

Observing Spatial Charge and Spin Correlations in a Strongly Interacting Fermi Gas

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In this Letter, we explore two-dimensional attractive Fermi gases at the microscopic level by probing spatial charge and spin correlations *in situ*. Using atom-resolved continuum quantum gas microscopy, we directly observe fermion pairing and study the evolution of two- and three-point correlation functions as interspin attraction is increased. The precision of our measurement allows us to reveal nonlocal anticorrelations in the pair correlation function, fundamentally forbidden by the mean-field result based on BCS theory but whose existence we confirm in exact auxiliary-field quantum Monte Carlo calculations. We demonstrate that the BCS prediction is critically deficient not only in the superfluid crossover regime but also deep in the weakly attractive side. Guided by our measurements, we find a remarkable relation between two- and three-point correlations that establishes the dominant role of pair correlations. Finally, leveraging local single-pair losses, we independently characterize the short-range behavior of pair correlations, via the measurement of Tan's contact, and find excellent agreement with numerical predictions. Our measurements provide a novel microscopic view into strongly correlated two-dimensional Fermi gases in the continuum.

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Ultracold Fermi gases provide a powerful test bed for the exploration of two-dimensional (2D) fermionic matter, with a high level of control and exquisite probing capabilities [1,2]. The two-component (spin $\uparrow$ and spin $\downarrow$) Fermi gas with attractive contact interactions constitutes a paradigmatic model of many-body physics, with a rich phenomenology and deep connections with condensed matter physics [3,4].

Crucially, the interspin attraction can be varied experimentally by means of a Feshbach resonance from very weak to arbitrarily large, where two opposite spins form a bosonic dimer, thus realizing a situation where the quantum statistics of the system can be dynamically tuned. At sufficiently low temperature, an ensemble with balanced spin populations can be continuously driven from the state of a BCS superfluid, with nonlocal fermion pairs, to a BEC

of tightly bound dimers [5–8], remaining in the superfluid state for any interaction strength [see Fig. 1(a)]. At higher temperature, the normal phase is well understood with the system evolving from a Fermi to a Bose liquid behavior when the attraction is increased, but at intermediate temperature and sufficiently strong interaction a pseudogap regime may exist right above the normal-to-superfluid transition line, where precursor pairs are formed in the absence of superfluidity [9–11]. In quasi-2D superconductors, the microscopic origin of the pseudogap remains largely debated [12].

In addition, the reduced dimensionality raises fundamental questions. In two-dimensions, the Mermin-Wagner theorem precludes the existence of true long-range order in the thermodynamic limit when interactions are short-ranged [13], and the transition to the superfluid state is of the Berezinskii-Kosterlitz-Thouless type [14,15]. For finite-size samples, the possibility of full coherence over the system leads to a subtle interplay with the Berezinskii-Kosterlitz-Thouless transition [16], with the existence of a significant condensed fraction even above the transition. Dimensionality also has profound effects on the symmetries of the system, which can evolve from being scale

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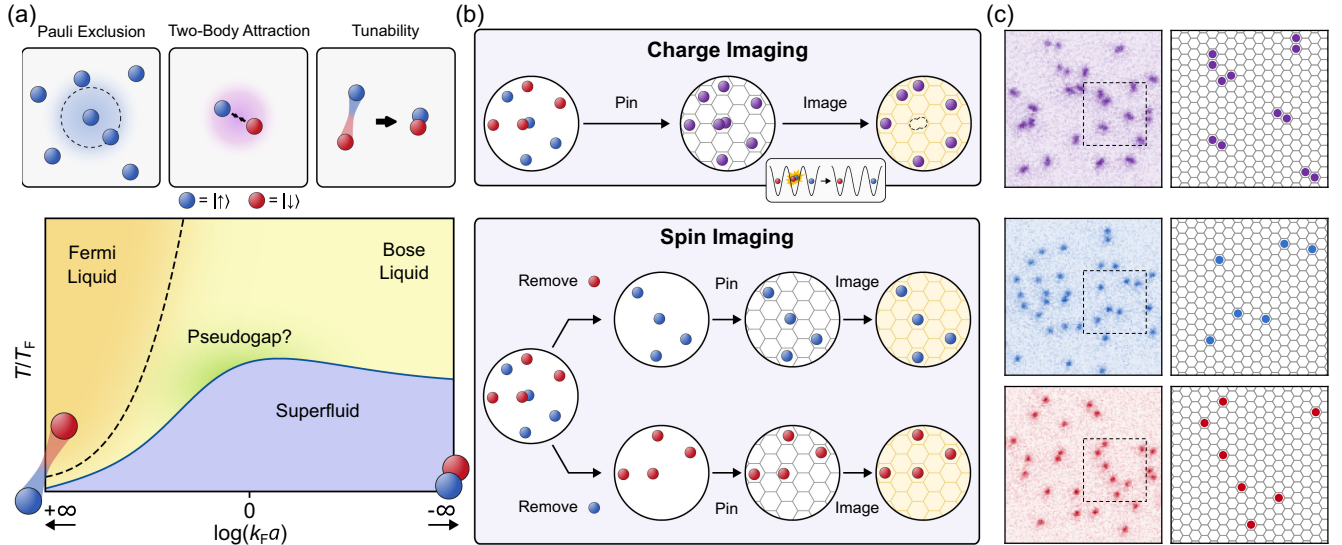


