

Exploring the BEC-BCS Crossover with an Ultracold Gas of ${}^6\text{Li}$ Atoms

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Abstract

We present an overview of our recent measurements on the crossover from a Bose-Einstein condensate of molecules to a Bardeen-Cooper-Schrieffer superfluid. The experiments are performed on a two-component spin-mixture of ${}^6\text{Li}$ atoms, where a Feshbach resonance serves as the experimental key to tune the s-wave scattering length and thus to explore the various interaction regimes. In the BEC-BCS crossover, we have characterized the interaction energy by measuring the size of the trapped gas, we have studied collective excitation modes, and we have observed the pairing gap. Our observations provide strong evidence for superfluidity in the strongly interacting Fermi gas.

1 Introduction

The crossover from a Bose-Einstein condensate (BEC) to a Bardeen-Cooper-Schrieffer (BCS) superfluid has for decades attracted considerable attention in condensed matter theory [1, 2, 3, 4]. The observation of BEC of molecules in ultracold trapped Fermi gases of ${}^6\text{Li}$ and ${}^{40}\text{K}$ [5, 6, 7, 8, 9] has opened up a unique route to explore this BEC-BCS crossover. Magnetically tuned scattering resonances, known as Feshbach resonances [11], play the key role to control the two-body interaction and to vary the coupling strength over a very broad range. Exploiting Feshbach tuning, recent experiments have begun to explore the crossover by studying elementary properties of the system under variable interaction conditions. The internal interaction energy was measured by detecting the cloud size of a trapped gas [12] and by observing the expansion of the gas after release [8]. The condensed nature of fermionic atom pairs was demonstrated by rapid conversion of the “Fermi condensate” into a molecular BEC [13, 14]. The study of collective excitation modes [15, 16, 17] provided first insight into changes of the equation of state and hydrodynamics of the system in the crossover. Spectroscopic measurements of the pairing energy [18] showed the crossover from molecular pairing to fermionic “Cooper” pairing. The results of these experiments provide strong evidence of “resonance superfluidity” [19, 20, 21, 22] in a strongly interacting Fermi gases.

Here we summarize the BEC-BCS crossover experiments that we recently performed in Innsbruck on an ultracold gas of ${}^6\text{Li}$ atoms. Degenerate Fermi gases of ${}^6\text{Li}$ have been produced by several groups [23, 24, 25, 26, 5]. A mixture of the two lowest spin states of ${}^6\text{Li}$ is particularly interesting because it is stable against two-body decay and it exhibits a broad Feshbach resonance [27] in combination with a narrow one [28]. The broad resonance has been widely employed by us and other groups to create a strongly interacting Fermi gas [29], to study interaction effects [30], to form stable weakly bound molecules [31, 32], to create Bose-Einstein condensates

of molecules [5, 7, 8, 9], and to study the BEC-BCS crossover [12, 14, 16, 17, 18]. After obtaining the experimental data summarized here, we recently performed high-precision spectroscopic experiments on the ${}^6\text{Li}$ molecular interaction parameters [33]. We here discuss our experimental crossover data [12, 16, 18] with up-to-date knowledge of the two-body scattering properties.

2 Creation of a molecular BEC

Our molecules are weakly bound ${}^6\text{Li}_2$ dimers in the last bound level very close to the dissociation threshold. A key property of these molecules is their stability against inelastic decay resulting from the fermionic nature of the constituent atoms [34]. For molecule formation and evaporative cooling towards BEC, we choose a magnetic field of 764 G, which is below the center of the resonance at 834 G [33]. Here the s -wave scattering length is $a = 4500 a_0$ and the molecular binding energy is $E_b = \hbar^2/(ma^2) = k_B \times 1.4 \mu\text{K}$, where a_0 denotes Bohr's radius and k_B is Boltzmann's constant.

