Pairing without Superfluidity: The Ground State of an Imbalanced Fermi Mixture

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Radio-frequency spectroscopy is used to study pairing in the normal and superfluid phases of a strongly interacting Fermi gas with imbalanced spin populations. At high spin imbalances the system does not become superfluid even at zero temperature. In this normal phase full pairing of the minority atoms is observed. This demonstrates that mismatched Fermi surfaces do not prevent pairing but can quench the superfluid state, thus realizing a system of fermion pairs that do not condense even at the lowest temperature.

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Fermionic superfluidity has many manifestations in nature and occurs in such diverse systems as superconducting materials, liquid 3He, neutron stars, and ultracold quantum gases. At its heart lies the formation of fermion pairs. While the Pauli principle forbids identical fermions to occupy the same quantum state, pairs of fermions can condense and thus become superfluid. Superconductivity, the flow of electrical current without resistance, is a manifestation of fermionic superfluidity in a condensed matter system. Superconductors are characterized by a temperature $T^*$ where electrons start to pair and a critical temperature $T_c$ for the onset of superconductivity. In conventional superconductors, understood within the framework of Bardeen-Cooper-Schrieffer (BCS) theory, fermion pairs form and condense simultaneously, i.e. $T^* = T_c$. In high-temperature superconductors strongly correlated electrons exist in the normal phase at $T^* > T_c$. The interactions that mediate pairing and ultimately lead to superconductivity in these complex systems are still under debate. Another strongly interacting, but comparatively simple fermion system is an ultracold gas of neutral fermionic atoms. In these gases, high-temperature superfluidity has been recently observed, opening a new approach to explore the highly correlated normal phase of strongly interacting fermions and its relation to the onset of superfluidity.

Ultracold atomic Fermi mixtures of two spin states close to a Feshbach resonance realize a highly controllable model system for strongly interacting fermions. By resonantly changing the interaction strength between the fermionic atoms the crossover from BCS superfluidity of loosely bound pairs to Bose-Einstein condensation (BEC) of tightly bound molecules can be explored. BEC-BCS crossover theory at finite temperature contains pairing in the normal phase below a temperature $T^* > T_c$. Evidence for pairing above $T_c$ in ultracold Fermi gases was found via radio-frequency (rf) spectroscopy. In the present work, we use rf spectroscopy to study primarily the normal state of an imbalanced spin mixture. An imbalance in the spin populations of the two-state Fermi system leads to a qualitative change of the phase diagram: above a certain, interaction dependent population imbalance the transition to the superfluid state is suppressed even at zero temperature. This is known as the Chandrasekhar-Clogston (CC) or Pauli paramagnetic limit of superfluidity. In several works the CC limit is assumed to imply pair dissociation and is referred to as “Pauli pair breaking”. $T^*$ and $T_c$ are assumed to vanish simultaneously.

The CC limit has been previously observed and characterized in ultracold atomic gases. Here, we report on the observation of a gap in a single-particle excitation spectrum (representing a spin response function) of a highly imbalanced sample. This implies that the system is in a correlated state and that the minority component is almost completely paired. Pairing of fermions is thus not necessarily a precursor to superfluidity: $T^*$ is finite even when $T_c$ vanishes. The CC limit of superfluidity, at least for strong interactions, is not associated with breaking of fermion pairs but only with the quenching of the superfluid state. Another and probably very different system with finite $T^*$ and vanishing $T_c$ has been discussed in strongly underdoped cuprates.

The rf spectra presented in this work were also correlated with an indirect signature for superfluidity by determining pair condensate fractions. We conclude that rf spectra cannot distinguish, at present experimental resolution, between normal and superfluid states.

In the experiment a strongly interacting, imbalanced spin mixture of $^6$Li fermions in the two lowest hyperfine states, labeled $|1\rangle$ and $|2\rangle$ (corresponding to the $|F = 1/2, m_F = 1/2\rangle$ and $|F = 1/2, m_F = -1/2\rangle$ states at low magnetic field) was created in an optical dipole trap at 833 G, the center of the $|1\rangle - |2\rangle$ Feshbach resonance (see refs. [15] and [16] for details). On resonance all interactions in the $|1\rangle - |2\rangle$ mixture are universal as the Fermi energy $E_F$ and the inverse Fermi wavenumber $1/k_F$ are the only relevant energy and length scales. The imbalance $\delta$ of the mixture was controlled as reported in...
FIG. 1: The temperature-imbalance diagram shows where the rf spectra presented in Fig. 2 (black circles), 4 A–C (blue diamonds) and 4 D–F (red triangles) have been taken. All spectra were obtained on resonance at 833 G. The arrows indicate the order in which the spectra are displayed in the figures. As a guide to the eye the shaded region indicates the superfluid phase. The spectra corresponding to the open circles and triangles are similar to the spectra of Fig. 2A to 2C and are shown in the supplemental information. Except for the data close to zero imbalance, for which the interacting temperature $T'$ is given, temperatures have been determined from the non-interacting wings of the majority cloud [23].

