Evidence for Superfluidity in a Resonantly Interacting Fermi Gas

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We observe collective oscillations of a trapped, degenerate Fermi gas of ^{6}Li atoms at a magnetic field just above a Feshbach resonance, where the two-body physics does not support a bound state. The gas exhibits a radial breathing mode at a frequency of 2837(05) Hz, in excellent agreement with the frequency of $\nu_H \equiv \sqrt{10\nu_x\nu_y/3} = 2830(20)$ Hz predicted for a *hydrodynamic* Fermi gas with unitarity-limited interactions. The measured damping times and frequencies are inconsistent with predictions for both the collisionless mean field regime and for collisional hydrodynamics. These observations provide the first evidence for superfluid hydrodynamics in a resonantly interacting Fermi gas.

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Strongly-interacting two-component Fermi gases provide a unique testing ground for the theories of exotic systems in nature, ranging from super-high temperature superconductors to neutron stars and nuclear matter. The feature that all of these systems have in common is a strong interaction between pairs of spin-up and spin-down particles. In atomic Fermi gases, tunable, strong interactions are produced using a Feshbach resonance [1–3]. Near the resonance, the zero-energy s-wave scattering length a exceeds the interparticle spacing, and the interparticle interactions are unitarity limited and universal [4–6]. In this region, high temperature Cooper pairing has been predicted [7–10].

In this Letter, we present measurements of the frequencies and damping times for the radial hydrodynamic breathing mode of a trapped, highly degenerate gas of ^{6}Li atoms just above a Feshbach resonance at 822(3) G [11]. A cross-check of the measurement method is provided by observing the breathing mode of a noninteracing gas.

Hydrodynamic behavior in a collisionless quantum gas at very low temperature is known to be a hallmark of superfluidity. Previously, we observed hydrodynamic, anisotropic expansion of a strongly interacting, ultracold, two-component Fermi gas [12]. However, an initially collisionless gas could have become collisionally hydrodynamic as the Fermi surface significantly deformed during the expansion [13]. Thus, the observations suggested superfluid hydrodynamics, but were not conclusive.

Superfluidity has been observed in Bose-Einstein condensates (BECs) of molecular dimers, which have been produced from a two-component strongly interacting Fermi gas. The first experiments produced the dimer BECs at a magnetic field below the Feshbach resonance, where the atoms have a nonzero binding energy [14–17]. Although the two-body physics does not support a bound state at magnetic fields above the Feshbach resonance, for fermionic atoms, the many-body physics does. Observations of BECs originating from such dimers are consistent with the existence of preformed pairs [11,18]. These experiments indirectly explore the microscopic structure, while our experiments are complementary in that they directly measure the macroscopic dynamics.

One method for distinguishing between a BEC and a superfluid Fermi gas is to examine their collective hydrodynamic modes at a low temperature where the trapped gas is collisionless [19]. For a weakly repulsive BEC contained in a nearly cylindrically symmetric trap, the radial breathing mode occurs at a frequency of $\nu_B = 2\sqrt{\nu_x\nu_y}$, where ν_i is the harmonic oscillation frequency in Hz of a noninteracting gas in the ith direction of the trap. In contrast to a weakly repulsive BEC, a superfluid Fermi gas in a cigar-shaped trap is predicted to have a radial breathing mode at the hydrodynamic frequency

$$\nu_H = \sqrt{\frac{10}{3}\,\nu_x\nu_y}. \tag{1}$$

This result is obtained in the unitarity limit, where the shift from the interparticle interactions vanishes for a hydrodynamic gas [20,21]. In general, hydrodynamics with the frequency ν_H can arise from superfluidity or from collisions in a normal fluid. However, at low temperature, Pauli-blocking is expected to suppress the collision rate in a Fermi gas, *increasing* the damping rate of the collisionally hydrodynamic modes as the temperature is lowered.

In our experiments with a trapped Fermi gas, Pauli-blocking of collisions is expected to be effective at the lowest temperatures achieved. Nevertheless, a weakly damped radial mode at precisely the hydrodynamic frequency of ν_H is observed, and the damping rate *decreases* strongly as the temperature is lowered below $\simeq 30\%$ of the Fermi temperature for a noninteracting gas. These observations provide the first evidence for superfluid hydrodynamics in a resonantly interacting Fermi gas.

