Observation of Pair Condensation in the Quasi-2D BEC-BCS Crossover

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The condensation of fermion pairs lies at the heart of superfluidity. However, for strongly correlated systems with reduced dimensionality the mechanisms of pairing and condensation are still not fully understood. In our experiment we use ultracold atoms as a generic model system to study the phase transition from a normal to a condensed phase in a strongly interacting quasi-two-dimensional Fermi gas. Using a novel method, we obtain the in situ pair momentum distribution of the strongly interacting system and observe the emergence of a low-momentum condensate at low temperatures. By tuning temperature and interaction strength, we map out the phase diagram of the quasi-2D BEC-BCS crossover.

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The characteristics of quantum many-body systems are strongly affected by their dimensionality and the strength of interparticle correlations. In particular, strongly correlated two-dimensional fermionic systems have been of interest because of their connection to high-$T_c$ superconductivity. Although they have been the subject of intense theoretical studies [1–8], a complete theoretical framework has not yet been established.

Ultracold quantum gases are an ideal realization for exploring strongly interacting 2D Fermi gases, as they offer the possibility of independently tuning the dimensionality and the strength of interparticle interactions. Reducing the dimensionality [9] led to the observation of a Berezinskii-Kosterlitz-Thouless (BKT)-type phase transition to a superfluid phase in weakly interacting 2D Bose gases [10,11]. Tuning the strength of interactions in a three-dimensional two-component Fermi gas made it possible to explore the crossover between a molecular Bose-Einstein Condensate (BEC) and a BCS superfluid [12–15].

Recently, efforts have been made to combine reduced dimensionality with the tunability of interactions and to experimentally explore ultracold 2D Fermi gases [16–21]. However, the phase transition to a condensed phase has not yet been observed. Here, we report on the condensation of pairs of fermions in the quasi-2D BEC-BCS crossover.

The BEC-BCS crossover smoothly links a bosonic superfluid of tightly bound diatomic molecules to a fermionic superfluid of Cooper pairs in 2D as well as 3D systems. However, changing the dimensionality leads to some inherent differences. In two dimensions, there is a two-body bound state for all values of the interparticle interaction. Furthermore, because of the enhanced role of fluctuations in 2D, true long-range order is forbidden for homogeneous systems at finite temperature [22,23]. Still, a low temperature superfluid phase with quasi-long-range order can emerge due to the BKT mechanism [24,25].

In a 2D gas with contact interactions, the interactions can be described by the 2D scattering length $a_{2D}$. Using the Fermi wave vector $k_F$, the dimensionless crossover parameter is given by $\ln(k_Fa_{2D})$. The crossover regime is reached for $|\ln(k_Fa_{2D})| \lesssim 1$. For $\ln(k_Fa_{2D}) \ll -1$, the binding energy is large and the system consists of deeply bound bosonic dimers. For $\ln(k_Fa_{2D}) \gg 1$, the dimer binding energy tends to zero. For a thermal energy $k_BT$ significantly larger than the binding energy, the dimers are dissociated due to thermal excitations and the system becomes fermionic.

Two-dimensional gases are realized by a strongly anisotropic confinement, which leads to a freezing out of the degrees of freedom in one spatial direction. Such a quasi-2D gas captures the essential properties of a 2D system. Corrections to the 2D physics may arise from the residual influence of the third dimension.

In our experiment we use ultracold atoms as a generic model system to study the phase transition from a normal to a condensed phase in a strongly interacting quasi-two-dimensional Fermi gas. Using a novel method, we obtain the in situ pair momentum distribution of the strongly interacting system and observe the emergence of a low-momentum condensate at low temperatures. By tuning temperature and interaction strength, we map out the phase diagram of the quasi-2D BEC-BCS crossover.