FIG. 1. Single-charge and single-spin imaging of interacting 2D Fermi gases. (a) Schematic phase diagram of the spin-balanced 2D attractive Fermi gas across the BEC-BCS crossover. At sufficiently low temperatures, the system is superfluid for any nonzero attraction. At higher temperatures, it exhibits well-understood Fermi and Bose liquid behaviors, but the state right above the normal-to-superfluid temperature is believed to display a pseudogap behavior below a certain threshold (black dashed line). (b) The spin-1/2 mixture is imaged via atom-resolved quantum gas microscopy giving access to the total density (charge), the spin- $\uparrow$ component, and the spin- $\downarrow$ component. Single-spin images are obtained after removal of the other spin component using a resonant light pulse. Sites occupied by two atoms upon pinning appear empty after imaging due to light-assisted collisions, which we use as an independent probe of short-range correlations. (c) Raw single-charge (top) and single-spin (middle and bottom) experimental images along with their processing. In the shown charge image, fermions are seen to organize by pairs.

invariant [17,18] to displaying a quantum anomaly [19,20] depending on the interaction strength. Finally, spin-imbalanced 2D Fermi gases are believed to be prime candidates for hosting the elusive Fulde-Ferrell-Larkin-Ovchinnikov phase [21–23].

Continuum quantum gas experiments have had great success in investigating strongly interacting 2D fermions, with a wide range of measurements addressing their thermodynamics [24–28], transport [8,29], coherence [7,20,30], or spectral [11,31–33] properties. For almost two decades, however, the available imaging techniques have limited the ability to acquire quantitative knowledge at the microscopic scale, i.e., resolving their spatial organization at length scales below the interparticle spacing. Recent progress in that direction was achieved for magnified few fermion systems [34,35].

In this Letter, we probe strongly interacting 2D Fermi gases at low temperatures via atom-resolved *in situ* imaging. By measuring spatial charge and spin correlations over a wide range of interaction strengths, we reveal the microscopic behavior of this strongly correlated system. While strongly interacting fermionic ensembles are in general extremely challenging to tackle theoretically, the case of equal spin populations represents a rare example for which numerically exact calculations can be performed [36–39]. We take advantage of this to perform a high-precision comparison of our measurements with cutting-edge auxiliary-field quantum Monte Carlo (AFQMC) calculations. We also contrast our results with BCS theory,

charting the regimes of its breakdown for various microscopic observables. Our Letter demonstrates capabilities to directly and precisely measure spatial correlations in a strongly correlated system, which will readily apply to situations where accurate computations are significantly more challenging, such as Fermi gases where spin populations are unequal, as well as where interactions are repulsive or long-range.

