Observation of the Berezinskii-Kosterlitz-Thouless Phase Transition in an Ultracold Fermi Gas

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(Received 11 May 2015; published 30 June 2015)

We experimentally investigate the first-order correlation function of a trapped Fermi gas in the two-dimensional BEC-BCS crossover. We observe a transition to a low-temperature superfluid phase with algebraically decaying correlations. We show that the spatial coherence of the entire trapped system can be characterized by a single temperature-dependent exponent. We find the exponent at the transition to be constant over a wide range of interaction strengths across the crossover. This suggests that the phase transitions in both the bosonic regime and the strongly interacting crossover regime are of Berezinskii-Kosterlitz-Thouless type and lie within the same universality class. On the bosonic side of the crossover, our data are well described by the quantum Monte Carlo calculations for a Bose gas. In contrast, in the strongly interacting regime, we observe a superfluid phase which is significantly influenced by the fermionic nature of the constituent particles.

DOI: 10.1103/PhysRevLett.115.010401 PACS numbers: 05.30.Jp, 05.10.Ln, 05.30.Fk, 67.85.Lm

Long-range coherence is the hallmark of superfluidity and Bose-Einstein condensation (BEC) [1,2]. The character of spatial coherence in a system and the properties of the corresponding phase transitions are fundamentally influenced by dimensionality. The two-dimensional case is particularly intriguing as, for a homogeneous system, true long-range order cannot persist at any finite temperature due to the dominant role of phase fluctuations with large wavelengths [3–5]. Although this prevents Bose-Einstein condensation in 2D, a transition to a superfluid phase with quasi-long-range order can still occur, as pointed out by Berezinskii, Kosterlitz, and Thouless (BKT) [6–8]. A key prediction of this theory is the scale-invariant behavior of the first-order correlation function $g_1(r)$, which, in the low-temperature phase, decays algebraically according to $g_1(r) \propto r^{-\eta}$ for large separations r. Importantly, the BKT theory for homogeneous systems predicts a universal value of $\eta_c = 1/4$ at the critical temperature, accompanied by a universal jump of the superfluid density [9].

Several key signatures of BKT physics have been experimentally observed in a variety of systems such as exciton-polariton condensates [10], layered magnets [11,12], liquid ^{4}He films [13], and trapped Bose gases [14–20]. Particularly in the context of superfluidity, the universal jump in the superfluid density was measured in thin films of liquid ^{4}He [13]. More recently, in the pioneering interference experiment with a weakly interacting Bose gas [14], the emergence of quasi-long-range order and the proliferation of vortices were shown.

There are still important aspects of superfluidity in two-dimensional systems that remain to be understood, which we aim to elucidate in this work with ultracold atoms. One question is whether the BKT phenomenology can also be extended to systems with nonuniform density. Indeed, if the microscopic symmetries are the same, the general physical picture involving phase fluctuations should be valid also for inhomogeneous systems. However, it is not known if algebraic order persists at all in the presence of inhomogeneity and, particularly, whether the correlations in the whole system can still be characterized by a single exponent. Another fundamental issue that arises in the study of superfluidity is the pairing of fermions. While fermionic superfluidity has been extensively investigated in 3D systems [21–23], there are open experimental questions in the 2D context. In particular, what is the long-range behavior of spatial coherence of a 2D fermionic superfluid, and can it also be described in the BKT framework like its bosonic counterpart?

In this work, we probe the first-order correlation function $g_1(r)$ of a trapped Fermi gas in the two-dimensional BEC-BCS crossover regime [24,25]. The correlation function is determined from a measurement of the *in situ* momentum distribution of the gas. We demonstrate that, even in this inhomogeneous system, algebraic order persists in $g_1(r)$ below a critical temperature. Furthermore, a quantitative analysis of the scaling exponents across the crossover reveals the validity of the BKT theory also in the fermionic regime.

Our measurements are performed with a gas of 10^5 ^{6}Li atoms confined in a highly anisotropic potential. The axial and radial trapping frequencies are $\omega_z \approx 2\pi \times 5.5$ kHz and $\omega_r \approx 2\pi \times 18$ Hz, respectively, leading to an aspect ratio of approximately 300:1. Our experimental system and methodology have been described in detail in Ref. [24]. We perform *in situ* imaging of the sample as a function of temperature and interaction strength. From the central density, we define the Fermi momentum k_F and Fermi temperature T_F, which constitute the relevant scales in the system. As shown in Ref. [24], for our experimental parameters, all the relevant energy scales are smaller than the axial confinement energy $\hbar\omega_z$. Hence, the system is in the quasi-2D regime.