We prepare a degenerate 50-50 mixture of the two lowest spin states of ^{6}Li atoms by forced evaporation in an ultrastable CO_2 laser trap [12], at a chosen magnetic field in the range 770–910 G. The trap depth is lowered by a factor of $\simeq$580 over 4 s, then recompressed to 4.6% of the full trap depth in 1 s and held for 1 s to assure equilibrium. For our parameters, the typical Fermi temperature T_F for a noninteracting gas is $\simeq 2.5\ \mu$K, small compared to the final trap depth of 35 μK.

Absorption images of the cloud use a probe pulse of 5 μs duration and a two-level optical transition [12]. The entire imaging system has a measured resolution of 5.5 μm. For low temperatures T where $T/T_F \leq 0.4$, the ratio T/T_F is determined by fitting a Thomas-Fermi profile for a noninteracting Fermi gas to the transverse (x) distribution obtained by integrating the column density in the axial (z) direction. At 910 G, this procedure yields temperatures as low as $T/T_F = 0.06$ and excellent fits. However, at fields closer to resonance, slightly higher temperatures are obtained, and the shape may not be precisely Thomas-Fermi due to many-body effects. For measurements at the highest temperatures $T/T_F =$ 0.5–1.2, the expansion dynamics of the gas may not be perfectly hydrodynamic, and hence temperature estimates are less precise. Here, we assume hydrodynamic expansion of a Maxwell-Boltzmann spatial distribution for a noninteracting gas. The measured temperatures therefore indicate the trend, but not necessarily the absolute temperature. We find consistency between the measured number of atoms, temperature, and the initial cloud size obtained by hydrodynamic scaling [12]. For the strongly interacting gas, we include a reduction of the cloud radius arising from the mean field [5]. By correcting selected images for our estimated saturation $I/I_{\mathrm{sat}} =$ 0.2, we estimate that the true temperatures are lower by 0.03 T_F and the true atom numbers are increased by a factor $\simeq$1.15 compared to the values given in Table I.

Trap oscillation frequencies at 4.6% of the full well depth are measured by parametric resonance in a weakly-interacting sample. The gas is cooled by forced evaporation over 25 s to temperatures of 0.3 T_F at a field of 300 G, and the trap depth is then modulated by 0.1% for 4 s. During this period, the low collision rate produces little damping, but permits the gas to thermalize. After modulation, imaging at 526 G is used to measure the release energy versus drive frequency. Well-resolved resonances are obtained at $2\omega_x = 2\pi \times 3200(20)$ Hz and $2\omega_y = 2\pi \times 3000(20)$ Hz. Because of the low frequency, the axial resonance is measured at full trap depth. We obtain $2\omega_z = 2\pi \times 600(20)$ Hz, yielding $\omega_z = 2\pi \times 70(3)$ Hz at 4.6% of full trap depth, including a quadratically combined magnetic field curvature contribution of 21 Hz at 870 G. From these measurements, $\nu_\perp \equiv \sqrt{\nu_x \nu_y} =$ 1550(20) Hz.

To excite the transverse breathing mode, the trap is turned off abruptly ($\leq 1\ \mu$s) and turned back on after a delay of $t_0 = 50\ \mu$s. Then the sample is held for a variable time t_{hold}. Finally, the trap is extinguished suddenly, releasing the gas which is imaged after 1 ms. To show that our excitation is a weak perturbation, we estimate the energy increase, which arises principally from the change in potential energy in the transverse directions. Assuming approximately ballistic expansion, $\Delta E_\perp = E_\perp(\omega_\perp t_0)^2/2 = 0.1\ E_\perp$. For initial temperatures of 0.1–0.15 T_F, the corresponding temperature change is $\Delta T/T_F \simeq 0.05$ when the gas thermalizes, consistent with our measurements.

TABLE I. Breathing mode frequencies ν and damping times τ_{damp}. B is the applied magnetic field, T/T_F is the initial temperature, and N is the total number of atoms, uncorrected for saturation. x_{rms} is the time-averaged root-mean-square size of the oscillating cloud. Error estimates are from the fit only.