refs. [13] and [17], where $\delta = (N_1 - N_2)/(N_1 + N_2)$ with $N_1$ and $N_2$ the atom number in state $|1\rangle$ and $|2\rangle$, respectively. Here, $E_F$, $k_F$ and the Fermi temperature $T_F$ are given for a non-interacting Fermi gas with the same atom number as the majority component. To access a broader range of temperatures two optical traps with different waists were used, characterized by the axial and radial trapping frequencies $\omega_a$ and $\omega_r$ which are given in the figure captions of the rf spectra.

The interactions were spectroscopically probed in a three-level system [18]. A 2-ms rf pulse resonant with the transition from state $|2\rangle$ (the minority component) to a third state, labeled $|3\rangle$ ($|F = 3/2, m_F = -3/2\rangle$ at low field) was applied. Immediately after the rf pulse the optical trap was switched off and the cloud was allowed to expand for absorption imaging. Two absorption images of atoms in state $|2\rangle$ and $|1\rangle$ were taken successively and the atom number fraction $N_2/(N_1 + N_2)$ was obtained as a function of the applied rf. The rf spectra at the highest imbalances were taken with a population transfer smaller than 3% of the total number of atoms. The data points in all spectra are the average of three independent measurements. Temperature was adjusted by evaporation to different depths of the optical trap followed by recompression. Spectra presented as a data set were taken with the same final trap depth. Fig. 1 provides an overview of the imbalances and temperatures at which the rf spectra have been obtained. Specific details are given in the figure captions and in the supplemental information. All radio-frequencies were referenced to the $|2\rangle - |3\rangle$ resonance recorded in the absence of atoms in state $|1\rangle$.

The rf spectroscopy measures a single-particle spin excitation spectrum for the minority component of the mixture [19, 21, 22]. To understand the expected rf spectra one can use a simplified description of the gas as a mixture of free atoms and molecule-like pairs which is strictly valid only far on the BEC side of the Feshbach

FIG. 2: RF spectroscopy of the minority component in an imbalanced ($\delta \sim 0.9$), strongly interacting mixture of fermionic atoms above the Chandrasekhar-Clogston (CC) limit of superfluidity. As the temperature is lowered full pairing develops in the absence of superfluidity. A: An asymmetric and broad peak centered at the position of the atomic line is observed. The asymmetry and the large width might be caused by the presence of pairing correlations already at $T/T_F = 1.9$. Only for this spectrum heating was applied and the atom number in state $|3\rangle$ was recorded (see the supplemental information). B and C: The pairing peak emerges. D: at $T/T_F = 0.5$ the pairing peak remains and the minority atoms are almost fully paired (see also Fig. 4A). As a guide to the eye a Lorentzian fit to the atomic line and a Gaussian fit to the pairing peak are included. The spectra were taken for the following parameters (the black circles in Fig. 1): A) $\delta = 0.87$, $E_F = h \times 260$ kHz, $T/T_F = 1.9$; B) $\delta = 0.94$, $E_F = h \times 360$ kHz, $T/T_F = 1.0$; C) $\delta = 0.94$, $E_F = h \times 360$ kHz, $T/T_F = 0.9$; D) $\delta = 0.93$, $E_F = h \times 340$ kHz, $T/T_F = 0.5$, where $h$ is Planck’s constant. The trapping frequencies were $\omega_r = 2\pi \times 3.5$ kHz and $\omega_a = 2\pi \times 77$ Hz.
resonance. Transferring an unbound atom from state $|2\rangle$ into state $|3\rangle$ requires an energy $\Delta E_{23}$. As the $|1\rangle - |3\rangle$ mixture is also strongly interacting due to a $|1\rangle - |3\rangle$ Feshbach resonance located at 690 G \[18\], we first assume, as in refs. \[6\] and \[7\], that mean field shifts (i.e. shifts corresponding to Hartree terms) are absent in the rf spectrum. Then $\Delta E_{23}$ and the width of the atomic $|2\rangle - |3\rangle$ transition are independent of the density of atoms in state $|1\rangle$. If, however, an atom in state $|2\rangle$ is paired with an atom in state $|1\rangle$, the rf photon has to provide the binding energy $E_B$ required to break the pair in addition to $\Delta E_{23}$. Therefore, if pairing is present in the system, a second peak emerges in the minority rf spectrum that is separated from the atomic line and associated with pairing \[6\], \[7\]. In a Fermi cloud, pairing is strong only near the Fermi surface. Since the rf photons can excite atoms in the whole Fermi sea the observed spectral gap $\Delta \nu$ may have to be interpreted as a pair binding energy averaged over the Fermi sea. Indeed in the BCS limit one has $h \Delta \nu \propto \Delta^2/E_F$, where $\Delta$ is the BCS pairing gap \[22\].