We tune the interparticle interactions by using a Feshbach resonance located at 832 G. Using the 3D scattering length $a_{3\mathrm{D}}$ [26], the axial oscillator length ℓ_z [27], and the Fermi momentum, we construct the effective 2D scattering length $a_{2\mathrm{D}}$ and crossover parameter $\ln(k_F a_{2\mathrm{D}})$ [25]. For $\ln(k_F a_{2\mathrm{D}}) \ll -1$ and $\ln(k_F a_{2\mathrm{D}}) \gg 1$, we are in the bosonic and fermionic limit of the crossover, respectively.

In addition to the measurements, we perform path-integral quantum Monte Carlo (QMC) computations of a Bose gas [28,29] in a highly anisotropic 3D trap with parameters similar to those employed in the experiment. In the simulations, the bosons interact via the molecular scattering length $a_{\mathrm{mol}} = 0.6 a_{3\mathrm{D}}$ [30]. The relevant parameters that describe the system in terms of pointlike bosons are the effective bosonic coupling strength $\tilde{g} = \sqrt{8\pi} a_{\mathrm{mol}}/\ell_z$ and the condensation temperature of an ideal 2D Bose gas $T^0_{\mathrm{BEC}} = \sqrt{6N}(\hbar\omega_r/\pi k_B) \approx 140$ nK, where N is the number of particles. We use these bosonic parameters to compare our measurements to QMC calculations at the lowest magnetic field values, where we have $\tilde{g} = 0.6, 1.07, 2.76, 7.75$ [31]. From the QMC computations, we obtain the local density profile and the one-body density matrix $\rho_1(\mathbf{x}, \mathbf{x}') = \langle \hat{\phi}^\dagger(\mathbf{x}) \hat{\phi}(\mathbf{x}') \rangle$ for different interaction strengths and temperatures, where $\hat{\phi}(\mathbf{x})$ is the bosonic field operator.

The global off-diagonal correlations in the system are encoded in the momentum distribution of particles. To reliably measure the in-plane momentum distribution $\tilde{n}(\mathbf{k})$ of our sample, we employ the matter-wave focusing technique described in Refs. [16,32,33], where the gas expands freely in the axial direction while being focused by a harmonic potential in the radial plane. After expansion for a quarter of the period of the focusing potential, the initial momentum distribution is mapped to the spatial density profile, which we then image. We combine this focusing method with a rapid magnetic field ramp into the weakly interacting regime. This rapid ramp technique—along with the fast axial expansion due to the large anisotropy of the trap—ensures that interparticle collisions during the focusing do not cause significant distortions to the measured momentum distribution. From $\tilde{n}(\mathbf{k})$, we extract the absolute temperature T by means of a Boltzmann fit to the high-$\mathbf{k}$ thermal region [34].

To quantitatively investigate the spatial coherence in our system, we determine the first-order correlation function $g_1(\mathbf{r})$ by means of a 2D Fourier transform of the measured $\tilde{n}(\mathbf{k})$. It is related to the one-body density matrix $\rho_1(\mathbf{x}, \mathbf{x}')$ by means of

