High-temperature pairing in a strongly interacting two-dimensional Fermi gas

Puneet A. Murthy,1,† Mathias Neidig,1† Ralf Klemt,1† Luca Bayha,1 Igor Boettcher,2 Tilman Enss,3 Marvin Holten,1 Gerhard Zürn,1 Philipp M. Preiss,1 Selim Jochim1

The nature of the normal phase of strongly correlated fermionic systems is an outstanding question in quantum many-body physics. We used spatially resolved radio-frequency spectroscopy to measure pairing energy of fermions across a wide range of temperatures and interaction strengths in a two-dimensional gas of ultracold fermionic atoms. We observed many-body pairing at temperatures far above the critical temperature for superfluidity. In the strongly interacting regime, the pairing energy in the normal phase considerably exceeds the intrinsic two-body binding energy of the system and shows a clear dependence on local density. This implies that pairing in this regime is driven by many-body correlations, rather than two-body physics. Our findings show that pairing correlations in strongly interacting two-dimensional fermionic systems are remarkably robust against thermal fluctuations.

Fermion pairing is the key ingredient for superconductivity and superfluidity in fermionic systems (1). In a system with s-wave interactions, two scenarios can occur: In the first one, as realized for weakly attractive fermions that are described by the theory of Bardeen-Cooper-Schrieffer (BCS), formation and condensation of pairs both take place at the same critical temperature (Tc) (2). In the second scenario, fermion pairing accompanied by a suppression of the density of states at the Fermi surface occurs at temperatures exceeding the critical temperature. Finding a description of this so-called pseudogap phase, especially for two-dimensional (2D) systems, is thought to be a promising route to understanding the complex physics of high-temperature superconductivity (3–6).

The Bose-Einstein condensation (BEC)-BCS crossover of ultracold atoms constitutes a versatile framework with which to explore the normal phase of strongly correlated fermions (Fig. 1A). The crossover smoothly connects two distinct regimes of pairing: the BCS regime of tightly bound molecules and the BCS regime of weakly bound Cooper pairs. In 2D (unlike 3D) systems with contact interactions, a two-body bound state with binding energy E0 exists for arbitrarily small interactions between the atoms. The interactions in the many-body system are captured by the dimensionless parameter $\ln(k_F a_{BCS})$, where $k_F$ is the Fermi momentum and $a_{BCS}$ is the 2D scattering length. As we tune the interaction strength from the BEC [large negative $\ln(k_F a_{BCS})$] to the BCS side ([large positive $\ln(k_F a_{BCS})$]), the character of the system smoothly changes from bosonic to fermionic (7). A strongly interacting region lies between these two weakly interacting limits, where $a_{\text{eff}}$ is of the same order as the interparticle spacing ($k_F a_{\text{eff}}$). Previously, a matter-wave focusing method was used to measure the pair momentum distribution of a 2D Fermi gas across the crossover, leading to the observation of the Berezinskii-Kosterlitz-Thouless (BKT) transition at low temperatures (8, 9). An outstanding question concerns the nature of the normal phase above the critical temperature—specifically, how does the normal phase cross over from a gapless Fermi liquid on the weakly interacting BCS side to a Bose liquid of two-body dimers on the BEC side? Is there an interaction regime in which pairing is driven by many-body effects rather than the two-body bound state? Although previous cold atom experiments have explored this problem both in 3D (10–14) and 2D (15, 16) systems, a consensus is yet to emerge (3, 7, 17–20).

We addressed these questions by studying the normal phase of such a 2D ultracold Fermi gas trapped in a harmonic potential. The underlying potential leads to an inhomogeneous density distribution, and therefore we can use the local density approximation to directly measure the density dependence of many-body properties. We performed our experiments with a two-component mixture of $^6$Li atoms with $-3 \times 10^4$ particles per spin state that were loaded into a single layer of an anisotropic harmonic optical trap. The trap frequencies were $\omega_x = 2 \pi \times 6.95$ kHz and $\omega_y = 2 \pi \times 22$ Hz in the axial and radial directions, leading to an aspect ratio of about 300:1. We reached the kinematic 2D regime by ensuring that the thermodynamic energy scales, temperature (T), and chemical potential ($\mu$) are smaller than the axial confinement energy (21, 22). We tuned the scattering length $a_{2D}$ by means of a broad magnetic Feshbach resonance (23).