Under these working assumptions we interpret the emergence of a gap in the spectrum as a pairing effect.

The presence of pairing in the normal phase has been observed in the rf spectra for a highly imbalanced mixture, with $\delta \sim 0.9$, on resonance at 833 G (Fig. 2). At high temperature only the atomic peak was present, and as the temperature was lowered, a second peak, the pairing peak emerged and separated from the atomic peak. At sufficiently low temperatures essentially only the pairing peak remained. This behavior is qualitatively similar to what has been observed in an equal mixture \[6\]. The spectral gap $\Delta \nu$, i.e. the shift of the pairing peak relative to the atomic line increases as the temperature is lowered. At the lowest temperature of 0.08 $T/T_F$ (Fig. 4A) we measured a shift of 0.38 $E_F$.

All the spectra in Fig. 2 have been obtained at high imbalances above the CC limit of superfluidity. Here the system cannot undergo a phase transition to the superfluid state even at zero temperature. For a trapped gas on the BCS side of the Feshbach resonance \(a_{12}\) is the s-wave scattering length in the $|1\rangle - |2\rangle$ mixture. The rf spectrum was taken for the following parameters: $E_F = h \times 280$ kHz and $T/T_F = 0.3$. The trapping frequencies were $\omega_r = 2 \pi \times 2.9$ kHz and $\omega_\theta = 2 \pi \times 64$ Hz.

![FIG. 3: RF spectrum of the minority component obtained at a magnetic field of 937 G ($1/k_F a_{12} = -0.18$) and imbalance $\delta = 0.88$, demonstrating strong pairing above the CC limit also on the BCS side of the Feshbach resonance ($a_{12}$ is the s-wave scattering length in the $|1\rangle - |2\rangle$ mixture). The rf spectrum was taken for the following parameters: $E_F = h \times 280$ kHz and $T/T_F = 0.3$. The trapping frequencies were $\omega_r = 2 \pi \times 2.9$ kHz and $\omega_\theta = 2 \pi \times 64$ Hz.](image)

indirect indicators of superfluidity have been correlated with the presence of quantized vortices, i.e. superfluid flow.