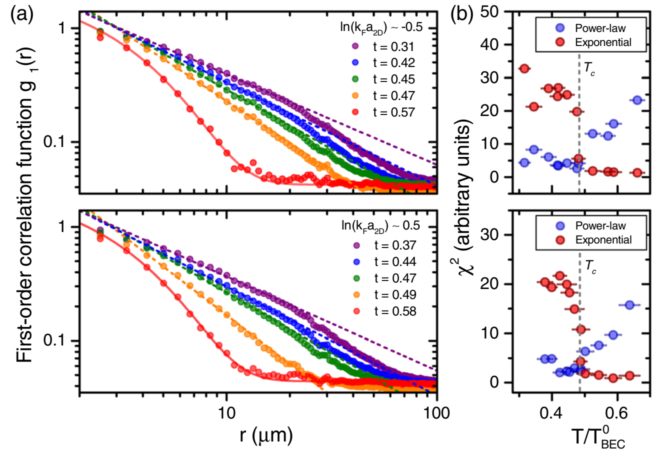

FIG. 1 (color online). First-order correlation function $g_1(r)$ for different temperatures at $\ln(k_F a_{2\mathrm{D}}) \simeq -0.5$ (upper left panel) and $\ln(k_F a_{2\mathrm{D}}) \simeq 0.5$ (lower left panel). The temperature scale used here is $t = T/T^0_{\mathrm{BEC}}$. (a) At high temperatures, correlations decay exponentially as expected for a gas in the normal phase. At low temperatures, we observe algebraic correlations $[g_1(r) \propto r^{-\eta(T)}]$ with a temperature-dependent scaling exponent $\eta(T)$. (b) This qualitative change of behavior is clearly visible in the χ^2 for both exponential and algebraic fits (right panel), where a small value signals a good fit. In particular, this allows for an accurate determination of the transition temperature T_c (vertical dashed lines) [31].

$$g_1(\mathbf{r}) = \int d^2k \tilde{n}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{r}}$$
$$= \int d^2R \rho_1(\mathbf{R} - \mathbf{r}/2, \mathbf{R} + \mathbf{r}/2). \tag{1}$$

A derivation of these relations is given in Supplemental Material [31]. The function $g_1(\mathbf{r})$ is a trap-averaged function, which captures the off-diagonal correlations of all particles in the system. Similarly, one can also define the central correlation function $G_1(\mathbf{r}, 0) = \langle \hat{\phi}^\dagger(\mathbf{r}) \hat{\phi}(0) \rangle$, measured in the interference experiments [14,35], which characterizes the correlations only in the central region of the trap, where the density is approximately uniform. In general, the two functions do not contain the same information and are equivalent only in a translation invariant system [31]. Note that, due to the radial symmetry of the trapping and focusing potentials, the correlations depend only on distance, and therefore it suffices to consider the azimuthally averaged function $g_1(r)$.

Figure 1 shows the experimentally determined $g_1(r)$ for different temperatures in the strongly interacting crossover regime. The correlation functions are normalized such that $g_1(0) = 1$. As expected, at high temperatures, $g_1(r)$ decays exponentially with correlation lengths on the order of the thermal wavelength ($\lambda_T \sim 1.5$ μm). As we lower the temperature, we eventually observe the onset of coherence over an extended spatial range that corresponds to several radial oscillator lengths ℓ_r, with $\ell_r \approx 6.8$ μm. This shows that phase fluctuations in the system are nonlocal and span