Our experiment starts with a two-component spin mixture of fermionic ${}^6\text{Li}$ atoms ($|\uparrow\rangle$ and $|\downarrow\rangle$), corresponding to the third-lowest and lowest hyperfine states of ${}^6\text{Li}$ with equal spin populations. Atoms are confined to a single plane using a strong laser-induced trap in the vertical z direction, with frequency $\omega_z/2\pi = 1.125(50)$ kHz corresponding to a temperature $T_z = \hbar\omega_z/k_B = 54(2)$ nK, with $\hbar$ the reduced Planck constant and k_B the Boltzmann constant. This temperature scale is much larger than the absolute temperature $T \lesssim 5$ nK, and at least on the order of the Fermi temperature $T_F = \pi n \hbar^2 / mk_B$ of our samples, n being the average total density near the center of the trap and m the atomic mass (see Ref. [40]). This corresponds to the interesting regime where the system can significantly depart from the purely 2D regime only in the presence of strong interactions, allowing the population of higher z levels. This quasi-2D geometry and the finite size of our cloud favors an increase of the critical temperature on the order of $T_c \sim 0.15T_F$ in the crossover [7,46,47], such that most of our samples are in the superfluid regime with reduced temperatures as low as $T/T_F \approx 0.08$.

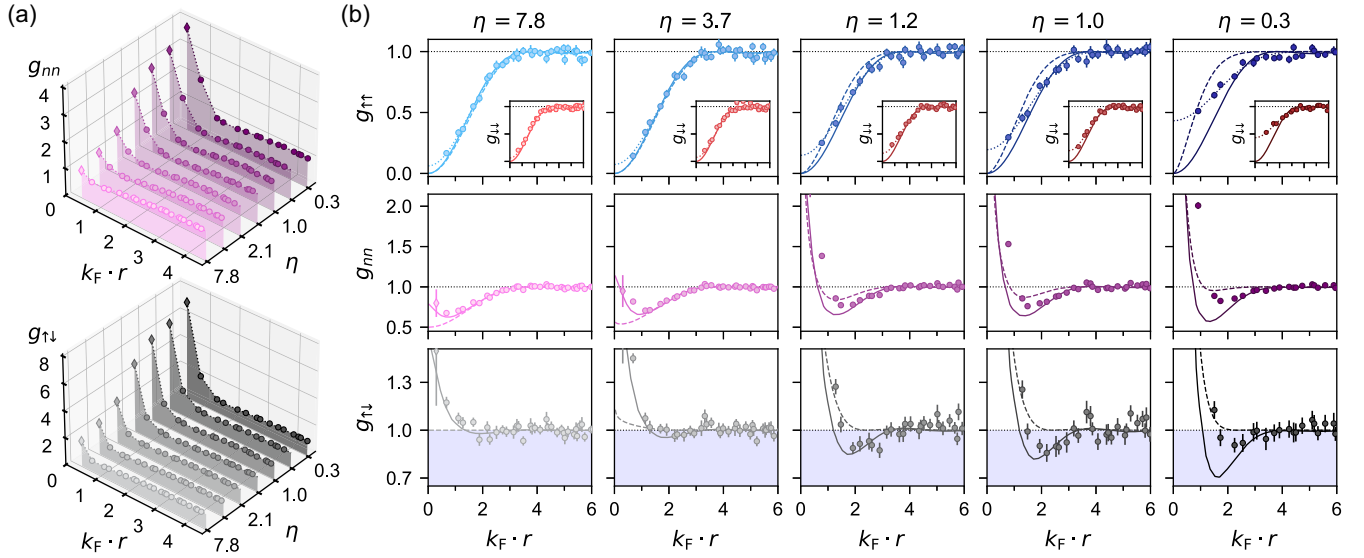


FIG. 2. Two-point charge and spin correlations. (a) Charge and pair correlations as a function of the interaction parameter η (the values in the labels are rounded for readability). The diamonds at short distance are obtained via pair-loss measurements (see text). The upshoot at short range represents a direct observation of fermion pairing in real space. (b) Close-up of correlations for selected values of η . Top row: equal-spin correlations. Middle row: charge correlations. Bottom row: pair correlations. Dashed lines: mean-field BCS theory. Solid lines: AFQMC calculations for the 2D gas at our experimental values of η and reduced temperature T/T_F . Blue dotted lines (top row): two-parameter fit of $g_{\sigma\sigma}$ (see Ref. [40]). Black dotted lines: expected results for an uncorrelated gas. For all interactions the measured correlations display clear deviations from the BCS prediction. Furthermore, interspin correlations display a dip where $g_{\uparrow\downarrow} < 1$, in violation of BCS theory, which is also observed in the AFQMC results. In the weakly interacting regime we find excellent agreement between our data and AFQMC. In the crossover region interactions induce the occupation of excited z levels, leading to a reduced contrast in $g_{\uparrow\uparrow}$ and expected differences with AFQMC in 2D.

