Editors' Suggestion

Observing the Influence of Reduced Dimensionality on Fermionic Superfluids

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(Received 7 December 2021; accepted 28 June 2022; published 17 August 2022)

Understanding the origins of unconventional superconductivity has been a major focus of condensed matter physics for many decades. While many questions remain unanswered, experiments have found the highest critical temperatures in layered two-dimensional materials. However, to what extent the remarkable stability of these strongly correlated 2D superfluids is affected by their reduced dimensionality is still an open question. Here, we use dilute gases of ultracold fermionic atoms as a model system to directly observe the influence of dimensionality on the stability of strongly interacting fermionic superfluids. We find that the superfluid gap follows the same universal function of the interaction strength regardless of dimensionality, which suggests that there is no inherent difference in the stability of two- and three-dimensional fermionic superfluids. Finally, we compare our data to results from solid state systems and find a similar relation between the interaction strength and the gap for a wide range of two- and three-dimensional superconductors.

DOI: 10.1103/PhysRevLett.129.083601

Fermionic particles such as the electrons in superconductors have half-integer spin and therefore obey the Pauli exclusion principle. This prevents systems of noninteracting fermions from condensing into a macroscopic wave function and becoming superfluid. However, in the presence of an effective attractive interaction it can become energetically favorable for fermions with opposite spin to form bosonic pairs. These pairs can then condense into a coherent many-body state and become superfluid, as laid out by Bardeen, Cooper, and Schrieffer (BCS) in their famous theory of superconductivity [1]. The energy that is required to break one of these pairs is called the superfluid gap Δ, as the pairing manifests itself as a gap in the excitation spectrum of fermionic superfluids. Since breaking the pairs destroys the superfluid, the size of this gap determines the stability of the superfluid and sets its critical temperature.

Over the last decades, new classes of superconductors have been discovered that exhibit higher critical temperatures and stronger interactions than conventional BCS superconductors [2]. Of particular interest are systems where superfluidity occurs in two-dimensional structures, as they are the ones where the highest ambient-pressure critical temperatures have been observed [3]. This raises interesting questions about the role of dimensionality in these systems, as thermal fluctuations prohibit true long-range order in two dimensions [4], and superfluidity is only restored through the Kosterlitz-Thouless mechanism [5]. However, as the dimensionality of these systems cannot be changed without dramatically altering their other properties as well, it is unclear to what extent the surprising stability of their superfluidity is affected by their two-dimensional nature [6].

In this Letter, we directly observe the effect of reduced dimensionality on the stability of strongly interacting fermionic superfluids. We measure the superfluid gap of a quasi-2D Fermi gas as a function of interaction strength and compare the results with our recent measurement of the gap in a three-dimensional system [7]. We find that the superfluid gap follows the same universal function of the chemical potential in both systems, which suggests that dimensionality has only limited influence on the stability of strongly interacting fermionic superfluids.

For our experiments, we use ultracold atomic Fermi gases of ^{6}Li atoms. Such gases have two key advantages that make them uniquely suited for performing experiments that isolate the effect of dimensionality on the stability of superfluids: The first is that they are systems with simple and well-understood interparticle interactions that can be easily tuned using Feshbach resonances [56]. The second is that the dimensionality of the system can be controlled freely by changing the shape of the confining potential [57–64]. By combining these two features, we can create systems that have the same microscopic physics but different dimensionality.

To perform a quantitative comparison between these systems, we examine the effect of the reduced dimensionality on the superfluid gap. The gap is well suited for this purpose, as it directly determines both the critical current and the critical temperature of a fermionic superfluid and thus constitutes an excellent measure for its stability. As reliable measurements of the gap are available for three-dimensional Fermi gases [7,65,66], we can focus our experiments on measuring the gap in two-dimensional systems [67].