Evaporative cooling is performed in a single-beam optical dipole trap [5]. A 1030-nm laser beam, which is focused to a waist of $25 \mu\text{m}$, is loaded with 2×10^6 optically precooled atoms. For forced evaporative cooling, the laser power is exponentially ramped down from the initial value of 10 W to a few mW with a time constant of 460 ms. The molecules are formed during the evaporation following a chemical atom-molecule equilibrium [36, 37]. Finally, all remaining atoms form molecules and the pure molecular sample condenses into a BEC. As a consequence of molecular Bose-Einstein condensation we first observed that, at the end of the evaporation, the number of atoms confined in a very shallow trap exceeded the number of quantum states available for fermionic atoms by almost an order of magnitude [5]. We furthermore observed a collective excitation mode and demonstrated magnetically tuned mean-field effects [5]. Using in-situ absorption imaging we also observed the phase transition in characteristic bimodal distributions of the trapped cloud [12]; see Fig. 1. The images provide a lower bound for the condensate fraction of 90% and thus demonstrate that an essentially pure molecular BEC is formed.

We measured very long lifetimes of the molecular BEC. After recompression in the optical dipole trap to a peak number density of $1.0(5) \times 10^{13} \text{cm}^{-3}$ we observed a lifetime of 40s. This corresponds to a very low upper bound for the binary loss coefficient of $1 \times 10^{-14} \text{cm}^3/\text{s}$, which demonstrates the enormous stability of weakly bound ${}^6\text{Li}_2$ molecules [31, 32, 34].

The pure molecular BEC has served as a starting point for all our experiments on the BEC-BCS crossover, as described in the following.

3 Conversion of a molecular BEC to a degenerate Fermi gas

For exploring the crossover to a Fermi gas we apply slow magnetic field ramps. We typically change the magnetic field from the BEC production value to a final value in 1 s. This is slow enough for the gas to react adiabatically. In a test experiment [12] we checked the reversibility of the crossover process by linearly ramping up the magnetic field from 764 G to 1176 G and down again to 764 G within 2 s. The comparison of the spatial profiles did not show any significant deviations. This experiment showed that

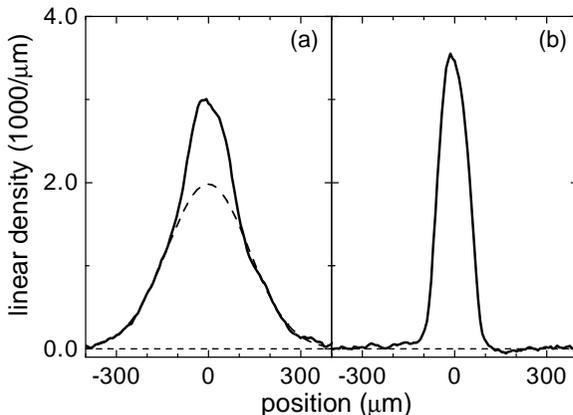


Figure 1: Molecular BEC is observed using *in situ* axial density profiles of the trapped cloud [12]. (a) A partially condensed cloud with 4×10^5 molecules is obtained when the evaporation is stopped at a final laser power of 28 mW, and (b) an essentially pure BEC of 2×10^5 molecules is obtained at a final laser power of 3.8 mW.

the conversion into a degenerate Fermi gas and its back-conversion into a molecular BEC takes place without loss and heating in a fully reversible way. This remarkable possibility to change the character of the gas in a reversible and isentropic way highlights the outstanding properties of ${}^6\text{Li}$ Fermi gases for BEC-BCS crossover studies. Note that the isentropic conversion of a molecular BEC into a degenerate Fermi gas goes along with a substantial temperature reduction [35].

In a first set of experiments we measured spatial profiles of the trapped ultracold gas for magnetic fields between 740 G and 1440 G [12]. These profiles provide information on the interaction energy in the sample and on the equation of state. The recorded axial density profiles are in general well fit by Thomas Fermi profiles. Fig. 3(b) shows how the measured root-mean-square axial size z_{rms} changes with the magnetic field. For comparison, Fig. 3(a) displays the magnetic-field dependence of the atomic scattering length a [33]. Up to 950 G the observed increase in z_{rms} is due to the crossover from the molecular BEC to the degenerate Fermi gas. For higher magnetic fields, the shrinking of the axial cloud size is caused by an increasing magnetic confinement [12]. To remove the explicit trap dependence, we normalize the observed size to the one expected for a non-interacting Fermi gas. In Fig. 3(c) we show the normalized axial size $\zeta = z_{\text{rms}}/z_0$, where z_0 is the rms axial size of a non-interacting zero-temperature Fermi gas with $N = 4 \times 10^5$ atoms.