To investigate fermion pairing in our system, we used radio-frequency (RF) spectroscopy. We performed experiments with the three lowest-lying hyperfine states of $^6$Li, which at low magnetic fields are given by $|1\rangle = |F = \frac{1}{2}, m_F = -\frac{1}{2}\rangle$, $|2\rangle = |F = \frac{1}{2}, m_F = +\frac{1}{2}\rangle$, and $|3\rangle = |F = \frac{3}{2}, m_F = 0\rangle$. We started with a two-component mixture of atoms in hyperfine states $|a\rangle |b\rangle = |1\rangle |2\rangle$ or $|a\rangle |b\rangle = |1\rangle |3\rangle$ (fig. S1) (21). A RF pulse transferred atoms from state $|b\rangle$ to the third unoccupied hyperfine state $|a\rangle$, and we subsequently imaged the remaining density distribution in $|b\rangle$. The idea underlying this technique is that the atomic transition frequencies between hyperfine states are shifted by interactions or pairing effects in an ensemble. For example, a state of coexisting pairs and free atoms (Fig. 1B) will lead to two energetically separated branches in the RF spectrum, from which we can gain quantitative information on pairing and correlations in the many-body system. Creating initial samples in either $|1\rangle |2\rangle$ or $|1\rangle |3\rangle$ allows us to access a wide range of interaction strengths and minimize final state interaction effects (21).

In our inhomogeneous 2D system, the local Fermi energy depends on the local density $n(r)$ in each spin state according to $E_F(r) = m w^2 r^2 n(r)$, where $m$ is the mass of a $^6$Li atom (24). As a consequence, the thermodynamic quantities $T$ and $\ln(k_F a_{BCS})$ also vary spatially across the cloud. We applied the thermometry developed in (21, 25) to extract these local observables. We measured the local spectral response (20) by choosing a RF pulse duration ($\tau_{\text{RF}} = 4 \mu s$) that is sufficiently short to prevent diffusion of transferred atoms, but also sufficiently long that we obtained an adequate Fourier limited frequency resolution $\delta w_{\text{RF}} = 2 \pi \times 220$ Hz (fig. S2) (21). In Fig. 1C, we show a typical absorption image of the 2D cloud that is used as a reference and another with a RF pulse applied at a particular frequency. The difference between the two images features a spatial ring structure, which qualitatively shows that for a given frequency, the depletion of atoms in initial state $|b\rangle$ occurs at a well-defined density/radius. By performing this measurement for a range of RF frequencies, we can tomographically reconstruct the spatially resolved spectral response function $I(r, \omega_{\text{RF}}) = \langle n_0(r) - n^*(r, \omega_{\text{RF}}) \rangle / n_0(r)$ where $n_0(r)$ and $n^*(r, \omega_{\text{RF}})$ are the density distribution of atoms in state $|b\rangle$ without and with the RF pulse, respectively. An example of the tomographically reconstructed spectra, taken at $\ln(k_F a_{BCS}) \sim 1.5$, is shown in Fig. 1D. The frequency of maximum response depends smoothly on the radius and therefore the local density. Such density-dependent shifts may arise from pairing effects, in which the effective binding energy between fermions is dependent on the density of the medium, or Hartree shifts, which are...
Fig. 1. Exploring fermion pairing in a strongly interacting 2D Fermi gas. (A) Schematic phase diagram of the BEC-BCS crossover. In this work, we investigated the nature of pairing in the normal phase of the crossover regime between the weakly interacting Bose and Fermi liquids. (B) Illustration of RF spectroscopy of a 2D two-component Fermi gas. Pairing and many-body effects shift the atomic transition frequencies between the hyperfine states \( |b\rangle \to |c\rangle \), which results in observable signatures in the RF response of the system. (C) Absorption images of the cloud [taken at \( \ln(k_{a_{020}}) = 1.5 \) and \( T / T_F < 0.3 \)] without RF (reference) and with RF at a particular frequency, and the difference between the two images. The ring feature in \( \delta n(r) \) reveals the density dependence of the RF response. (D) Spatially resolved spectral response function reconstructed from absorption images taken at different RF frequencies. At low temperatures in the spin-balanced sample, the occupation of the free-particle branch is too low to be observable, which makes it difficult to distinguish between mean-field shifts and pairing effects.