Figure 4A–C illustrates that working with high imbalances has the advantage of reducing line broadening effects that arise from averaging over the inhomogeneous density distribution of the sample. The narrowest line was observed at the highest imbalance (Fig. 4A), where the minority is considerably smaller than the majority cloud. The homogeneous linewidth should reflect the wavefunction of a single fermion pair. The observed narrow linewidth indicates localization in momentum space well below the Fermi momentum $k_F$, and hence a pairsize on the order of the interparticle spacing. We now examine the assumptions underlying our interpretation of the peaks in the rf spectra. In particular we address the question whether our observations can distinguish between pairing correlations and mean field effects. Indeed, mean-field-like shifts are observed, for example in the rf spectrum of Fig. 2C where the atomic line shows a shift of 0.03 $E_F$ to higher energy. Although the $|1\rangle - |3\rangle$ interactions are in the unitary regime for a typical value of $k_F a_{13} \simeq -3.3$ (varying for example from -3 to -3.6 across the minority cloud in Fig. 2C), they may not have fully converged to their value at unitarity and thus cause the observed shifts. Here $a_{13}$ is the s-wave scattering length in the $|1\rangle - |3\rangle$ mixture. However, all shifts of the atomic line are small compared to the size of the spectral gap of up to 0.38 $E_F$ and are only seen in the presence of the pairing peak. Fig. 7 displays all observed shifts of atomic and pairing peaks versus temperature. While the shifts of the atomic line are small at all temperatures, the shifts associated with the pairing peak start rising below $T/T_F \approx 1$, accompanied by a decrease in the weight of the atomic line. In the intermediate temperature range where the rf spectra show a double-peak structure, the pairing peak should
FIG. 4: RF spectra of the minority component obtained while crossing the phase transition by reducing imbalance \((A - C)\) and temperature \((D - F)\). The rf spectra do not reveal the phase transition. The onset of superfluidity is indirectly observed by fermion pair condensation. The condensate fractions for \(A\) and \(B\) are zero and 35(2)% in \(C\). The onset of superfluidity as a function of temperature occurs between \(D\) and \(F\), with condensate fractions of 0% in \(D\), 3(2)% in \(E\), and 17(3)% in \(F\). The left insets show the column density profile (red) of the minority cloud after a rapid magnetic field ramp to the BEC side and further expansion (see the supplemental information). The blue dashed line is a Gaussian fit to the thermal background. The right insets in \(D - F\) show phase contrast images for a trapped cloud, obtained at imbalances of the opposite sign. The spectra were taken for the following parameters \(A - C\): A) \(\delta = 0.87, \theta = h \times 27 \text{ kHz}, \frac{T}{T_F} = 0.08\); B) \(\delta = 0.73, \theta = h \times 27 \text{ kHz}, \frac{T}{T_F} = 0.10\); C) \(\delta = 0.00, \theta = h \times 23 \text{ kHz}, \frac{T'}{T_F} = 0.10\). See also the blue diamonds in Fig. 1. The trapping frequencies were \(\omega_r = 2\pi \times 143 \text{ Hz}\) and \(\omega_a = 2\pi \times 23 \text{ Hz}\). For the spectrum in \(C\) we quote the temperature \(T'\) obtained from a fit to the interacting Fermi gas (see the supplemental information); \(D - F\): D) \(\delta = 0.37, \theta = h \times 38 \text{ kHz}, \frac{T}{T_F} = 0.18\); E) \(\delta = 0.32, \theta = h \times 38 \text{ kHz}, \frac{T}{T_F} = 0.14\); F) \(\delta = 0.29, \theta = h \times 35 \text{ kHz}, \frac{T}{T_F} = 0.09\). See also the filled red triangles in Fig. 1. The trapping frequencies were \(\omega_r = 2\pi \times 192 \text{ Hz}\) and \(\omega_a = 2\pi \times 23 \text{ Hz}\).

originate primarily from the higher density region in the center of the cloud and the atomic peak from the low density wings. Therefore, if one would normalize the data according to the local density of majority atoms, the data points for the atom peaks would shift up in \(T/T_F\) by a factor between 1.5 and 5, the smaller factor reflecting the cases of large imbalance, where the minority cloud is considerably smaller than the majority cloud. As a result, near \(T/T_F^{\text{local}} = 0.5\), we have observed both atomic peaks and pairing peaks, which is an indication for the local coexistence of unpaired and paired minority atoms. However, in this possible coexistence region, either the peak separation is small or one peak has very small weight. Therefore more work is needed to study the possibility of coexistence. An alternative interpretation assumes single local peaks and a sudden onset of peak shifts below \(T/T_F \sim 1\). Also the second scenario appears to be incompatible with a local mean-field approximation: the mean field in the unitarity limit should saturate when \(T\) approaches \(T_F\) and not vary strongly for \(T < T_F\), since the relative momentum of two particles in this regime is dominated by the Fermi momentum and not by the thermal momentum. Furthermore a sudden onset of interactions would likely affect the density distribution of the minority atoms. However, the minority clouds observed in expansion are well fit by a single Thomas-Fermi profile [24].