FIG. 1 (color online). Experimental setup. A quasi-2D gas (the red disk) is created by loading a two-component ultracold Fermi gas of $^6$Li atoms into a single layer of a standing-wave trap created by two interfering laser beams ($\lambda = 1064$ nm, the green arrows) that cross under a small angle (14°). Using absorption imaging along the vertical direction (the red arrow) we obtain the column density of the sample.

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We perform our measurements using a two-component Fermi gas of $^6$Li atoms in the lowest two Zeeman sublevels, which we denote as $|1\rangle$ and $|2\rangle$ [26]. The ultracold gas initially consists of 40000–50000 atoms per spin state, which are bound into dimers at a temperature of approximately 50 nK and a magnetic offset field of 795 G ($\ell_z/a_{3D} = 1.08$) [27]. It is loaded into a hybrid trap consisting of a single layer of a standing-wave optical dipole potential and a weak magnetic potential. The combined trapping frequencies are $\omega_r = 2\pi \times 17.88(3)$ Hz and $\omega_z = 2\pi \times 17.82(4)$ Hz in radial, and $\omega_z = 2\pi \times 5.53(3)$ kHz in axial direction. This leads to a pancake-shaped cloud with an aspect ratio of $\omega_z/\omega_r \approx 310$ (see Fig. 1) and an axial harmonic oscillator length $\ell_z = \sqrt{\hbar/m\omega_z} \approx 551$ nm with the reduced Planck’s constant $\hbar$, the atom mass $m$, and the axial trapping frequency $\omega_z$. We ensure that there is no significant population of axially excited states by measuring the axial momentum distribution of the gas [18,27]. Assuming that the internal structure of pairs, i.e., the relative wave function of the fermions inside the pairs, has only negligible effect beyond the two-body sector [36], our system can be described in the 2D framework with the effective 2D scattering length $a_{2D} = \ell_z \sqrt{\pi/A} \exp[-\sqrt{\pi/2(\ell_z^2/a_{3D})}]$ [3,16,27,37], where $A = 0.905$.

To explore the phase diagram of the quasi-2D BEC-BCS crossover, we tune the temperature by heating the sample, and the interaction strength by adiabatically ramping the magnetic offset field to values between 692 G ($\ell_z/a_{3D} = 7.11$) and 982 G ($\ell_z/a_{3D} = -2.35$) [27]. We probe the 2D density distribution via absorption imaging along the vertical direction (see Fig. 1). The density distributions for different interaction strengths are shown in Fig. 2(a) for the coldest accessible temperatures. For growing $\ln(k_F a_{3D})$, the width of the sample increases while its central density decreases from approximately 2.7/μm$^2$ at $\ln(k_F a_{3D}) = -7.13$ to approximately 0.76/μm$^2$ at $\ln(k_F a_{2D}) = 3.24$. This change of the density distribution illustrates the crossover from a dense condensate of bosonic molecules to a degenerate Fermi gas whose density is reduced by the Fermi pressure. However the phase transition into a condensed phase, which manifests itself in the enhanced density of pairs with vanishing momentum, is not directly visible in the measured density distributions.

We thus conceived a method to probe the in situ pair momentum distribution of our strongly interacting system by combining a quench of interactions with a matter wave focusing technique in which the sample expands ballistically in a weakly confining radial harmonic potential [38–41]. Because of its large aspect ratio, our sample expands rapidly and almost exclusively in the $z$ direction after the release from the optical trap. Hence, its density suddenly drops and interactions between the expanding particles are quenched. Redistribution of momentum in the radial direction during the expansion is thus negligible at the weakest probed interaction strengths and does not affect the momentum distribution. To minimize interaction effects also in the strongly interacting regime, we perform a fast ramp to the lowest accessible interaction strength on the BEC side ($B = 692$ G, $\ell_z/a_{3D} = 7.11$) on a time scale shorter than 125 μs just before the release. This is fast enough that the density and momentum distributions cannot adjust to the new interaction parameter [27,41]. At the same time, pairs of atoms are projected onto deeply bound molecules whose binding energy $E_B$ significantly exceeds the energy scale given by the axial confinement ($\hbar\omega_z$) and one obtains the pair momentum distribution [42]. A similar technique was already used to explore the three-dimensional BEC-BCS crossover [13,14,44]. However, these experiments could not take advantage of the interaction quench and the subsequent ballistic expansion since they were lacking the fast expansion in the $z$ direction.