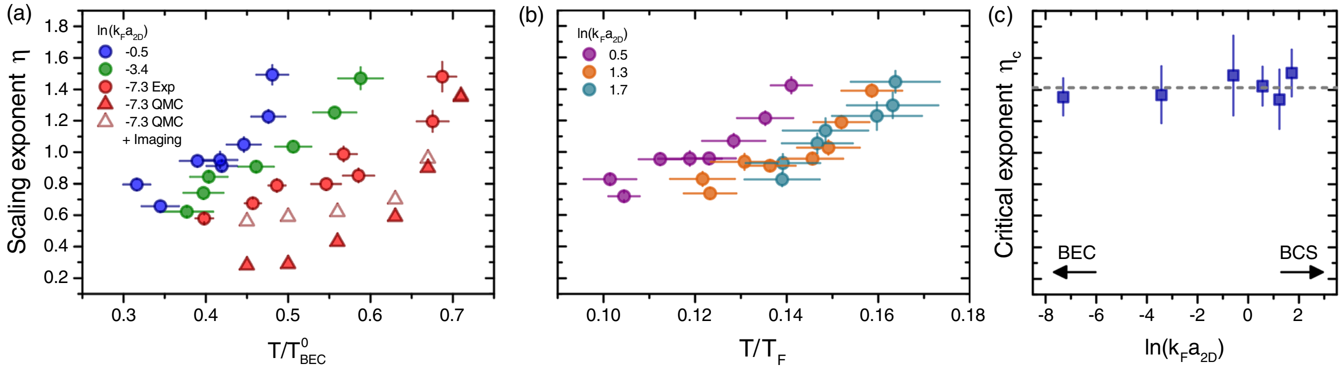

FIG. 2 (color online). Power-law scaling exponents across the two-dimensional BEC-BCS crossover. The temperature-dependent scaling exponent $\eta(T)$ in (a) the bosonic limit and (b) the crossover regime is shown. The relevant temperature scales in these cases are given by T^0_{BEC} and T_F, respectively. The crossover parameter $\ln(k_F a_{2D})$ is mildly temperature dependent. For reference, we display the value at the critical temperature. For $\tilde{g} = 0.60$ [$\ln(k_F a_{2D}) \simeq -7.3$], we show the prediction from QMC calculations for a Bose gas (filled red triangles) and an estimate of the effect of the finite imaging resolution present in the measured data (open red triangles) [31]. We find an exponent which increases with temperature in agreement with the BKT theory. The power-law decay eventually ceases at T_c, where a maximal exponent η_c is reached. (c) The value of η_c is approximately constant for all $\ln(k_F a_{2D})$ where we have previously observed condensation of pairs [24]. This strongly suggests that the associated phase transitions are within one universality class.

regions of the sample where the density is not uniform. As pointed out in Refs. [36,37], such extended spatial coherence in an interacting system is a sufficient condition for superfluidity in two-dimensional systems.

As the temperature is lowered below a critical value, we find that the correlation function in an intermediate range $3\lambda_T < r < 20\lambda_T$ is well described by a power-law decay, whereas exponential behavior is clearly disfavored. We quantify this by extracting the χ^2 for both fit functions at different temperatures and observe a clear transition from exponential to algebraic decay [see Fig. 1(b)]. This qualitative change in $g_1(r)$ provides an alternative way to determine the phase transition temperature T_c from the kink in $\chi^2(T)$ [31]. We find that the corresponding T_c obtained in this manner agrees with the temperature associated with the onset of pair condensation that was measured in our previous work [24].

The power-law decay of $g_1(r)$ means that the spatial coherence of the entire sample is characterized by a single exponent η. Figure 2 shows the experimentally determined η for all the interaction strengths accessed in this work. We find $\eta(T)$ to increase with temperature until it reaches a maximal value at T_c, indicating a slower falloff of correlations at lower temperatures. Although such temperature dependence is qualitatively consistent with the BKT theory, we observe the values of the exponents to be in the range 0.6–1.4 for the temperatures accessed in the measurement, which is substantially above the expectation of $\eta \leq 0.25$ for the homogeneous setup.

To confirm the large scaling exponents in the trapped system, we compute the one-body density matrix on the bosonic side by using the QMC technique described above. This allows us to determine both the trap-averaged correlation function $g_1(r)$ as well as the central correlation function $G_1(r,0)$. The trap-averaged $g_1(r)$ shows the same behavior as in the experimental case, i.e., a transition from exponential to algebraic decay at low temperatures. The corresponding QMC transition temperatures also agree with the measured values of T_c for $\tilde{g} = 0.60$, 1.07, and 2.76. Furthermore, the maximal scaling exponent at T_c extracted from the QMC $g_1(r)$ for $\tilde{g} = 0.6$ is approximately 1.35, which is close to the experimentally determined $\eta(T_c) \simeq 1.4$. The central correlation function $G_1(r,0)$ shows a transition to algebraic order as well—with the same T_c as in the experiment—but with a maximal exponent of approximately 0.25, as expected for a homogeneous system. This finding is also in agreement with the measurement of $G_1(r,0)$ in the interference experiments [14] and is explained by the nearly uniform density in the center of the trap.

Figure 2(a) shows the comparison between the experimental and QMC values of $\eta(T)$ for $\tilde{g} = 0.60$ [$\ln(k_F a_{2D}) \simeq -7.3$]. Although both show similar dependence on temperature, we find a considerable quantitative deviation between them. As discussed in Supplemental Material [31], this discrepancy can mostly be attributed to the effect of the finite imaging resolution in the measurement of $\tilde{n}(\mathbf{k})$, which leads to an apparent broadening at low momenta and thus overestimates the value of η. We show an estimate of this temperature-dependent effect on the exponents (open red triangles) in Fig. 2(a). There may be other effects in the experiment that contribute additionally to the deviation, such as higher-order corrections to the determination of $\tilde{g}$ from the fermionic scattering parameters and density-dependent inelastic loss processes.