$B(G)$	T/T_F	$N(10^3)$	$x_{\mathrm{rms}}(\mu\mathrm{m})$	ν(Hz)	τ_{damp}(ms)
526[b]	0.30(0.02)	288(18)	35.2	3212(30)	2.04(0.4)
770	0.13(0.03)[a]	138(20)	29.3	3000(150)	2.00(1.1)
815	0.14(0.04)[a]	198(24)	24.0	2931(19)	3.60(1.5)
860	0.14(0.04)	294(26)	28.6	2857(16)	3.67(1.1)
870[b]	0.17(0.06)	288(30)	32.0	2837(05)	3.85(0.4)
870[c]	0.15(0.03)	225(36)	33.5	2838(06)	6.01(1.4)
870[d]	0.18(0.04)	207(28)	41.8	5938(18)	1.44(0.2)
870[b]	0.33(0.02)	379(24)	46.1	2754(14)	2.01(0.3)
870[b]	0.50(0.06)	290(32)	45.1	2775(08)	1.39(0.1)
870	1.15(0.10)	244(10)	41.7	2779(50)	1.08(0.4)
880	0.12(0.04)	258(30)	30.0	2836(16)	3.95(1.5)
910	0.11(0.06)	268(17)	27.8	2798(15)	3.30(1.1)

[a]From the tails of a bimodal distribution.
[b]Shown in the figures.
[c]For $t_0 = 25\ \mu$s.
[d]At 18.8(0.9)% trap depth, $t_0 = 25\ \mu$s and 0.8 ms expansion time.

To study a noninteracting sample, breathing modes are excited at 526 G, where the scattering length is nearly zero [22,23], after cooling at 300 G as described above. Figure 1 shows $\sqrt{\langle x^2 \rangle}$ for the expanded gas ($\langle x \rangle \equiv 0$), plotted versus t_{hold}. Fitting with a damped sinusoid $x_{\mathrm{rms}} + A\exp(-t/\tau_{\mathrm{damp}})\sin(2\pi\nu t + \varphi)$, we obtain $\nu =$ 3212(30) Hz, in excellent agreement with the frequency 3200(20) Hz measured by the parametric resonance method for the x direction which is imaged in the experiments. The damping time $\tau_{\mathrm{damp}} = 2.04(0.4)$ ms is consistent with a small anharmonicity from the Gaussian profile of the trap potential.

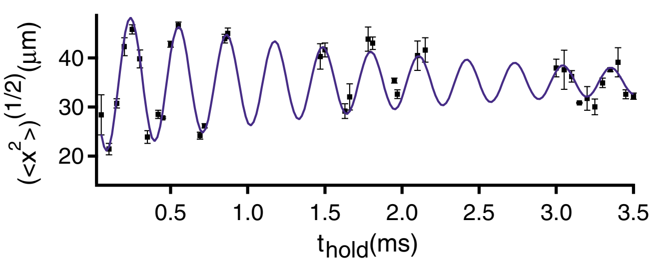

FIG. 1 (color online). Excitation of the breathing mode in a noninteracting Fermi gas of ^{6}Li at 526 G. Error bars = 68% confidence interval.

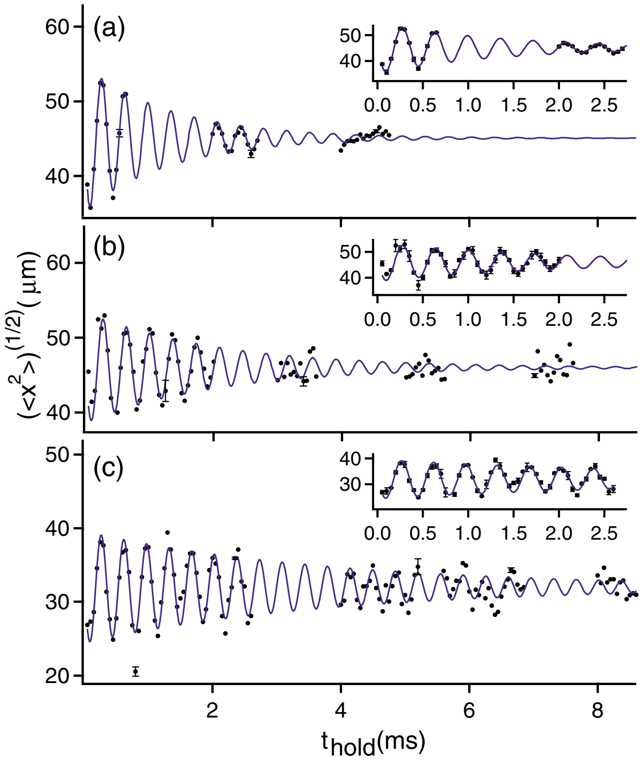

FIG. 2 (color online). Excitation of the breathing mode in a strongly interacting Fermi gas of ^{6}Li at 870 G. (a) $T/T_F = 0.50$. (b) $T/T_F = 0.33$. (c) $T/T_F = 0.17$. Error bars = 68% confidence interval.