Interspin interactions are characterized by the 2D scattering length,

$$a = \ell_z \sqrt{\pi/B} \exp(-\sqrt{\pi/2} \ell_z / a_{3D}), \quad (1)$$

reflecting the combined effect of the interspin scattering length in three-dimensional space a_{3D} and the vertical harmonic oscillator length $\ell_z = \sqrt{\hbar/m\omega_z}$, with $B \approx 0.905$ [5,48,49]. At the many-body level, the relevant interaction parameter is $\eta = \log(k_F a)$, where $k_F = \sqrt{2\pi n}$ denotes the Fermi wave number. The BCS and BEC regimes correspond respectively to $\eta \gg 1$ and $\eta \ll -1$, where the pair size is much greater than the interparticle spacing in the former case, and much smaller in the latter.

We probe the system using continuum quantum gas microscopy, which consists in freezing the motion of the atoms initially evolving in continuous space before imaging their positions. This is achieved by suddenly turning on a pinning optical lattice, and subsequently exposing the atoms to cooling light, which drives their fluorescence while maintaining them in individual lattice wells [50,51]. Prior to pinning, we either remove one of the spin components, which results in images of single-spin spatial distributions, or we directly image the total density, corresponding to single-charge imaging, as depicted in Fig. 1(b). Charge imaging does not allow the detection of

doubly occupied sites [40] but owing to the extreme diluteness of our clouds, this does not introduce any detrimental effect, and we later exploit this feature to measure the short-range behavior of the pair correlations. By acquiring charge, spin- $\uparrow$, and spin- $\downarrow$ images from ~ 750 separate experimental runs each, we obtain all relevant two-point correlation functions,

$$\begin{aligned} g_{nn}(r) &= \frac{\langle n(0)n(r) \rangle}{\langle n(0) \rangle \langle n(r) \rangle}, \\ g_{\sigma\sigma}(r) &= \frac{\langle n_\sigma(0)n_\sigma(r) \rangle}{\langle n_\sigma(0) \rangle \langle n_\sigma(r) \rangle}, \quad \sigma = \uparrow, \downarrow \\ g_{\uparrow\downarrow}(r) &= \frac{\langle n_\uparrow(0)n_\downarrow(r) \rangle}{\langle n_\uparrow(0) \rangle \langle n_\downarrow(r) \rangle}, \end{aligned} \quad (2)$$

with $r \neq 0$. The functions g_{nn} , $g_{\uparrow\uparrow}$, and $g_{\downarrow\downarrow}$ are directly measured from the data, while $g_{\uparrow\downarrow} = g_{\downarrow\uparrow}$ is retrieved via the relation

$$g_{nn}(r) = \frac{1}{2} g_{\uparrow\uparrow}(r) + \frac{1}{2} g_{\downarrow\downarrow}(r), \quad (3)$$

valid in the spin-balanced case, where $g_{\uparrow\uparrow} = g_{\downarrow\downarrow}$.

In Fig. 2(a), we show an overview of the measured spatial charge and pair correlations for seven interaction strengths, $\eta = 7.77^{+0.38}_{-0.34}$, $3.70^{+0.21}_{-0.18}$, $2.08^{+0.13}_{-0.13}$, $1.21^{+0.10}_{-0.09}$,

