodality cannot be discerned). Hence, the absence of bimodality does not imply an absence of superfluidity.

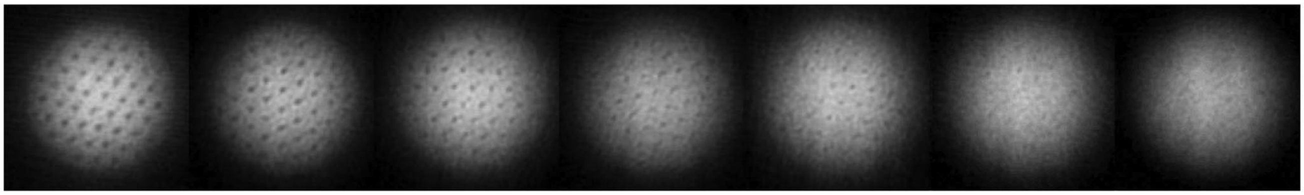

FIG. 5. Loss of vortex contrast on resonance at 834 G. Shown are absorption images after a fixed total time of flight, but for different expansion times on resonance (2, 2.5, 3, 3.5, 4, 5, and 6 ms) before the magnetic field was swept to the BEC side for further expansion. A gradual loss of the vortex contrast from about 15% (after 2 ms of expansion on resonance) to 3% (after 5 ms) was observed across the whole cloud. The field of view of each image is 1.2 mm × 1.2 mm.

expansion although vortices were still visible (see Fig. 4 for details). The absence of bimodality therefore does not indicate a breakdown of superfluidity.

So far we have studied the expanding gas on the BCS side of the Feshbach resonance. On the BEC side and on resonance, $T_C$ is proportional to $T_F$ so that $T/T_C$ is constant during expansion. Therefore, one would not expect to observe a breakdown of superfluidity. Figure 5 shows absorption images obtained after initial expansion of the cloud on resonance at 834 G. In contrast to the situation on the BCS side of the resonance no vortices were lost. Instead, the vortex contrast decreased uniformly across the cloud for longer expansion times. Vortices have been detected at total densities as low as $1.2 \times 10^{11}\ \mathrm{cm}^{-3}$ in the wings of the expanded cloud. Here the critical temperature $T_C$ of approximately $0.2T_F$ [23,24] was below 20 nK ($k_BT_F$ is the local Fermi energy). We believe that the decrease in vortex contrast is due to the low density of the gas after long expansion on resonance: after the magnetic field sweep the vortex cores cannot adjust quickly enough to the high contrast and large size they would have in equilibrium on the BEC side. This reduction of contrast limited our study of the breakdown of superfluidity to magnetic fields above 880 G.

In conclusion, we have shown that superfluid pairs can survive during the expansion of a strongly interacting Fermi gas. This is the first observation of nonequilibrium superfluid flow in such systems. It has allowed us to observe fermionic superfluidity at total densities as low as $1.2 \times 10^{11}\ \mathrm{cm}^{-3}$. Our results show that future experiments with expanding, superfluid Fermi gases can be carried out *in situ*, i.e., without magnetic field sweeps to the BEC side. An intriguing question is whether fermion pairs expanding from two clouds can coherently interfere.

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[18] We find $\frac{\hbar\dot{\Delta}}{\Delta^2} = \frac{\hbar}{\Delta} \times \frac{\dot{n}}{n} \times (\frac{2}{3} + \frac{\pi}{6k_F|a|})$. Because the gas expands to a very good approximation only radially, we assume that the density varies as $n(t) = n_0/(1 + \omega_r^2 t^2)$, and obtain $|\frac{\hbar\dot{\Delta}}{\Delta^2}| = \frac{\hbar}{\Delta} \frac{2\omega_r^2 t}{1+\omega_r^2 t^2} (\frac{2}{3} + \frac{\pi}{6k_F|a|})$. For the experimental parameters when the vortices in the center of the cloud are lost we find that $\hbar\dot{\Delta}/\Delta^2 \leq 0.4$.
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