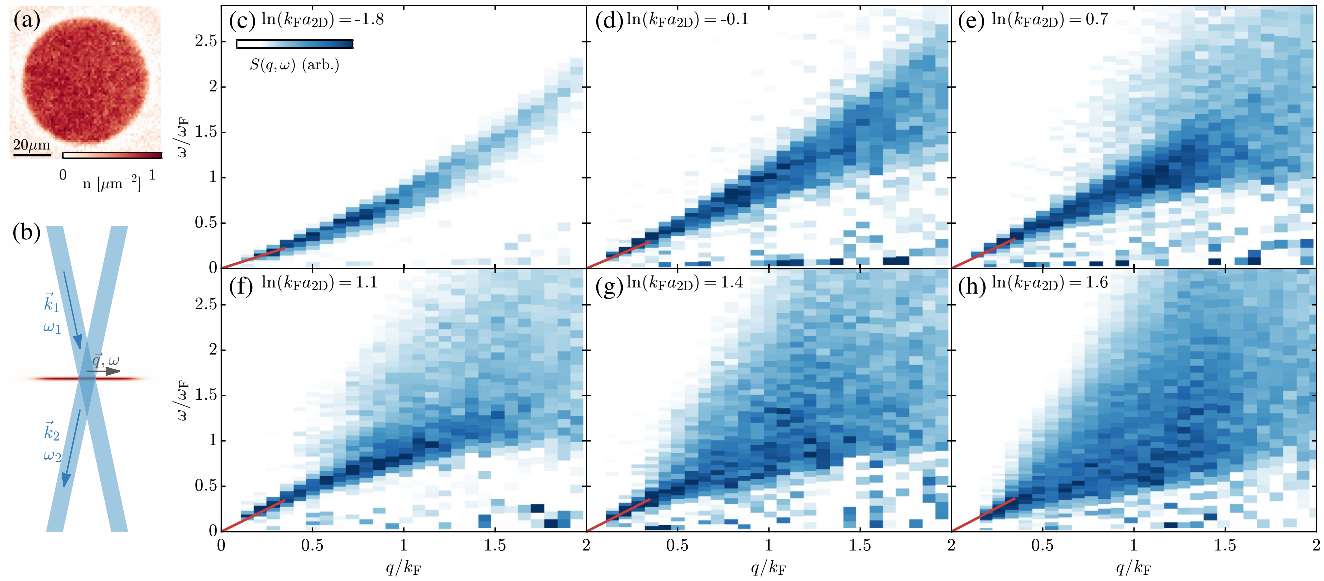

FIG. 1. Excitation spectrum of a 2D Fermi gas in the BEC-BCS crossover. (a) Absorption image showing the density $n(\vec{r})$ of our homogeneous quasi-2D Fermi gas. (b) Sketch of the experimental setup for measuring the excitation spectrum of our system. Two far-detuned laser beams drive a two-photon transition with energy and momentum transfer $\hbar\omega = \hbar(\omega_1 - \omega_2)$ and $\hbar q = \hbar|\vec{k}_1 - \vec{k}_2|$, and the dynamic structure factor $S(q, \omega)$ can be obtained from the resulting heating rate. (c)–(h) Measurements of $S(q, \omega)$ taken at different values of the 2D interaction parameter $\ln(k_F a_{2D})$. For strong attractive interactions (c) the system consists of tightly bound molecules which are excited as unbroken pairs, and consequently $S(q, \omega)$ shows the Bogoliubov dispersion of an interacting Bose gas. Moving into the crossover regime [(d), (e), (f)], the pairs become more weakly bound and pair breaking excitations begin to appear at higher momenta. These excitations become more pronounced as we approach the BCS limit where the system shows the expected broad pair breaking continuum [(g), (h)]. In addition to these pair breaking excitations, it is also possible to excite sound waves in the superfluid. These appear in our spectra as a linear mode at low momenta, with a slope that corresponds to the speed of sound in the system and is in excellent agreement with previous measurements [red lines in panels (c)–(h), [8]]. The data in panel (a) [(c)–(h)] was obtained by averaging over 26 (3–8) individual measurements. The behavior observed in [(c)–(h)] closely resembles results obtained in 3D Fermi gases [7,9].

To bring our system into the two-dimensional regime, we apply a strong confining potential along one direction such that the chemical potential and temperature are well below the level spacing. This strongly suppresses all excitations in this direction and thereby creates a quasi-2D system [9,69–72].