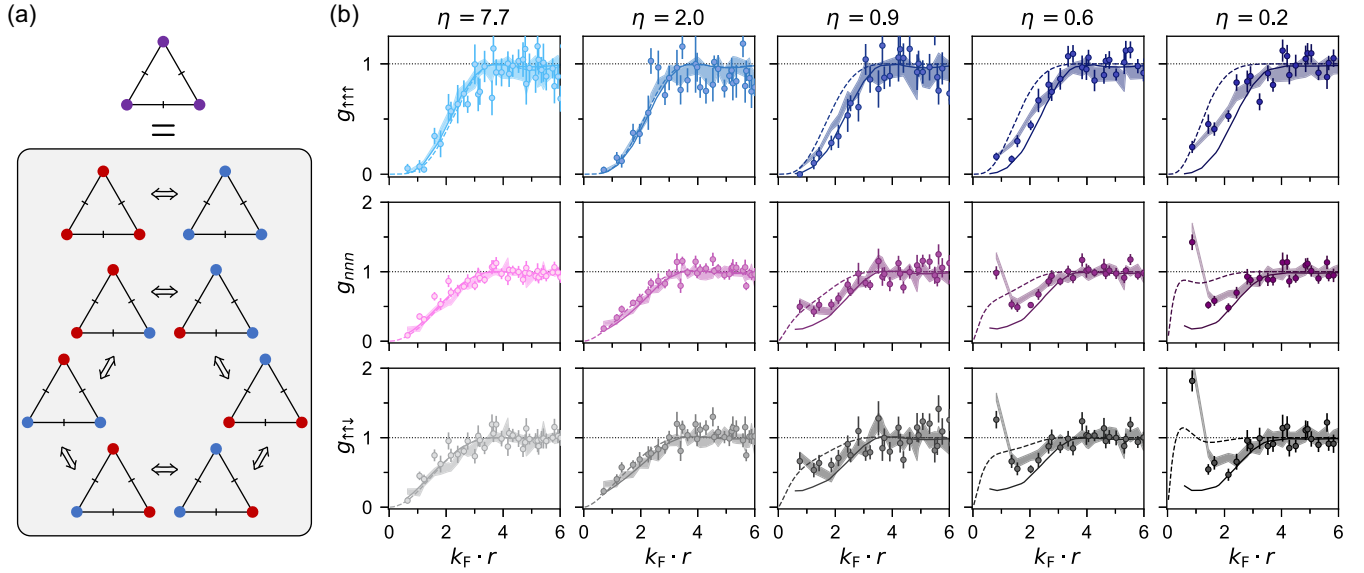


FIG. 3. Three-point charge and spin correlations. (a) On equilateral triangles and for balanced spin populations there are enough symmetries to extract all relevant three-point correlation functions from the single-spin and single-charge images. (b) Measured three-point correlations on equilateral triangles for various values of the interaction parameter η (rounded for readability). Markers: measured three-point correlations. Shaded areas: experimental results obtained from Eqs. (5)–(7) using two-point correlations, showing very good agreement with three-point correlations. Dashed lines: BCS prediction. Solid lines: AFQMC calculations at the same reduced temperatures as in the experiments. These show very good agreement for $\eta \lesssim 2$, as well as in the crossover when $k_F r \gtrsim 2$. The observed discrepancies at short distance are expected due to interaction-induced population of excited z levels, leading to an offset in $g_{\uparrow\uparrow\uparrow}$ and an enhanced rise of g_{nnn} and $g_{\uparrow\uparrow\downarrow}$. The small difference in the values of η with respect to Fig. 2 is due to the use of a slightly larger region of the cloud to measure g_3 (see Ref. [40]).

$0.98^{+0.09}_{-0.09}$, $0.66^{+0.06}_{-0.06}$, and $0.28^{+0.06}_{-0.08}$, at reduced temperatures, $T/T_F = 0.18(2)$, $0.16(1)$, $0.11(1)$, $0.09(1)$, $0.09(1)$, $0.08(1)$, and $0.08(1)$, respectively. The effect of interactions is immediately visible in the upshoot of g_{nn} at short distance that increases with the attraction. This signals the formation of increasingly tight $\uparrow\downarrow$ pairs as one moves from the BCS toward the BEC side. A close-up of these correlations for representative values of η is shown in Fig. 2(b) (see also extended data in Ref. [40]), and reveals their highly nonlocal nature with prominent anticorrelations at a length scale $\sim 2k_F^{-1}$. In the absence of interaction, the spin- $\uparrow$ and spin- $\downarrow$ components are uncorrelated; hence $g_{\uparrow\downarrow}(r) = 1$, and $g_{nn}(r) = [g_{\uparrow\uparrow}(r) + 1]/2$ tends to $1/2$ at $r = 0$.