Below the Feshbach resonance, the observed dependence of the cloud size agrees well with the mean-field behavior of a molecular BEC in the Thomas-Fermi limit. In this regime, the normalized size is given by $\zeta = 0.688(a_{\text{mol}}/a)^{1/5}(E_{\text{F}}/E_{\text{b}})^{1/10}$, where E_{F} is the Fermi energy of the gas without interactions. Fig. 3(c) shows the corresponding curve (solid line) calculated with a molecule-molecule scattering length $a_{\text{mol}}/a = 0.6$ [34]. We find that this BEC limit provides a reasonable approximation up to ~ 780 G; here the molecular gas interaction parameter is $n_{\text{mol}}a_{\text{mol}}^3 \approx 0.05$. Alternatively, the interaction strength can be expressed as $k_{\text{F}}a \approx 2$, where the Fermi wavenumber k_{F} is related to the Fermi energy by $E_{\text{F}} = \hbar^2 k_{\text{F}}^2 / (2m)$. The crossover to the Fermi

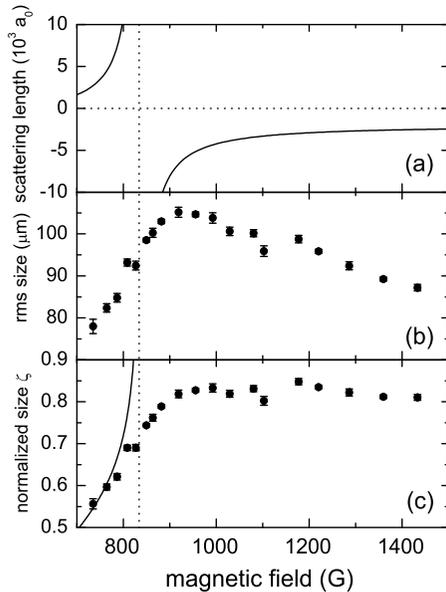


Figure 2: Cloud size measurements across the Feshbach resonance [12]. In (a) the atomic scattering length a is shown according to [33]; the resonance at 834 G is marked by the vertical dashed line. The data in (b) display the measured rms cloud sizes. In (c), the same data are plotted after normalization to a non-interacting Fermi gas. The solid line shows the expectation from BEC mean-field theory with $a_{\text{mol}} = 0.6 a$.

gas is observed in the vicinity of the Feshbach resonance between 780 G and 950 G; here ζ smoothly increases with the magnetic field until it levels off at 950 G, where the interaction strength is characterized by $k_{\text{F}}a \approx -1.4$. Our results show that the crossover occurs within the range of $-0.7 < (k_{\text{F}}a)^{-1} < 0.7$, which corresponds to the strongly interacting regime.

The case of resonant two-body interaction is of particular interest for many-body quantum physics. For $|a| \rightarrow \infty$ a universal regime is realized [38, 39, 40], where scattering is fully governed by unitarity and the scattering length drops out of the description. The normalized cloud size can be written as $\zeta = (1 + \beta)^{1/4}$, where β parameterizes the mean-field contribution to the chemical potential in terms of the local Fermi energy [40]. At 834 G, our measurements show $\zeta = 0.72 \pm 0.07$ which provides $\beta = -0.73^{+0.12}_{-0.09}$. Here the total error range includes our best knowledge of statistic and systematic uncertainties, with the particle number giving the dominant contribution to the error budget. Recent quantum Monte Carlo calculations yielded $\beta = -0.56(1)$ [41] and $-0.58(1)$ [42]. Our experimental results are close to these predictions, but they show a deviation somewhat larger than our assumed experimental error range. If we, in turn, use the theoretical predictions on β to calibrate our particle number we obtain 2.0×10^5 trapped atoms, which only slightly falls outside of our estimated uncertainty range.