The experimental and simulated data raise the question why correlations in the trapped system decay with a larger scaling exponent than in the homogeneous case. To elucidate the role of inhomogeneity, we consider the bosonic field operator given by $\hat{\phi}(\mathbf{r}) \simeq \sqrt{\rho(\mathbf{r})}\exp[i\hat{\varphi}(\mathbf{r})]$. In this representation, it is clear that one contribution to the decay of

$g_1(r)$ in Eq. (1) comes from the spatial variation of the superfluid density $\rho(\mathbf{r})$. Using a local density approximation and assuming the superfluid density to have a Thomas-Fermi profile, we estimate a contribution of approximately 0.3–0.4 [31] to the effective exponent. Still, this fails to explain the large exponents observed in the experiment and the QMC simulations close to T_c. This suggests that the increase in the effective exponents is predominantly due to phase fluctuations in the inhomogeneous system, whose spectrum is modified by the discrete level structure of the harmonic trapping potential and the Thomas-Fermi profile of the superfluid. This inference is further supported by calculations of phase fluctuations in a trapped 2D Bose gas at low temperatures [38], which indicate a trap-induced increase of the effective exponent by up to a factor of 3.

Our measurements of $g_1(r)$ and $\eta(T)$ across the two-dimensional BEC-BCS crossover provide a unique opportunity to study BKT physics even in the fermionic regime. Figure 2 displays the measurement of the scaling exponent across the crossover. Remarkably, we find that—despite varying the scattering length by several orders of magnitude—the maximal scaling exponent η_c at the transition shows no dependence on the interaction strength [see Fig. 2(c)]. We note that the actual value of $\eta_c \simeq 1.4$ might depend on parameters specific to the experiment, such as the particle number and trapping frequencies. Nevertheless, the fact that η_c remains constant across the BEC-BCS crossover unambiguously shows that the long-range properties at the transition are independent of interparticle interactions. This is evidence that all the observed transitions for different interaction strengths lie in the same universality class. In particular, it shows that, even as we cross over to the fermionic side [$\ln(k_F a_{2D}) > 0$], the observed transitions are of BKT type.

We now turn to a quantitative investigation of local properties of the system. This allows us to benchmark our measurements with (i) the QMC results for pointlike bosons in the same quasi-2D trapping potential as realized in the experiment and (ii) QMC calculations of the homogenous 2D Bose gas [39,40]. For this, we investigate the phase space density (PSD)

$$\mathcal{D} = n\lambda_T^2. \tag{2}$$

Herein, n is the 2D density of atoms in a single hyperfine state and $\lambda_T^2 = 2\pi\hbar^2/Mk_BT$ is the thermal wavelength of bosons with M being twice the fermion mass. Note that n coincides with the density of dimers in the bosonic limit.

We first consider coupling strengths $\tilde{g} = 0.60$, 1.07, and 2.76 on the bosonic side of the crossover. Figure 3(a) shows the comparison between the experimentally measured and QMC-computed values of the PSD in the trap center for $\tilde{g} = 2.76$. We find excellent agreement between the two data sets. In particular, at T_c, the central PSD for all three $\tilde{g}$ are found to agree very well with $\mathcal{D}_c = \ln(380/\tilde{g})$ derived for a homogeneous 2D Bose gas with weak interactions (horizontal dashed line) [39,40]. This shows that the onset