Our data is compared to both BCS mean-field theory (at $T = 0$), and AFQMC calculations performed at the experimentally determined interaction strength η and reduced temperature T/T_F . Remarkably, BCS theory already fails at $\eta \approx 7.8$, incorrectly predicting a nearly uncorrelated gas behavior. Moving toward the center of the crossover, we observe a net violation of BCS theory's constraint $g_{\uparrow\downarrow} \geq 1$ [52]. Our measured pair correlations display a marked dip at $k_F r \sim 2$, reaching values well below 1, which is also present in the AFQMC calculations. This pair-correlation dip signals a correlation beyond independent pairs and is a nontrivial signature in interacting Fermi gases.

Quantitatively, excellent agreement is found between experiments and AFQMC calculations for $\eta \approx 7.8$ and 3.7

when the samples are well in the 2D regime [40]. For smaller values of η , which are closer to the crossover, the large interaction energy allows fermions to occupy higher motional z levels of the vertical confinement, not taken into account in the simulations. The exact role of the third dimension, which relates to important questions in the context of quasi-2D superconductivity [12] and is a source of interesting theoretical opportunities [53,54], will be the subject of future work. The occupation of higher z levels is evidenced in the measured $g_{\uparrow\uparrow}$ correlations [Fig. 2(b), first row] by an offset at $r = 0$, whose value is a measure of the excited states population [51]. In the strictly 2D case, our AFQMC calculations show that $g_{\uparrow\uparrow}$ is indistinguishable from the one of an ideal Fermi gas at the corresponding temperature [40] for all interaction values considered here. This is in stark contrast to the result of BCS theory [see Fig. 2(b), first row], which predicts that the Fermi hole shrinks significantly near the crossover. Instead, we find that all the way from the far BCS side to the middle of the crossover near $\eta = 0$, particles organize themselves in a remarkable manner where each spin component displays two-point correlations that are indistinguishable from those of an ideal Fermi gas [40], while ensuring strong interspin correlations. This raises the fundamental question of whether higher order correlations contain any information that is not already contained in the two-point equal-spin and pair correlations.

To partially address this question we measure the charge, equal-spin, and interspin three-point correlations functions from the same samples. We focus on correlations between three equidistant fermions, which only depend on a single spatial parameter $k_F r$, with r the distance between each pair. This symmetry, which is native to our triangular pinning lattice [40], has the crucial advantage to make all six interspin correlations equivalent [see Fig. 3(a)], and one can show that

$$g_{nnn}(r) = \frac{1}{4}g_{\uparrow\uparrow\uparrow}(r) + \frac{3}{4}g_{\uparrow\uparrow\downarrow}(r), \quad (4)$$

where g_{nnn} , $g_{\uparrow\uparrow\uparrow}$, and $g_{\uparrow\uparrow\downarrow}$ are defined according to the same convention as their two-point counterparts in Eq. (2). As previously, g_{nnn} and $g_{\uparrow\uparrow\uparrow}$ are directly measured from the images, while $g_{\uparrow\uparrow\downarrow}$ is retrieved via Eq. (4), which is only possible owing to the symmetries of the equilateral triangle. Our results are reported in Fig. 3(b) for $\eta = 7.72^{+0.39}_{-0.35}$, $2.04^{+0.14}_{-0.15}$, $0.94^{+0.13}_{-0.12}$, $0.61^{+0.11}_{-0.10}$, and $0.22^{+0.10}_{-0.11}$ at reduced temperatures $T/T_F = 0.19(2)$, $0.12(1)$, $0.10(1)$, $0.09(1)$, and $0.08(1)$, respectively. In contrast to the case of two-point correlations, the prediction of BCS theory agrees well with our data and the AFQMC calculations up to $\eta \approx 2$, and only starts failing in the crossover, displaying the wrong trend for $k_F r \lesssim 3$. The observed rise of the measured charge and interspin correlations at short distance strikingly contradicts the drop to zero of the BCS result. We expect the presence of interaction-induced occupation of z levels to enhance correlations at short distances, but the possibility of a true divergence already present in strictly 2D systems cannot be excluded. While one may argue that the proximity of a pair of equal spins should necessarily result in the vanishing of these correlations at short distances, this argument was invalidated in 3D, where it was shown analytically that the interspin three-point correlation diverges at short distances [55]. The question is not answered in 2D. AFQMC calculations also do not capture the rapid rise of the measured g_{nnn} and $g_{\uparrow\uparrow\downarrow}$ in the crossover, which we attribute to the presence of interaction-induced occupation of z levels, but the agreement is nonetheless very good down to $k_F r \sim 2$, and the upturn displayed by the calculations might be the precursor of a true divergence. Our observations call for analytical and experimental studies of the short-range behavior of three-point correlations in 2D Fermi gases and a more complete characterization of three-point correlations in a generic geometry.