Fig. 2. Quasi-particle spectroscopy in the BEC and BCS limits. (A) We created a slightly imbalanced mixture of hyperfine states so as to artificially populate the free-particle branch. The density distributions of the majority and minority spins are shown, as well as the corresponding local imbalance (inset). (B) and (C) Schematic illustration of single-particle dispersion relations in the BEC and BCS limits at zero temperature. Paired atoms reside in the lowest branch (Bound) and are transferred to the continuum of unoccupied states. The excess majority atoms are unpaired and occupy the upper quasi-particle (Free) branch in the spectrum preferentially at \( k \to 0 \) (BEC) and \( k \to k_F \) (BCS). The energy difference between the free-particle dispersion in a noninteracting system (blue dashed line) and the continuum (blue solid line) is the bare hyperfine transition energy and serves as the reference for (D) and (E). (D) and (E) The transition of paired atoms into the continuum yields an asymmetric response with a sharp threshold in the RF spectral function. The quasi-particle transition contributes another peak, which appears at \( \omega_R = 0 \) on the BEC side and \( \omega_R = -\Delta \) on the BCS side, where \( \Delta \) is the BCS gap parameter. Their relative difference yields the pairing energy \( \Delta E \), which reveals the distinction between two-body \( \Delta E < E_B \) and many-body pairing \( \Delta E > E_B \) in the two limits.
Fig. 3. From two-body dimers to many-body pairing. The spatially resolved response function \(I(r, \omega_B)\) shows qualitatively different behavior for two different scattering lengths. (A and B) \(I(r, \omega_B)\) for central \(\ln(k_{s2D})\) ~ -0.5 and 1.0, respectively. The gray lines correspond to local \(T/T_F \sim 0.7\) in (A) and \(T/T_F \sim 1\) in (B). The 3D visualization was obtained by using a linear interpolation between 3000 data points, each of which is an average of 30 realizations. The black solid line is the peak position of the free branch, the red line is the threshold position of the bound branch, and the black dashed line is displaced from the free peak by the two-body binding energy \(E_B\). The energy difference between free and bound branches is the pairing energy \(\Delta E\), which is seen to agree with \(E_B\) in (A) (BEC regime) but exceeds \(E_B\) in (B) (crossover regime). The differential density dependence of the energy of the two branches implies that the pair wave function is strongly modified by the many-body system. (C and D) Local spectra at a fixed radius indicated by gray lines in (A) and (B) corresponding to a homogeneous system with \(T/T_F \sim 0.7\) and 1, respectively. The solid blue curves are the fits to the data; the black and red curves are Gaussian and threshold fits to the two branches (21).

Fig. 4. Normal phase in the 2D BEC-BCS crossover regime. (A) Pairing energy \(\Delta E\) in units of \(E_B\) plotted as a function of \(T/T_F\) for different interaction strengths [central \(\ln(k_{s2D})\)]. Each point in (A) is the result of fits to local spectra (Fig. 3, C and D), which are averaged over 30 shots. (B) Many-body-induced high-temperature pairing. We plot \(\Delta E/E_B\) as a function of \(\ln(k_{s2D})\) for fixed ratio \(T/T_F \sim 0.5\). Red and blue circles correspond to measurements taken with \(|1\rangle|3\rangle\) and \(|1\rangle|2\rangle\) mixtures, respectively. The dashed black line is a guide to the eye. The errors indicated as shaded bands in (A) and bars in (B) are obtained from the fitting procedure explained in (21). For \(\ln(k_{s2D}) \leq 0.5\) (strong attraction), we have \(\Delta E/E_B \sim 1\), with negligible density dependence, indicating two-body pairing. For larger \(\ln(k_{s2D})\) (less attraction), \(\Delta E/E_B\) exceeds 1 and reaches a maximum of 2.6 before showing a downward trend. At \(\ln(k_{s2D}) \sim 1\), we have a critical temperature of \(T_c \sim 0.17T_F\) (8), which indicates the onset of many-body pairing at temperatures several times \(T_c\).
branch increases continuously with decreasing temperature, even as we crossed the superfluid transition. This indicates that in the crossover regime, a many-body gap opens in the normal phase rather than at $T_c \approx 0.17 T_F$ as expected from BCS theory (fig. S8) (21). This observation is the first main result of this work.