The BEC-side picture of a mixture of single atoms and molecules seems to extend into the resonance region in the sense that fermion pairs form high above the superfluid transition temperature and possibly coexist locally with unpaired atoms. However, the fermion pairs on resonance behave differently compared to “real” molecules: their binding energy increases with lower temperature and higher atomic density. Most importantly fermion pairs above the CC limit do not condense at low temperature as bosonic molecules would do at any imbalance. While some extensions of BCS mean-field theories to the
imbalanced case do not predict pairing at imbalances $\delta$ above the CC limit [25], a survival of Cooper pairs “far from the transition region” has been predicted [26] for a superconducting system that is driven into the normal, paramagnetic phase by Zeeman splitting.

The observed spectral gaps appear to be insensitive to the density of the minority atoms (see Fig. 4A-C). At very high imbalances one should indeed approach the limit of one minority atom immersed in a fully polarized Fermi sea. In refs. [23, 27, 28] the ground state energy for this scenario has been calculated to be about $-0.6 E_F$, for example by using a modified Cooper-pair wave-function ansatz [27]. These calculations do not provide an excitation spectrum and do not distinguish between pairing (correlation) energies and mean field (Hartree) terms. Therefore the theoretical result cannot be directly compared to our spectroscopic measurement of $\hbar \Delta \nu = -0.38 E_F$ at $T/T_F = 0.08$.

There is still a debate, whether superfluidity can occur for large imbalances and low atom numbers in highly elongated geometries [29]. In light of our findings, it may be important to clearly distinguish between the effects of pairing and of superfluidity. It has also been suggested that the presence of an atomic peak next to the pairing peak in the minority cloud at zero temperature and high imbalance could provide evidence for exotic forms of superfluidity like the Fulde-Ferrel-Larkin-Ovchinnikov state [30]. However, for the parameters studied here, the atomic peak is seen to disappear as the temperature is reduced (see Fig. 2, 4A).

In conclusion, working with imbalanced Fermi gases, we were able to study and characterize pairing in a situation where no superfluidity occurs even at zero temperature. The spectral gap $\Delta \nu$ appears to be only weakly dependent on the imbalance. This suggests that near unitarity certain pairing correlations in the superfluid state are similar to those in a dilute cloud of minority atoms immersed into the Fermi sea of the majority. Moreover, this implies that the energetics which drives the normal-to-superfluid phase transition is not simply the observed pairing energy. Further studies of the strongly correlated normal state might yield new insights into the microscopic physics of the superfluid state.

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SUPPLEMENTAL INFORMATION

Experimental Details

Determination of the atomic reference line: For the data taken at the center of the $|1\rangle - |2\rangle$ Feshbach resonance the resonance frequency of the $|2\rangle - |3\rangle$ transition in the absence of atoms in state $|1\rangle$ was determined to be $81.700\text{ MHz} \pm 1\text{ kHz}$, corresponding to a magnetic field of about 833 G. The FWHM of a Lorentzian fit to the resonance was less than 1 kHz. These values reflect day to day fluctuations and correspond to a magnetic field stability better than 0.2 G. The resonance frequency of the $|2\rangle - |3\rangle$ transition on the BCS-side of the Feshbach resonance (Fig. 3) was $81.187\text{ MHz} \pm 1\text{ kHz}$ (corresponding to a magnetic field of 936.5 G), determined in the absence of atoms in state $|1\rangle$.

Rf pulse: For all data a rf pulse of 2 ms was applied. This pulse duration is optimized in terms of precision and minimizing a dynamic response of the system during the rf pulse. For each spectrum the rf power was adjusted to give an adequate signal-to-noise ratio.

Determination of the atom number fraction in state $|2\rangle$: To obtain the atom number fraction $N_2/(N_1 + N_2)$ two absorption images, one of the minority component in state $|2\rangle$ and the other of the majority component in state $|1\rangle$, were taken successively. The time-of-flight before the first absorption image as well as the delay time between the absorption images were adjusted depending on the imbalance $\delta$ of the mixture, final temperature and the trapping frequency of the optical dipole trap.

FIG. 5: Rf spectra of the minority component on resonance at 833 G. The spectra correspond to the open triangles shown in Fig. 1 of the letter and were obtained for the following parameters: A) $\delta = 0.55$, $E_F = h \times 230\text{ kHz}$, $T/T_F = 0.9$; The trapping frequencies for A were $\omega_r = 2\pi \times 3.4\text{ kHz}$ and $\omega_a = 2\pi \times 76\text{ Hz}$. B) $\delta = 0.57$, $E_F = h \times 230\text{ kHz}$, $T/T_F = 0.5$; C) $\delta = 0.57$, $E_F = h \times 220\text{ kHz}$, $T/T_F = 0.25$. The trapping frequencies for B and C were $\omega_r = 2\pi \times 2.9\text{ kHz}$ and $\omega_a = 2\pi \times 64\text{ Hz}$.
time-of-flight before the absorption image of the minority varied between 200 µs and 8 ms, the delay time between the images was in the range of 500 µs and 2 ms.