We then measure the excitation spectrum of the gas to determine the size of the superfluid gap. We use momentum resolved Bragg spectroscopy to measure the dynamic structure factor $S(q, \omega)$ of the superfluid [77], which describes the probability of creating an excitation in the system by providing an energy and momentum transfer of $\hbar\omega$ and $\hbar q$ [Fig. 1(b)]. By tuning the strength of the interparticle interactions which is parametrized by the 2D interaction parameter $\ln(k_F a_{2D})$, we can perform such measurements throughout the crossover from a BCS superfluid of weakly bound Cooper pairs [$\ln(k_F a_{2D}) \gtrsim 1.5$] to a Bose-Einstein-condensate (BEC) of deeply bound molecules [$\ln(k_F a_{2D}) \lesssim -1.5$]. Here, a_{2D} is the 2D scattering length [69], $k_F = \sqrt{2mE_F}/\hbar$ is the Fermi wave vector, $E_F = \hbar\omega_F$ is the Fermi energy, and m is the mass of a ^{6}Li atom.

The results of these measurements are shown in Figs. 1(c)–1(h). We observe two different types of excitations [79]: The first are longer-range collective excitations of the superfluid, which are visible as a linear sound mode at low momentum transfers ($q \ll k_F$), with a slope that is in excellent agreement with the speed of sound measured in [8] [red lines in Figs. 1(c)–1(h)]. This is the Goldstone mode of the system, which arises from the breaking of the U(1) symmetry of the system when the gas condenses into a superfluid [66,81]. The second type of excitations are single-particle excitations that break a pair. As this process is only possible if the energy transfer is sufficiently high to overcome the energy gained from pairing, these excitations show a sharp onset at an energy transfer of 2Δ. This behavior is most apparent for BCS superfluids with weak attractive interactions [Figs. 1(g) and 1(h)], where a pronounced continuum of pair breaking excitations is clearly visible. When increasing the interparticle attraction, the size of the superfluid gap increases and, consequently, the onset of the pair breaking continuum shifts towards higher energies. Additionally, as the pairs are transformed from weakly bound Cooper pairs to tightly bound bosonic molecules, the onset of the pair breaking continuum moves towards higher momenta as pair breaking excitations are suppressed when the size of the pairs becomes small compared to the length scale of the perturbation [82,83]. This trend continues into the BEC regime, where the molecules are so tightly bound that pair breaking excitations become completely suppressed. The excitation spectrum then exhibits the well-known Bogoliubov dispersion relation of a superfluid Bose gas [see Fig. 1(c)].

To determine the superfluid gap Δ from our measurements, we determine the onset energy of the pair breaking continuum from these measurements. While the onset is partially masked by the presence of the Goldstone mode, it is nevertheless possible to extract the gap by measuring at low momentum transfers where phononic excitations are well separated from the continuum, or by integrating out the momentum axis if the weight of the continuum is sufficiently large [9]. The resulting values of the gap Δ are plotted in Fig. 2(c), together with the binding energy E_B of the bare two-body bound state (red line), which in 2D systems exists for any nonzero attractive interaction [70]. For smaller attractive interactions, the two-body binding energy is negligible, and the sizable gap of $\Delta \approx 0.3 E_F$ is entirely due to many-body effects. However, when going into the crossover regime, the trivial two-body binding energy increases and becomes comparable to the effect of the many-body BCS pairing. To separate these two contributions to the gap and thereby determine the evolution of the many-body contribution throughout the crossover, we subtract the known value of the two-body binding energy of a quasi-2D Fermi gas [70] from our measurements. As can be seen in Fig. 2(d), the many-body contribution $\Delta - E_B/2$ grows with increasing interactions in the BCS regime, reaches a maximum in the crossover regime and then decreases again towards the BEC side of the resonance, where the contribution of the two-body bound state begins to dominate as the gas turns into a BEC of deeply bound molecules. When comparing these results to theory, we find that they are in excellent agreement with mean-field theory [68] in the BCS regime, but begin to deviate from the mean-field results in the strongly correlated crossover region [$\ln(k_F a_{2D}) \approx 1$]. Quantum Monte Carlo (QMC) simulations [84–86] are in somewhat better agreement with our data in the crossover, but still predict larger values of $\Delta - E_B/2$ in the BEC regime.