It is very interesting to compare our data with recent predictions from advanced crossover theories. Ref. [43] compares spatial profiles calculated from a diagrammatic

theory including pairing fluctuations beyond mean-field with our experimental profiles. The diagrammatic theory itself [44] agrees very well with quantum Monte Carlo calculations [42], in particular in the range of our experiments. If we assume 2×10^5 atoms for our experiments, our data on spatial profiles and the size of the trapped gas are found to agree excellently with theory in the whole crossover range.

4 Measurements of collective oscillations

The investigation of collective excitation modes [45] is well established as a powerful method to gain insight into the physical behavior of ultracold quantum gases in different regimes of Bose [46] and Fermi gases [47]. Ref. [48] pointed out an interesting dependence of the collective frequencies in the BEC-BCS crossover of a superfluid Fermi gas. Superfluidity implies a hydrodynamic behavior which can cause substantial changes in the excitation spectrum and in general very low damping rates. However, in the crossover regime the strong interaction between the particles also results in hydrodynamic behavior in the normal, non-superfluid phase. Therefore the interpretation of collective modes in the BEC-BCS crossover in terms of superfluidity is not straightforward and needs careful investigation to identify the different regimes.

We studied two elementary collective excitation modes in the BEC-BCS crossover [16]. The slow *axial* compression mode confirmed theoretical expectations on the equation of state of the gas in the crossover and is in general well understood [49]. In the BEC limit we observed an oscillation frequency Ω_z consistent with the expected $\Omega_z = \sqrt{5/2}\omega_z = 1.581\omega_z$, where ω_z denotes the axial trap frequency. In the unitarity limit (at 834 G) we measured a 2% down-shift of the axial frequency, in agreement with the prediction $\Omega_z = \sqrt{5/2}\omega_z = 1.549\omega_z$. This down-shift is a consequence of the fact that the equation of state of the quantum gas changes from $\mu \propto n$ to $\mu \propto n^{2/3}$ [48, 49]. With the magnetic field increasing beyond the resonance, we observe a further decrease in the collective excitation frequency until a minimum is reached at about 900 G, where $1/(k_F a) \approx -0.5$. This observation is in agreement with theoretical expectations [49]. With further increasing magnetic field and decreasing interaction strength, we observe a gradual transition to a collisionless regime and a corresponding gradual increase of the collective frequency toward $\Omega_z/\omega_z = 2$.

At about 815 G, somewhat below the resonance point, we observed extremely low damping rates for the axial collective oscillations. Here the $1/e$ damping time corresponded to about 160 oscillations. This striking behavior may be seen as a strong piece of evidence for *superfluidity*.

The fast *radial* compression mode showed a surprising dependence on the magnetic field [16], which is not fully understood yet. Fig. 3 shows the observed radial oscillation frequency Ω_r and damping rate Γ_r , normalized to the radial trap frequency ω_r . The unitarity gas shows a large down-shift to $\Omega_r/\omega_r = 1.67(3)$, much larger than the expected value of $\Omega_r/\omega_r = \sqrt{10/3} = 1.826$ from hydrodynamic theory [48]. However, it is questionable whether simple hydrodynamic theory still applies for our experimental conditions [50].

The most striking feature of our radial oscillation data is the abrupt change of the excitation frequency at a field of ~ 910 G, which is accompanied by an anomalously large damping. Beyond this point the collective oscillations exhibit the collisionless value of $\Omega_r/\omega_r = 2$, which clearly shows that the gas loses its hydrodynamic properties. A plausible interpretation [50] of this breakdown of hydrodynamics is a coupling of