To evaluate the extent of the dependence of three-point correlation functions on the two-point ones, we compute the following quantities using the measured correlations:

$$\tilde{g}_{\uparrow\uparrow\uparrow}(r) = 3g_{\uparrow\uparrow\uparrow}(r) + 2[1 - g_{\uparrow\uparrow}(r)]^{3/2} - 2, \quad (5)$$

$$\begin{aligned} \tilde{g}_{nnn}(r) &= \frac{3}{2}[g_{\uparrow\uparrow}(r) + g_{\uparrow\downarrow}(r)] \\ &\quad + \frac{3}{2}[g_{\uparrow\uparrow}(r) - g_{\uparrow\downarrow}(r)]\sqrt{1 - g_{\uparrow\uparrow}(r)} \\ &\quad + 2[1 - g_{\uparrow\uparrow}(r)]^{3/2} - 2, \end{aligned} \quad (6)$$

$$\begin{aligned} \tilde{g}_{\uparrow\uparrow\downarrow}(r) &= g_{\uparrow\uparrow}(r) + 2g_{\uparrow\downarrow}(r) \\ &\quad + 2[g_{\uparrow\uparrow}(r) - g_{\uparrow\downarrow}(r)]\sqrt{1 - g_{\uparrow\uparrow}(r)} \\ &\quad + 2[1 - g_{\uparrow\uparrow}(r)]^{3/2} - 2. \end{aligned} \quad (7)$$

These relations are conjectured based on the Wick theorem, which applies to noninteracting or weakly interacting Fermi gases, but is expected to fail in the strongly interacting regime. The obtained results are reported in Fig. 3(b) as shaded areas. Remarkably, measured three-point correlations $g_{\uparrow\uparrow\uparrow}$, g_{nnn} , and $g_{\uparrow\uparrow\downarrow}$ agree to a high degree with the $\tilde{g}_{\uparrow\uparrow\uparrow}(r)$, $\tilde{g}_{nnn}(r)$, and $\tilde{g}_{\uparrow\uparrow\downarrow}(r)$ obtained from the measured two-point correlations via Eqs. (5)–(7). This observation should not, however, be interpreted as the Wick theorem being valid here, and we have verified using the AFQMC calculations that Wick relations involving the lowest order correlations fail in the crossover [40]. Instead this result signals that three-point correlations do not contain additional information compared to the two-point ones. A complete interpretation of the strongly correlated nature of the system requires investigating even higher order correlations, and specifically the role of pair-pair correlations. These open questions can be readily addressed with our combined experimental and computational capabilities.

We now turn to the short-range behavior of the pair-correlation function, which reads [56]

$$g_{\uparrow\downarrow}(r) \underset{r \rightarrow 0}{=} \frac{C}{k_F^4} \log^2 \left(\alpha \frac{r}{a} \right), \quad (8)$$

where $\alpha = e^\gamma/2$ and γ is Euler's constant. While this scaling is fully determined by two-body physics, the value of the coefficient C , the contact, is set by the many-body behavior of the system and depends on the interaction strength η . The contact represents an important overarching quantity, connecting the microscopic and macroscopic behavior of the system [57]. Equation (8) shows that the contact is linked to the probability of finding two opposite spins within a probe volume whose characteristic length is smaller than the relevant length scales of the system, k_F^{-1} and a . In our experiment, the lattice sites after projection constitute natural probe volumes to measure pair occupations. Owing to the extreme diluteness of our samples, the occupation of a lattice site by three or more particles is strongly suppressed, and the only relevant events are the single and double occupancies. Double occupancies are dominated by $\uparrow\downarrow$ pairs, since the probability for equal-spin pairs is strongly reduced by Pauli's exclusion principle. To