To obtain the radial momentum distribution, we perform this ballistic expansion in a weakly confining harmonic potential with trap frequency $\omega_{exp} = 2\pi \omega_{exp}$ in the radial direction. In a simple picture, the harmonic potential acts as a matter wave lens and brings the far field distribution to finite.

![FIG. 2 (color online). Density distributions at the lowest accessible temperature for different interaction strengths.](230401-2)
time scales. After an expansion time of $t_{\text{exp}} = \tau/4$, where $\tau = 1/\nu_{\text{exp}}$ is the period of the harmonic potential, the position of each particle depends only on its initial momentum in the radial plane. Thus $n(x, t = \tau/4) = \tilde{n}(\hbar k/(ma_{\text{exp}}), t = 0)$ and hence, by imaging the density profile after $t_{\text{exp}} = \tau/4$, we gain direct access to the initial 2D momentum distribution [38,39,41]. In our case, the radial profile after $t_{\text{exp}} = \tau/4$, we gain direct access to the initial 2D momentum distribution $\tilde{n}(k)$ of the sample from the high momentum tail of the distribution at $n_0$ changes by less than 10%. As $\tilde{n}_0$ is a measure for the long-range coherence of the system [45], the observed abrupt change indicates the phase transition to the condensed phase.

For a more quantitative analysis of our data, we azimuthally average the pair momentum distribution. Figure 3(a) shows the obtained radial distribution for the coldest accessible temperature at different interaction strengths. One observes a dramatic enhancement at low momenta which manifests itself in a sharp central peak. This feature is strongest on the BEC side and persists above $n_{\text{BEC}}$ [38]. In contrast to conventional time-of-flight expansion, where the initial spatial distribution of the sample influences the obtained momentum distribution—especially at low momenta—distortions are negligible in this method.

By combining the interaction quench with the projection onto molecules and the $\tau/4$ momentum imaging, we are able to access the radial in situ pair momentum distribution $\tilde{n}(k)$ in the whole crossover regime.

Figure 2(b) shows the obtained pair momentum distributions for the coldest attainable temperature at different interaction strengths. One observes a dramatic enhancement at low momenta which manifests itself in a sharp central peak. This feature is strongest on the BEC side and persists above $n_{\text{BEC}}$ [38]. In contrast to conventional time-of-flight expansion, where the initial spatial distribution of the sample influences the obtained momentum distribution—especially at low momenta—distortions are negligible in this method.

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Note that before the ramp of the interaction strength, the peak momentum density $\tilde{n}_0$ changes by less than 10%. As $\tilde{n}_0$ is a measure for the long-range coherence of the system [45], the observed abrupt change indicates the phase transition to the condensed phase.

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occurs at a significant non-Gaussian fraction of the measured values of the crossover region. Within their statistical uncertainties, slow increase of the measured critical temperature towards up to this point. The crossover to a fermionic description of the constituents of the bosonic dimers has the scattering amplitude diverges. This indicates that the fermionic nature of the constituents of the bosonic dimers has an effective description in terms of 2D bosons[52]. This theoretical prediction describes a BKT transition into a superfluid phase with algebraically decaying phase correlation below the critical temperature. However, because of the inhomogeneity of our system, a careful analysis is required to unambiguously confirm the BKT nature of the observed transition. Additionally, the equation of state can be extracted from the density distribution in the trap. Finally, the exploration of the dimensional crossover to 3D, in which an increased $T_c/T_F$ is predicted [55], offers new opportunities to understand mechanisms which lead to high critical temperatures.