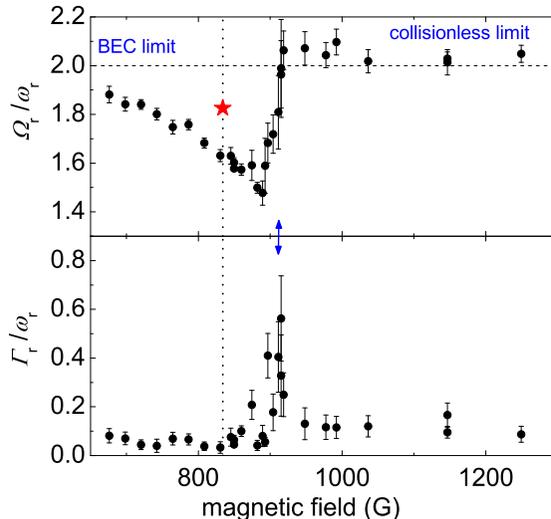


Figure 3: Measured frequency Ω_r and damping rate Γ_r of the radial compression mode, normalized to the trap frequency (sloshing mode frequency) ω_r . In the upper graph, the dashed line indicates $\Omega_r/\omega_r = 2$, which corresponds to both the BEC limit and the collisionless Fermi gas limit. The vertical dotted line marks the resonance position at 834 G. The star indicates the theoretical expectation of $\Omega_r/\omega_r = \sqrt{10/3}$ in the unitarity limit. A striking change in the excitation frequency occurs at ~ 910 G (arrow) and is accompanied by anomalously strong damping.

the collective oscillations to the fermionic pairs in the strongly interacting gas. This interpretation is supported by our measurements on pairing energies [18], see below.

The Duke group has performed experiments on radial collective oscillations in a set-up very similar to ours [15, 17]. They found a strong temperature dependence of the damping rate, which provides further evidence for superfluidity in the system [15]. On resonance, they measured a collective frequency in agreement with hydrodynamic theory and thus not consistent with our observation. Beyond the Feshbach resonance the Duke measurements confirmed our observation of a breakdown of hydrodynamics [17]. Clearly more measurements are needed on the radial excitation mode.

5 Observation of the pairing gap

The formation of pairs generally represents a key ingredient of superfluidity in fermionic systems. The “pairing gap”, which corresponds to the binding energy of the pairs, is a central quantity to characterize the pairing regime. We employed radio-frequency (rf) spectroscopy [51, 52, 53] to study pairing in the BEC-BCS crossover. Spectral signatures of pairing were theoretically considered in Refs. [54, 55, 56, 57, 58]. A clear signature of the pairing process is the emergence of a double-peak structure in the spectral response as a result of the coexistence of unpaired and paired atoms. The pair-related peak is located at a higher frequency than the unpaired-atoms signal as energy is required for pair breaking.

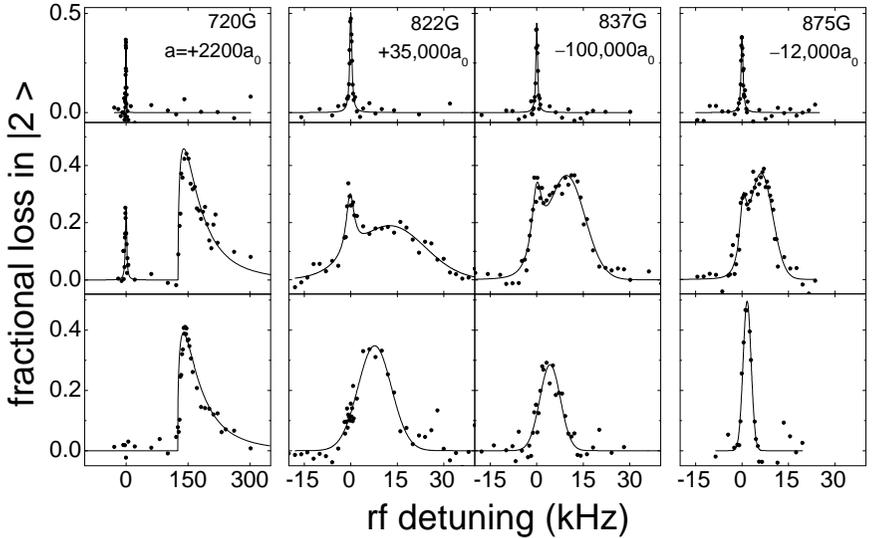


Figure 4: Radio-frequency spectra for various magnetic fields and different degrees of evaporative cooling. The rf offset is given relative to the atomic transition. The molecular limit is realized for $B = 720$ G (first column). The resonance regime is studied for $B = 822$ G and 837 G (second and third column). The data at 875 G (fourth column) explore the crossover on the BCS side. Upper row, signals of unpaired atoms at $T' \approx 6T_F$ ($T_F = 15 \mu\text{K}$); middle row, signals for a mixture of unpaired and paired atoms at $T' = 0.5T_F$ ($T_F = 3.4 \mu\text{K}$); lower row, signals for paired atoms at $T' < 0.2T_F$ ($T_F = 1.2 \mu\text{K}$). The solid lines are introduced to guide the eye.