We now proceed to compare our measurements to recent results from 3D Fermi gases. To perform such a comparison, we need to find a suitable parametrization of the interaction strength, as the dimensionless interaction parameters $\ln(k_F a_{2D})$ and $1/k_F a_{3D}$ that are commonly used in two- and three-dimensional systems parametrize the interactions differently and cannot be compared directly. Instead, we parametrize the interaction strength with the normalized chemical potential μ/E_F of the fermions. This choice is motivated by the fact that the chemical potential is a basic thermodynamic quantity that is defined independent of dimensionality and has monotonous and well-known relations to the 2D and 3D interaction parameters $\ln(k_F a_{2D})$ and $1/k_F a_{3D}$ [87,88,92,93]. Therefore, we can

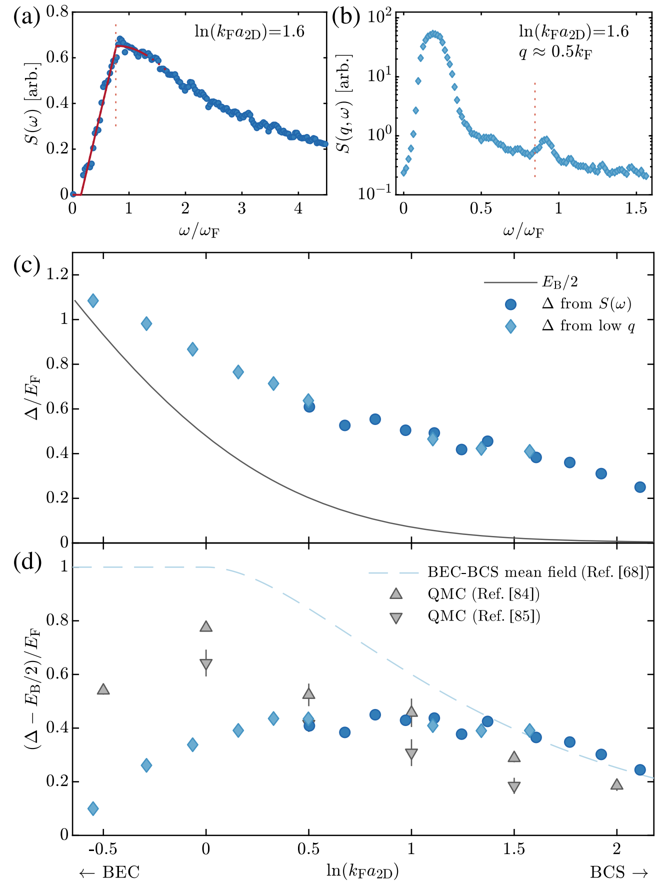

FIG. 2. Superfluid gap in the 2D BEC-BCS crossover. (a) Integrated dynamic structure factor $S(\omega) = \int S(q,\omega) q\, dq$ at an interaction strength of $\ln(k_F a_{2D}) = 1.6$, used to determine the gap Δ (dotted red line) from a phenomenological fit (solid red line) to the onset of pair breaking excitations at an energy of 2Δ [9]. (b) Dynamic structure factor $S(q,\omega)$ at a fixed momentum transfer of $q = 0.5 k_F$. At these small wave vectors, pair breaking is suppressed and strong driving is required to observe the onset of the pair breaking mode at 2Δ (dotted red line), which causes a strong saturation of the low-energy phononic mode [9]. (c) Measured superfluid gap Δ as a function of the interaction strength. The different symbols distinguish results obtained using the approaches shown in panel (a) [$S(\omega)$, blue dots] and (b) (low q, light blue diamonds). The contribution of the two-body bound state to the gap is shown as a solid line. (d) Many-body contribution $\Delta - E_B/2$ to the superfluid gap Δ. BEC-BCS mean field predictions (dashed line, [68]) are in agreement with our measurement in the BCS regime, but deviate in the strongly correlated crossover regime. Quantum Monte Carlo calculations (gray triangles, [84,85]) show better agreement in the crossover, but still deviate from the measurements in the BEC regime. Error bars denote 1σ confidence intervals of the fit and are smaller than the symbol size, the data shown in panels (a) [(b)] is the average of 8 (26) individual measurements.

perform our comparison by plotting the superfluid gap Δ/E_F as a function of the chemical potential μ/E_F for two- and three-dimensional systems. The results are shown in Fig. 3.