Our work constitutes a basis for future theoretical and experimental studies of quantum gases in the quasi-2D BEC-BCS crossover. The measured critical temperature suggests the validity of BKT theory on the bosonic side. Superfluidity and the algebraic decay of correlations below the transition remain to be validated. Indeed, our ability to extract the \textit{in situ} momentum distribution with negligible distortion offers direct access to the coherence properties of the system. A first analysis of the trap averaged first order correlation function, which we obtain by Fourier transforming the pair momentum distribution, suggests algebraically decaying phase correlations below the critical temperature. Part of this deviation might be due to residual axial excitations grow with increasing $\ln(kFa_{2D})$ [27]. Recently, it was predicted that they would lead to an increased critical temperature [55].

FIG. 4 (color online). Phase diagram of the strongly interacting 2D Fermi gas. The experimentally determined critical temperature $T_c/T_F$ is shown as black data points and the error bars indicate the statistical errors. Systematic uncertainties are discussed in detail in Ref. [27]. The color scale indicates the nonthermal fraction $N_q/N$ and is linearly interpolated between the measured data points (the white crosses). Each data point is the average of about 30 measurements. The dashed white line is the theoretical prediction for the BKT transition temperature given in Ref. [52].

$T_c/T_F$ by the intersection of linear fits to the regimes above and below the phase transition. For the example shown in Fig. 3, this results in a critical temperature of $T_c/T_F = 0.129(35)$, where the critical phase space density is $\rho_c = n_0\lambda_{2B,c}^2 = 3.9(6)$, where $\lambda_{2B,c}$ are the thermal de Broglie wavelength and the peak \textit{in situ} density at the critical temperature, respectively.

By repeating this analysis for all investigated interaction strengths, we obtain the transition temperature as a function of the interaction parameter $\ln(kFa_{2D})$. The resulting values are shown as black dots in Fig. 4 together with the corresponding non-Gaussian fraction $N_q/N$, which is displayed as a color scale. Comparing the data for $T_c/T_F$ and $N_q/N$, one finds that the phase transition occurs at a significant non-Gaussian fraction of $N_q/N \approx 0.3$ for all measured interaction strengths.

On the BEC side of the phase diagram, one observes a slow increase of the measured critical temperature towards the crossover region. Within their statistical uncertainties, the measured values of $T_c/T_F$ are in good agreement with an effective description in terms of 2D bosons [52]. This theoretical prediction describes a BKT transition into a superfluid phase with algebraically decaying phase coherence. Interestingly, the bosonic theory provides a reasonable description of the data up to $\ln(kFa_{2D}) = 0$, where the 2D scattering amplitude diverges. This indicates that the fermionic nature of the constituents of the bosonic dimers has only a small effect on the many-body physics of the system up to this point. The crossover to a fermionic description should thus occur at positive values of $\ln(kFa_{2D})$. This is in line with recent theoretical predictions [6,53].

Far on the BCS side, fermionic theories predict an exponential decrease of $T_c/T_F$ [7,54]. Although we can only give an upper limit for the critical temperature $T_c/T_F \leq 0.16$ for $\ln(kFa_{2D}) \geq 2$, the observed non-Gaussian fraction is consistent with a decrease towards the BCS limit. However, $T_c/T_F$ is systematically above the theoretical predictions for $\ln(kFa_{2D}) > 0$ [7,8,52]. Part of this deviation might be due to the residual influence of the third dimension. In our system, residual axial excitations grow with increasing $\ln(kFa_{2D})$ [27]. It was predicted that they would lead to an increased critical temperature [55]. Additionally, the three-dimensional internal structure of atom pairs might lead to corrections in the regime where $E_B \approx \hbar \omega_z$, which go beyond the two-body sector. Whether this effect has any influence on the measured phase diagram still needs further experimental and theoretical consideration. Initial steps in this direction have been taken [56].

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