We performed rf spectroscopy by driving transitions of the nuclear spin to an empty state [18]. The loss of atoms from the two-component spin-mixture as a function of the radio frequency constitutes our spectroscopic signal. We recorded rf spectra for different degrees of cooling and in various coupling regimes (Fig. 4). We realize the molecular regime at $B = 720$ G ($a = +2200 a_0$). For the resonance region, we examined two different magnetic fields, $B = 822$ G ($a \approx +35,000 a_0$) and $B = 837$ G ($a \approx -100,000 a_0$). We also studied the regime beyond the resonance with large negative scattering length at $B = 875$ G ($a = -1200 a_0$).

At a “high” temperature $T \approx 6T_F$ ($T_F = 15 \mu\text{K}$) we just observe the narrow atomic transition line (upper row in Fig. 4) without any effect of interactions. This line serves us as a frequency reference, and we present our spectra as a function of the rf offset with respect to this atomic frequency.

Already at $T'/T_F = 0.5$ [59], we observed the double-peak structure characteristic for the onset of pairing (middle row in Fig. 4). In the molecular regime ($B = 720$ G), the sharp atomic peak is well separated from the broad dissociation signal [60], which shows a molecular binding energy of $E_b = h \times 130 \text{ kHz} = k_B \times 6.2 \mu\text{K}$. For B approaching the resonance position, the peaks begin to overlap. In the resonance region (822 and 837 G), we still observe a relatively narrow atomic peak at the original position together with a pair signal. For magnetic fields beyond the resonance, we can resolve the double-peak structure for fields up to ~ 900 G.

At a very low temperature $T'/T_F < 0.2$ [59], realized with deep evaporative cooling, we observed a disappearance of the narrow atomic peak in the rf spectra (lower row in Fig. 4). This shows that essentially all atoms are paired. In the BEC limit (720 G) the dissociation lineshape is identical to the one observed in the trap at higher temperature and Fermi energy. Here the localized pairs are molecules with a size much smaller than the mean interparticle spacing, and the dissociation signal is independent of the density. In the resonance region (822 and 837 G) the pairing signal shows a clear dependence on density (Fermi energy), which becomes even more pronounced beyond the resonance (875 G).

For understanding the spectra in the fermionic many-body regime on resonance and beyond both the homogeneous lineshape of the pair signal [55, 57] and the inhomogeneous line broadening due to the density distribution in the harmonic trap need to be taken into account [58]. As an effect of inhomogeneity, fermionic pairing due to many-body effects takes place predominantly in the central high-density region of the trap, and unpaired atoms mostly populate the outer region of the trap where the density is low [61, 62, 58]. The spectral component corresponding to the pairs thus shows a large inhomogeneous broadening in addition to the homogeneous width of the pair-breaking signal. For the unpaired atoms the homogeneous line is narrow and the effects of inhomogeneity and mean-field shifts are negligible. These arguments explain why the RF spectra in general show a relatively sharp peak for the unpaired atoms together with a broader peak attributed to the pairs.

To quantitatively investigate the crossover from the two-body molecular regime to the fermionic many-body regime we measure the pairing energy in a range between 720 G and 905 G. The measurements were performed after deep evaporative cooling ($T'/T_F < 0.2$) for two different Fermi temperatures $T_F = 1.2 \mu\text{K}$ and $3.6 \mu\text{K}$ (Fig. 5). As an effective pairing gap we define $\Delta\nu$ as the frequency difference between the pair-signal maximum and the bare atomic resonance. In the BEC limit, the effective pairing gap $\Delta\nu$ simply reflects the molecular binding energy E_b (solid line in Fig. 5). With increasing magnetic field, in the BEC-BCS crossover, $\Delta\nu$ shows an increasing deviation from this low-density molecular limit and smoothly evolves into a density-dependent many-body regime where $h\Delta\nu < E_F$.