Results for the strongly interacting gas above resonance at 870 G are shown in Figs. 2(a)–2(c) and summarized for different temperatures and magnetic fields in Table I. For the strongly interacting gas at 870 G and $T/T_F = 0.17$, the measured radial breathing mode frequency 2837(05) Hz is in excellent agreement with the prediction of Eq. (1), $\nu_H = 2830(20)$ for a hydrodynamic Fermi gas, and it differs significantly from that of the noninteracting gas and the weakly-interacting Bose gas, $\nu_B = 3100$ Hz. For the axial direction, the measured amplitude of the oscillation is consistent with zero.

On the molecular side just below resonance, at 815 G at $T/T_F = 0.14$, we obtain $\nu = 2931(19)$, which is near ν_H, consistent with predictions that the response near resonance is fermionic [20,21]. At a much lower field of 770 G, we find $\nu = 3000(150)$ closer to the predicted Bose frequency of 3100(20) Hz. However, the data is not of as high quality as that shown in Fig. 2.

Over the range of magnetic fields studied, 770–910 G, our measured oscillation frequencies $\nu(B)$ at the lowest temperatures show the same magnetic field dependence as those of M. Bartenstein *et al.* [24]. However, our data show a much smaller shift with respect to ν_H of Eq. (1).

We estimate the frequency shifts $\Delta\nu \equiv \nu(\text{meas}) - \nu(\text{actual})$ arising from anharmonicity in the trapping potential [25]. For the hydrodynamic frequency, $\Delta\nu_H = -(32/25)\sqrt{10/3}\,\nu_\perp M\omega_\perp^2 x_{\text{rms}}^2/(b_H^2 U)$, where U is the trap depth, M is the ^{6}Li mass, and $\omega_\perp = 2\pi\nu_\perp$. Here, b_H is the hydrodynamic expansion factor, 11.3 after 1 ms [26]. The shift in the geometric mean of the transverse frequencies $\Delta\nu_\perp = -(6/5)\nu_\perp M\omega_\perp^2 x_{\text{rms}}^2/(b_B^2 U)$, where $b_B = 10.3$ is the ballistic expansion factor at 1 ms. Using Table I, these results yield a net $\Delta\nu \equiv \Delta\nu_H - \sqrt{10/3}\Delta\nu_\perp = +24$ Hz at 870 G and $T/T_F = 0.17$. For the three higher temperatures at 870 G, we find $\Delta\nu \simeq -35$ Hz at $T/T_F = 0.33$ and 0.5, and -16 Hz at $T/T_F = 1.15$, consistent with the measured $\simeq -60$ Hz shift below the lowest temperature data.

We have also investigated the effect of decreasing the oscillation amplitude to less than 10% by reducing t_0 to 25 μs at 870 G and $T/T_F = 0.15$. For small amplitudes, the aspect ratio of the cloud changes very little. Hence, we expect that the deformation of the Fermi surface is very small, so that collisional behavior is not induced. We obtain $\nu = 2838(06)$ Hz, in precise agreement with the results for $t_0 = 50$ μs. The damping time is somewhat increased to 6.00(1.4) ms, presumably due to the smaller energy input rather than reduced anharmonicity (since the frequency is unchanged).

The measured damping time shows a rapid increase with decreasing temperature, Fig. 3. The open circle shows the result at a trap depth increased by a factor of 4.1. The measured hydrodynamic frequency scales as $\sqrt{4.1}$ within 3% and the product $\nu_{\text{meas}}\tau_{\text{damp}}$ is consistent with those at lower trap depth. This is consistent with a damping rate which scales linearly with trap frequency, as expected for unitarity-limited interactions, where the rate scales with the Fermi energy. Note that anharmonicity cannot make a major contribution to the temperature dependence of our damping rates: The anharmonic contribution to $1/\tau_{\text{damp}}$ would be proportional to the frequency shift and therefore independent of trap depth for fixed T/T_F and N. Then, $\nu_{\text{meas}}\tau_{\text{damp}} \propto \nu_{\text{meas}}$, and the vertical position of the open circle would increase by a factor of 2. Further, the anharmonic contribution is identical for the three highest temperature points where the mean cloud sizes are nearly the same.