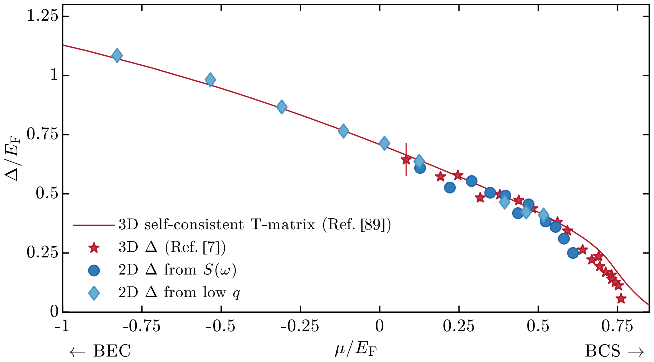

FIG. 3. Comparing the gaps of fermionic superfluids with different dimensionality. Superfluid gap Δ/E_F of quasi-2D (blue circles and diamonds) and 3D (red stars) Fermi gases as a function of the chemical potential μ/E_F taken from QMC calculations [87,88]. The measurements of the gap collapse onto a single curve, which is well described by theoretical predictions for the gap in three-dimensional Fermi gases (red line, [89,90]). Error bars denote 1σ confidence intervals of the fit.

Remarkably, we find that within the accuracy of our measurements, the results for Δ/E_F obtained for quasi-2D and 3D Fermi gases collapse onto a single curve. This suggests that for strongly interacting Fermi gases, the gap follows a single, universal function $f(\mu/E_F) = \Delta/E_F$ of the interaction strength that is independent of the dimensionality of the system. The function $f(\mu/E_F)$ appears to be well described by theoretical predictions for 3D Fermi gases [89], but qualitatively disagrees with theoretical predictions for 2D Fermi gases [9]. This discrepancy between our measurements and theoretical predictions for two-dimensional systems is unlikely to result from finite temperature effects or excitations along the tightly confined axis: Temperature effects are not expected to significantly affect the gap or the chemical potential as our system is well below the critical temperature, and excitations in the third direction would be expected to affect only the data in the BCS regime [9]. Consequently, our measurements imply that for a given coupling strength, there is no inherent difference in the stability of fermionic superfluidity between two- and three-dimensional quantum gases.

As we perform our experiments in an ideal model system, it is natural to ask to what extent our results apply to other, more complex materials. However, while the chemical potential provides an excellent measure for the interaction strength in our strongly interacting quantum gases, there are a large number of materials where it is not known with sufficient accuracy to be used as a parametrization of the interaction strength. To overcome this limitation, we make use of the dimensionless pair size ξk_F as an alternative parametrization of the interaction strength [68,94–97], for which we obtain an estimate from the onset of pair breaking excitations at a characteristic momentum in our measured dynamic structure factors [9]. We plot the resulting values of ξk_F as a function of μ/E_F and find that