To quantitatively study the change in the nature of pairing from the BCS to the BCS side, we measured the spectra at different magnetic fields and extracted $\Delta E$ in units of the two-body binding energy $E_B$. In fig. 4A, we plot the temperature dependence of $\Delta E/E_B$ for different interaction strengths, and the variation of $\Delta E/E_B$ as a function of $kTd_{2D}$ is shown in Fig. 4B for a fixed ratio $T/T_F \approx 0.5$. This constitutes an extremely high-temperature regime even in the context of ultracold fermionic superfluidity, where the largest observed critical temperatures are $T_c/T_F \approx 0.17$ (8, 9). We performed our measurements with both $[1]/[2]$ and $[1]/[3]$ mixtures (fig. 4B, blue and red points) in an overlapping interaction regime. The two mixtures differ in their final state interaction strengths, yet they show similar values of $\Delta E$ around $\Delta (kTd_{2D}) \approx 0.5$, demonstrating the robustness of the quantity $\Delta E$ against final state effects. For larger $\Delta (kTd_{2D})$, the two mixtures allow us to probe complementary regions of the crossover. Details of the experimental parameters used for the two mixtures are tabulated in table S1 (21).

In fig. 4, we observe that for $\Delta (kTd_{2D}) \approx 0.5$ the spectra are well described by two-body physics. By contrast, the pronounced density-dependent gap exceeding $E_B$ for $\Delta (kTd_{2D}) \approx 0.5$ signals the crossover to a many-body pairing regime. In particular, we observed that $\Delta E/E_B$ peaks at $\Delta (kTd_{2D}) \approx 1$, where $\Delta E \approx 2.6 E_B$ and is a considerable fraction of $E_B(0.6 E_B)$. The identification of this strongly correlated many-body pairing regime and the observation of many-body-induced pairing at temperatures several times the critical temperature is the second main result of this work. For larger $\Delta (kTd_{2D})$, we saw a downward trend in $\Delta E/E_B$, and for $\Delta (kTd_{2D}) > 1.5$, we observed only a single branch in the spectra near $\omega_{PF} \approx 0$, suggesting the absence of a gap larger than the scale of our experimental resolution (fig. S6) (21). Our qualitative observation of a vanishing gap for weaker attraction is consistent with the picture of the normal phase in the BCS limit being a gapless Fermi liquid (30). The nonmonotonous behavior of $\Delta E$ as a function of $kTd_{2D}$, as shown in Fig. 4B, is also qualitatively predicted by finite-temperature BCS theory (fig. S4) (21) for the superfluid phase.

Here, we discuss our results in the context of current theoretical understanding and previous experimental work. In (15), Sommer et al. performed trap-averaged RF spectroscopy in the 3D-2D crossover and found good agreement with the mean-field two-body expectation in the regime $\Delta (kTd_{2D}) \lesssim 0.5$. In (16), Feld et al. observed signatures of pairing in the normal phase using momentum-resolved (but trap-averaged) spectroscopy, in a similar interaction regime as (15), which were interpreted as a many-body pseudo-gap. However, subsequent theoretical work based on two-body physics only (18, 19) was consistent with that of many of the observations in (16). Beyond this previously explored regime, our measurements reveal that many-body effects enhance the pairing energy far above the critical temperature, with the maximum enhancement occurring at $\Delta (kTd_{2D}) \approx 1$, where a reliable mean-field description is not available. With regard to the long-standing question concerning the nature of the normal phase of a strongly interacting Fermi gas (7, 17, 31–33), our experiments reveal the existence of a state in the phase diagram whose behavior deviates from both Bose Liquid and Fermi liquid descriptions. Finding a complete description of this strongly correlated phase is an exciting challenge for both theory and experiment.

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SUPPLEMENTARY MATERIALS

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Materials and Methods

Supplementary text

Fig. S1 to S8

Table S1

References (34, 35)

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Tuning the atomic pairing
Cold atomic gases are extremely flexible systems; the ability to tune interactions between fermionic atoms can, for example, cause the gas to undergo a crossover from weakly interacting fermions to weakly interacting bosons via a strongly interacting unitary regime. Murthy et al. studied this crossover in a gas of fermions confined to two dimensions. The formation of atomic pairs occurred at much higher temperatures in the unitary regime than previously thought. Science, this issue p. 452