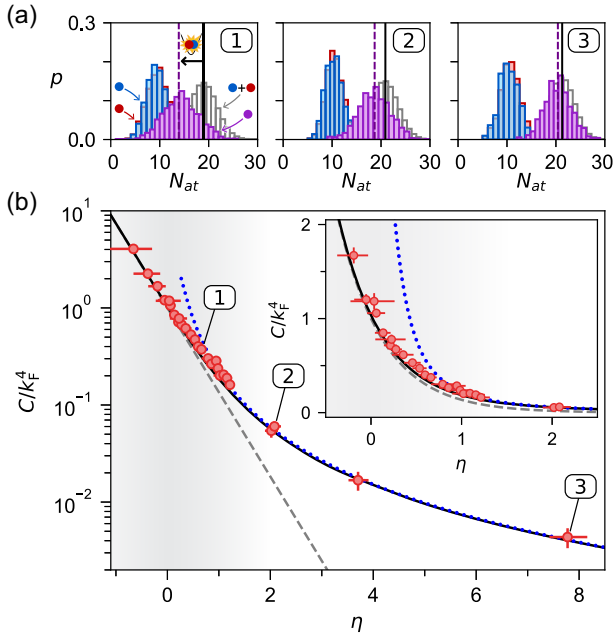


FIG. 4. Contact density. (a) Distribution of the atom number for spin $\uparrow$ (red), spin $\downarrow$ (blue) and both spins (purple) in a central subregion of the cloud for $\eta \approx 0.7, 2.1$, and 7.8 . The solid black line is the sum of the average atom number in state $\uparrow$ and in state $\downarrow$. The dashed purple line is the average atom number in images where no atoms are removed. In gray, we show the expected histogram for $N_{\uparrow} + N_{\downarrow}$ in the absence of light-assisted collisions. For increasing attraction, losses due to double occupancies become larger and yield a direct measure of the probability to find a $\uparrow\downarrow$ pair on the same site. (b) Contact density as a function of η . The contact density is measured via losses in different quasihomogeneous subregions of the cloud that correspond to different values of the interaction parameter η . The gray dashed line is the BCS mean-field prediction $1/(k_F a)^2$. The blue dotted line is obtained from Fermi-liquid theory [58]. The solid line is the result of AFQMC calculations at $T = 0$ [36]. Inset: linear scale contact density in the crossover.

count the number of $\uparrow\downarrow$ pairs per lattice site, we exploit light-induced losses that occur during imaging when two atoms occupy the same site, a known detrimental effect of quantum gas microscopy that we are able to turn here into a powerful probe of the contact parameter. By comparing the average atom numbers in single-spin and charge images respectively [see Fig. 4(a)], we infer the number of lost atoms, and therefore the probability to find a $\uparrow\downarrow$ pair per lattice site, taking into account the residual contribution of the equal-spin double occupancies [40]. The resulting contact measurement as a function of interaction strength is shown in Fig. 4, which we compare to zero-temperature AFQMC calculations [36], finding excellent agreement over 3 orders of magnitude. The comparison obtained here sets a new standard of cross-validation between experimental measurements and high-precision computations for microscopic phenomena in continuum systems.

We have probed an interacting Fermi gas with tuneable interspin attraction via atom-resolved *in situ* imaging,

directly observing fermion pairing and the spatial form of all relevant two- and three-point correlation functions. Our continuum quantum gas microscopy technique allowed us to probe these correlations at length scales below the interparticle spacing. We obtained a characterization of the system at the microscopic level with unprecedented precision, revealing critical deviations from BCS theory in both the superfluid crossover regime and the weakly attractive side, and we found a relationship between two- and three-point correlations that underscores the dominant role of pair correlations. We compared our measurements with numerically exact AFQMC computations, confirming their key qualitative features and finding excellent quantitative agreement when the systems are directly comparable. Our Letter, which combines atom-resolved experimental measurements and AFQMC calculations, can be readily extended to the study of fourth or higher order correlations and the finite temperature regime just above the normal-to-superfluid transition and beyond. A crucial direction is the exploration of strongly interacting fermions with unequal spin populations or repulsive interactions, where accurate computations are significantly more challenging. The experimental advances demonstrated here add a powerful dimension to the study of correlated quantum systems in the continuum and offer a unique opportunity to obtain a profound understanding of their microscopic inner workings.

Note added—We recently became aware of other work on quantum gas microscopy in the continuum [59,60].

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The authors declare no competing interests.

Data availability—The data that support the findings of this article are openly available [61].

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