Imaging atoms transferred to state [3]; Fig. 2A: For the rf spectrum in Fig. 2A, \( T/T_F \) was increased by shortly switching off the optical dipole trap and allowing for subsequent equilibration before the rf pulse. The number of atoms transferred to state [3] was recorded for a better signal-to-noise ratio. The absorption image had to be taken within 200 µs after applying the rf pulse. After longer time-of-flight atoms in state [3] decayed through collisions. This precluded imaging atoms in state [3] at lower temperatures where longer time-of-flights were required before absorption imaging to avoid saturation.

Weight of the atomic peak as function of imbalance:
The population imbalance affects the weight of the atomic peak in rf spectra obtained at the same \( T/T_F \) (compare Fig. 2D, 5C and 6B). As the imbalance decreases, the weight of the atomic peak increases. This is likely due to the higher relative temperature compared to the local binding energy in the the lower density region of the majority could. That effect will result in a higher fraction of unpaired atoms at small imbalances.

Temperature determination: Except for equal and nearly equal mixtures (\( \delta < 20\% \)), temperatures were determined from the non-interacting wings of the majority cloud after expansion [24]. In ref. [24] it was found that for imbalances \( \delta > 20\% \) the non-interacting wings of the majority cloud expand ballistically and are not affected by the hydrodynamic expansion of the interacting component. For equal or nearly equal mixtures the temperature \( T' \) was determined directly from a finite-temperature Thomas-Fermi fit to the whole density profile of the interacting majority cloud. If on applies the calibration of [31] the temperatures of \((0.1,0.34,0.67) T'/T_F \) in Fig. 4C, Fig. 6B, Fig. 6A) should correspond to about \((0.1,0.23,0.45)T/T_F \). Chandrasekhar-Clogston limit: The experimental value quoted of \( \delta_{c,\text{exp}} = 0.74(5) \) on resonance was obtained with the following probes for superfluidity: vortices and condensate fractions [13], bimodal density distributions of the minority cloud in time-of-flight [24]. We would like to emphasize, that the previous experimental determination of the critical imbalance included a measurement of its temperature dependence, which was found to be weak at low temperatures [13].

Condensate fractions: Condensate fractions were obtained as previously described in ref. [13] and [13]. The samples were prepared as in the rf experiment, but the rf pulse was not applied. Instead the gas was released from the trap and the magnetic field was switched in 200 µs to 690 G, where the cloud expanded for several ms. Then the magnetic field was ramped in 1 ms to 720 G for absorption imaging. Condensate fractions were determined from bimodal fits to the minority component. Condensates were only observed when condensate fractions are explicitly stated (Fig. 4).

FIG. 6: Rf spectra of the minority component on resonance at 833 G. Since the majority component of the nearly equal mixture also suffered significant losses after the rf pulse (probably due to inelastic collisions), we report here the un-normalized atom number in state [2] as a function of the applied radio frequency. The spectra correspond to the open circles shown in Fig. 1 of the letter and were obtained for the following parameters: A) \( \delta = 0.07, E_F = h \times 210 \text{ kHz}, T'/T_F = 0.67 \); B) \( \delta = 0.07, E_F = h \times 180 \text{ kHz}, T'/T_F = 0.34 \). The trapping frequencies were \( \omega_t = 2\pi \times 2.9 \text{ kHz} \) and \( \omega_a = 2\pi \times 64 \text{ Hz} \).

FIG. 7: Normalized shifts of the atomic peaks (black triangles) and pairing peaks (red circles) as a function of \( T'/T_F \). \( E_F \) (\( T_F \)) is the Fermi energy (temperature) of a non-interacting Fermi gas with the same number of atoms as the majority component. The black line is a linear fit to the atomic peak shifts. The temperatures \( T'/T_F \) for equal or nearly equal mixtures were scaled to \( T/T_F \) (see temperature calibration). The error bars reflect the full width at half maximum of a Gaussian fit to the peaks.

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