A comparison of the pairing energies at the two different Fermi energies (inset in Fig. 5) provides further insight into the nature of the pairs. In the BEC limit, $\Delta\nu$ is solely determined by E_b and thus does not depend on E_F . In the universal regime on resonance, E_F is the only energy scale and we indeed observe the effective pairing gap $\Delta\nu$ to increase linearly with the Fermi energy. We find a corresponding relation $h\Delta\nu \approx 0.2 E_F$. Beyond the resonance, where the system is expected to change from a resonant to a BCS-type behavior, $\Delta\nu$ is found to depend more strongly on the Fermi energy and the observed gap ratio further increases. We interpret this in terms of the increasing BCS character of pairing, for which an exponential dependence $h\Delta\nu/E_F \propto \exp(-\pi/2k_F|a|)$ is expected.

Our measurements on the effective pairing gap $\Delta\nu$ also support a possible interpretation of the abrupt frequency change of radial collective oscillations (see preceding section). When the magnetic field is increased to 910 G, we find the decreasing $\Delta\nu$ to reach the frequency of the radial compression mode (~ 1 kHz for the filled triangles in Fig. 5 and the conditions of Fig. 3). We conclude that the oscillations can then couple to the fermionic pairs, which leads to pair breaking and heating. This interpretation is further supported by measurements at higher Fermi energies (open triangles in Fig. 5 and collective mode measurements in Ref. [63]), which again show the abrupt change

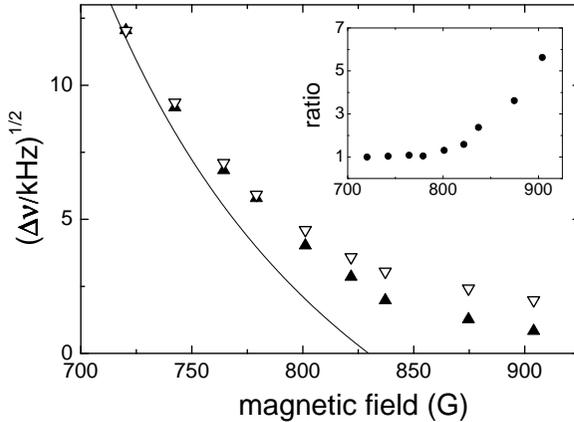


Figure 5: Measurements of the effective pairing gap $\Delta\nu$ as a function of the magnetic field B for deep evaporative cooling and two different Fermi temperatures $T_F = 1.2\mu\text{K}$ (filled symbols) and $3.6\mu\text{K}$ (open symbols). The solid line shows $\Delta\nu$ for the low-density limit where it is essentially given by the molecular binding energy. The inset displays the ratio of the effective pairing gaps measured at the two different Fermi energies.

when the collective oscillation frequency meets the effective pairing gap.

Radio-frequency spectroscopy in a harmonically trapped Fermi gas with resonant interactions was theoretically analyzed in Ref. [58]. The calculated RF spectra demonstrate how a double-peak structure emerges as the gas is cooled below $T/T_F \approx 0.5$ and how the atomic peak disappears with further decreasing temperature. In particular, the work addresses the role of the “pseudo-gap” regime [4, 22], in which pairs are formed before superfluidity is reached. According to the calculated spectra, the atomic peak disappears at temperatures well below the critical temperature for the phase-transition to a superfluid. A recent theoretical study of the BCS-BEC crossover at finite temperature [62] predicts the phase-transition to a superfluid to occur at a temperature that on resonance is only $\sim 30\%$ below the point where pair formation sets in. Our rf spectra thus provide strong evidence for superfluidity in the strongly interacting Fermi gas.

6 Conclusion

We have studied elementary macroscopic and microscopic properties of an ultracold gas in the BEC-BCS crossover. For resonant two-body interactions, we have obtained strong evidence for superfluidity by measuring low damping rates of collective oscillations and by observing the onset of pairing early in the evaporative cooling process. This, together with complementary observations made by other groups [13, 14, 15, 8], opens up intriguing prospects for further experiments on the fascinating properties of fermionic quantum matter.

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