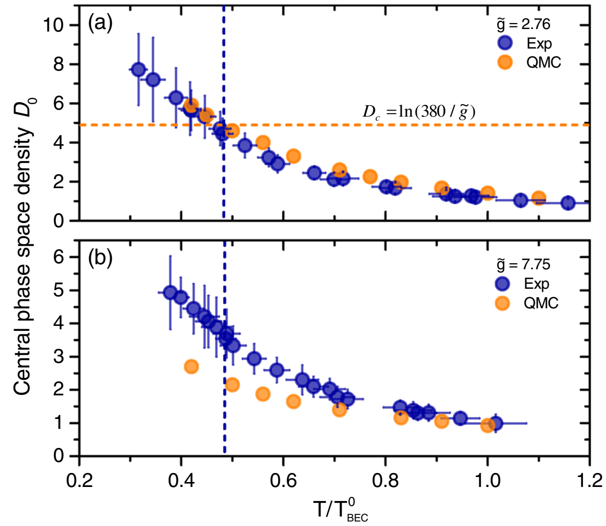

FIG. 3 (color online). Peak phase space density $\mathcal{D}_0 = n_0\lambda_T^2$ obtained from the central density n_0. (a) and (b) show experimental and simulated data (for bosons) for the coupling strengths $\tilde{g} = 2.76$ and $\tilde{g} = 7.75$, respectively. The vertical dashed lines indicate the corresponding critical temperatures obtained from the measured onset of algebraic order. (a) We find excellent agreement between experiment and QMC for $\tilde{g} = 2.76$, providing evidence that we realize a strongly interacting 2D Bose gas. We verify the applicability of $\mathcal{D}_c = \ln(380/\tilde{g})$ [39] at this interaction strength (horizontal dashed line). (b) For the stronger coupling $\tilde{g} = 7.75$, however, we find the bosonic simulations to deviate from the measured results, indicating fermionic superfluidity.

of algebraic correlations in the trapped system coincides with the local PSD in the center of the trap crossing the critical value of the homogeneous system [28].

As we further increase $\ln(k_F a_{2D})$, the effective boson coupling strength $\tilde{g}$ becomes very large. For $\tilde{g} = 7.75$ [$\ln(k_F a_{2D}) \simeq 0.5$], we find substantial deviations between the experimental and QMC data for the PSD at low temperatures [see Fig. 3(b)]. Moreover, our QMC calculations show that the associated 2D Bose gas is in its normal phase for all temperatures accessed in the experiment. In contrast, the measurements show a clear superfluid phase transition at this interaction strength, as shown in Fig. 1 (lower panel). This provides evidence for the crossover to a superfluid phase whose properties are not captured by a description that assumes pointlike dimers.

Both experimental and simulated data in the bosonic limit are obtained in a highly anisotropic 3D trapping potential. Still, local observables such as the central PSD and the central correlation function $G_1(r, 0)$ agree excellently in their critical properties with the theory of a homogenous 2D Bose gas and the corresponding BKT phenomena. In the case of global correlations, we showed that the inhomogeneity leads to significant deviations from the homogeneous case, most importantly an increase in the exponent of the power-law decay. However, the general features in the off-diagonal correlations—such as the temperature dependence of $\eta(T)$ and the independence of η_c from $\ln(k_F a_{2D})$—suggest that the long-range physics are still captured by the ideas underlying BKT theory for the two-dimensional XY model.

In conclusion, we investigated the nature of the phase transition of a trapped 2D ultracold Fermi gas. We measured for the first time the first-order correlation function of the entire system and extracted its long-range behavior. We showed that it is consistent with a description by a single power-law exponent for large distances. The transition temperature for the onset of algebraic order coincides with the one obtained from the onset of pair condensation in Ref. [24]. By comparing the experimental data to QMC calculations on the bosonic side, we found the system to realize a strongly interacting 2D Bose gas. The measured phase space densities and correlations on the fermionic side, instead, are not captured by a description in terms of pointlike bosons, which indicates the crossover to a fermionic superfluid.

Our measurements show that the spatial coherence even in trapped systems can be characterized by a single scaling exponent. However, understanding the underlying mechanism remains a challenge for future explorations and may lead to a deeper understanding of phase transitions in inhomogeneous systems.

We thank Z. Hadzibabic, T. Enss, T. Bourdel, and J. M. Pawlowski for insightful discussions. We thank T. Lompe, S. Pres, and J. E. Bohn for experimental and conceptual contributions to the project. We gratefully acknowledge support from the ERC starting Grant No. 279697, the ERC advanced Grant No. 290623, the Helmholtz Alliance HA216/EMMI, and the Heidelberg Center for Quantum Dynamics. M. H. was supported by ANR-12-BS04-0022-01, ANR-13-JS01-0005-01, and DIM Nano'K from Région Île-de-France. M. G. R. and I. B. acknowledge support by the Landesgraduiertenförderung Baden-Württemberg.

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