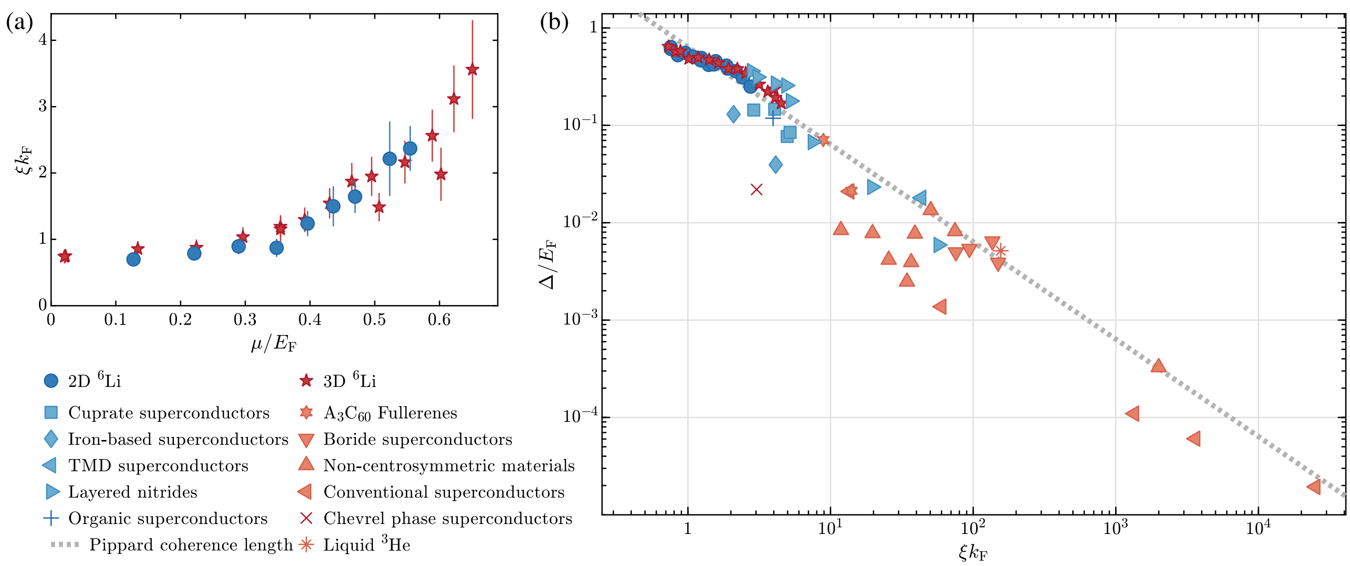

FIG. 4. Fermionic superfluidity in different materials. (a) Dimensionless pair size ξk_F plotted as a function of the dimensionless chemical potential μ/E_F. As ξk_F follows the same function of μ/E_F regardless of dimensionality, ξk_F can be used as an alternative parametrization of the interaction strength in our strongly interacting Fermi gases. Error bars denote 1σ confidence intervals. (b) Plot of the dimensionless gap Δ/E_F against the dimensionless pair size ξk_F for different fermionic superfluids. The Pippard coherence length $\xi_p = (\hbar^2 k_F/\pi m \Delta)$ [91] is shown as a dotted line. Remarkably, the superfluid gap is roughly proportional to the inverse of the dimensionless pair size for a wide range of materials that span 5 orders of magnitude in Δ/E_F and ξk_F. This observation applies equally to two- and three-dimensional systems, which suggests that strong correlations are more important for the stability of fermionic superfluids than the dimensionality of the system.

the results for the two- and three-dimensional systems collapse onto a single curve [Fig. 4(a)], indicating that the two parameters represent an equivalent mapping between 2D and 3D interaction strengths [97].

Consequently, we can now plot our measurements of the gap Δ/E_F as a function of the pair size ξk_F and compare the results to a wide variety of different superconductors [9]. The results are shown in Fig. 4(b). Remarkably, all materials fall into a single band, which extends from conventional superconductors with gaps on the order of 10^{-5} E_F and large coherence lengths to ultracold Fermi gases with gaps comparable to the Fermi energy and coherence lengths approaching the interparticle spacing, with a wide variety of exotic superconductors in between. Figure 4(b) therefore clearly shows a direct correlation between shorter coherence lengths and larger gaps [2,94] that holds from the weak coupling limit all the way into the strongly correlated regime. This correlation exists independent of the dimensionality of the material, in excellent agreement with our observations in ultracold Fermi gases. Therefore, our findings suggest that there is no inherent increase in the stability of a fermionic superfluid in two dimensions compared to a three-dimensional system with the same coupling strength.

In this Letter, we have used measurements of the excitation spectrum of strongly interacting ultracold Fermi gases to determine the superfluid gap and found that the gap follows a universal function of the interaction strength that is unaffected by the dimensionality of the system. By extending the comparison to other fermionic superfluids, we have shown that this observation appears to hold for a wide range of two- and three-dimensional systems. Consequently, our results suggest that there is no inherent increase in the stability of the superfluid phase in lower dimensions. Our results highlight that ultracold Fermi gases and strongly correlated superconductors can be realized at similar effective interaction strengths [98,99], enabling comparative studies of, e.g., the transition from a superfluid to a strongly correlated normal state at the critical temperature in a model system free from competing order parameters [3,100–102].

We thank G. Salomon, J. P. Brantut, and L. Mathey for helpful comments on the manuscript. This work is supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) in the framework of SFB-925—project 170620586—and the excellence cluster "Advanced Imaging of Matter"—EXC 2056—project ID 390715994.

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