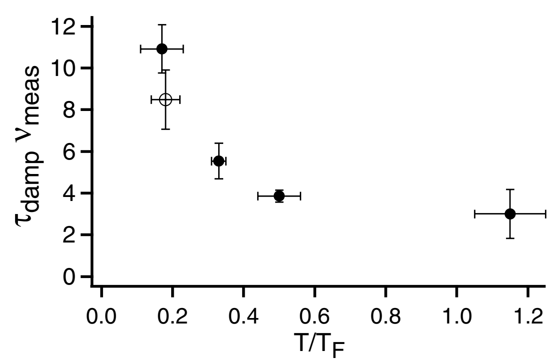

FIG. 3. Product of the damping time and the measured breathing mode frequency versus temperature. The open circle shows the result when the trap depth is increased by a factor of 4.1.

We have attempted to model the data at 870 G without invoking superfluidity. A first scenario is that the gas is nearly collisionless at the lowest temperature, and the long damping time and measured frequency are the result of collisionless mean field evolution. A second scenario is collisional hydrodynamics.

The collisionless mean field scenario requires a large negative mean field shift to explain the difference between the frequencies of 3212(30) and 2837(20) Hz measured for the noninteracting and strongly interacting samples, respectively. However, for a unitarity-limited interparticle interaction with a negative $\beta = -0.55$ [27], a Vlasov equation model [28] yields a +90 Hz shift relative to 3200 Hz, while we observe a −400 Hz shift. Also, for our trap, the same model shows that the coupling of the collisionless transverse modes by the interaction would produce a noticeable beat at 370 Hz with an amplitude minimum at 1 ms, which is not observed. Hence, the data are inconsistent with the collisionless scenario.

To investigate the second scenario, we considered a collisional hydrodynamic model, including two-body Pauli blocking [19,29]. A small negative shift at the higher temperatures might arise from the mean field in the hydrodynamic limit [20,21] or from the anharmonic shift described above. Neglecting these shifts, a relaxation approximation model [30] can be used to determine both the breathing mode frequency and the damping time in terms of the measured trap oscillation frequencies, for an arbitrary momentum relaxation rate. We find that a very large momentum relaxation rate is needed to fit the 4 ms damping time of the $T/T_F = 0.17$ data in a collisionally hydrodynamic regime. Then, the predicted damping time is large over a broad temperature range, inconsistent with the observed rapid decrease in damping time with temperature. Lowering the maximum relaxation rate, we can fit the damping times at the two highest temperatures. In this case, however, obtaining a 4 ms damping time requires a temperature below $T/T_F = 0.1$, i.e., a nearly collisionless regime, inconsistent with observations as described above.

In conclusion, at our lowest temperatures, we observe a breathing mode at precisely the hydrodynamic frequency as well as highly anisotropic hydrodynamic expansion, as in our previous experiments [12,28]. The damping time increases rapidly as the temperature is lowered [31], consistent with a transition from collisional to superfluid hydrodynamics at a temperature between 0.3 and 0.2 T_F. On the basis of the above arguments, we believe the data are not consistent with either collisionless mean field evolution or collisional hydrodynamics. It is therefore difficult to see how the observations can be explained without invoking superfluidity.

Recent theory describes the BCS-BEC crossover regime in terms of very large fermionic pairs, comparable in size to the interparticle spacing [32–34]. Falco and Stoof [33] predict BEC-like or BCS-like behavior *above* the Feshbach resonance, depending on whether $\epsilon_b \equiv \hbar^2/(a^2 m_{\rm atom})$ is $\leq 2k_BT_F$ or $\geq 2k_BT_F$ [35]. Near resonance, where $\epsilon_b \ll 2k_BT_F$, the majority of fermionic pairs (either Bose molecules or Cooper pairs) are very large. Hence, one expects that the response of the system to compression is fermionic, and scales with density as $n^{2/3}$ [36], consistent with our measurements and with predictions [20,21].

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