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Excitation Spectrum and Superfluid Gap of an Ultracold Fermi Gas

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Ultracold atomic gases are a powerful tool to experimentally study strongly correlated quantum many-body systems. In particular, ultracold Fermi gases with tunable interactions have allowed to realize the famous BEC-BCS crossover from a Bose-Einstein condensate (BEC) of molecules to a Bardeen-Cooper-Schrieffer (BCS) superfluid of weakly bound Cooper pairs. However, large parts of the excitation spectrum of fermionic superfluids in the BEC-BCS crossover are still unexplored. In this work, we use Bragg spectroscopy to measure the full momentum-resolved low-energy excitation spectrum of strongly interacting ultracold Fermi gases. This enables us to directly observe the smooth transformation from a bosonic to a fermionic superfluid that takes place in the BEC-BCS crossover. We also use our spectra to determine the evolution of the superfluid gap and find excellent agreement with previous experiments and self-consistent T-matrix calculations both in the BEC and crossover regime. However, toward the BCS regime a calculation that includes the effects of particle-hole correlations shows better agreement with our data.

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Quantum many-body systems are ubiquitous in nature, but unless they are weakly interacting, their theoretical treatment can be extremely challenging. An elegant solution to this problem was suggested by Landau, who realized that the low-energy excitation spectrum of a wide range of many-body systems can be understood in terms of particlelike excitations, which are adiabatically connected to the excitations of a noninteracting system [1]. The residual interaction between these so-called quasiparticles in turn leads to the presence of collective modes, which have no counterpart in noninteracting systems. Landau's quasiparticle theory has been spectacularly successful and is an indispensable tool for the description of interacting many-body systems [2].

For an interacting Fermi gas, the relevant quasiparticles are particle-hole excitations, where one particle is removed from the Fermi sea and a hole is created in its place. If the Fermi gas is below the critical temperature for BCS superfluidity, this requires the breaking of a Cooper pair and the excitation has to overcome the pairing gap Δ. The second type of excitations in the system are collective excitations of the superfluid, which correspond to Bogoliubov-Anderson phonons and form the Goldstone mode of the system [3,4].

Experimentally, these physics can be studied using ultracold Fermi gases, where the strength of the interparticle interactions can be controlled via Feshbach resonances [5]. This makes it possible to adiabatically convert a BCS superfluid [6] of weakly bound Cooper pairs into a BEC of molecules [7,8]. After the first observation of this BEC-BCS crossover in [9–12], various measurements of the change of the macroscopic properties of ultracold Fermi gases in the BEC-BCS crossover have been performed. Starting from studies of collective oscillations [13,14], experiments progressed to measurements of the speed of sound [15] and critical velocity [16,17], and finally culminated in measurements of the equation of state [18–21]. Remarkably, the evolution of all these macroscopic quantities of the system can be linked to a single microscopic property of the system: the size of the fermion pairs, which shrink from weakly bound Cooper pairs on the BCS side of the crossover to tightly bound molecules in the BEC regime. The properties of these pairs, including the pairing gap, have been explored by probing the excitation spectrum with techniques such as rf spectroscopy [22–25], fixed-momentum Bragg spectroscopy [26,27] and rf dressing [28]. However, no measurement of the full low-energy excitation spectrum of fermionic superfluids in the BEC-BCS crossover has been performed.

In this work, we use momentum-resolved Bragg spectroscopy to measure the excitation spectrum of a homogeneous ultracold Fermi gas. This allows us to directly observe the evolution of both single-particle excitations and collective modes in the BEC-BCS crossover. From our observations of the collective mode, we extract the speed of sound in the system, while the shifting onset of the pair breaking continuum reveals the evolution of the superfluid gap throughout the BEC-BCS crossover. Finally, we compare current state-of-the-art theories with our measurement of the gap.

For our experiments, we use an ultracold gas of ^{6}Li atoms [Fig. 1(b)] in a balanced spin mixture of the lowest two hyperfine states. We follow an approach similar to the one taken in [29,30] and trap the gas in a cylindrical box potential whose walls are formed by blue-detuned laser beams. This results in a system with an almost constant density per spin state of $n \approx 0.4/\mu\mathrm{m}^3$, which corresponds to a Fermi energy of $E_F \approx h \times 7$ kHz. The strength of the interparticle interactions is parametrized by the dimensionless parameter $1/k_F a$, where a is the s-wave scattering length and $k_F = (6\pi^2 n)^{1/3}$ the Fermi wave vector. The temperature of homogenous Fermi gases in the BEC-BCS crossover is challenging to measure [31], but for systems with an interaction strength of $1/k_F a = 0$ a technique based on measuring the total energy of the gas has been developed [32]. For our system this approach gives us an estimate of $T/T_F \approx 0.13$, where T is the temperature and $T_F = E_F/k_B$ is the Fermi temperature of the gas.

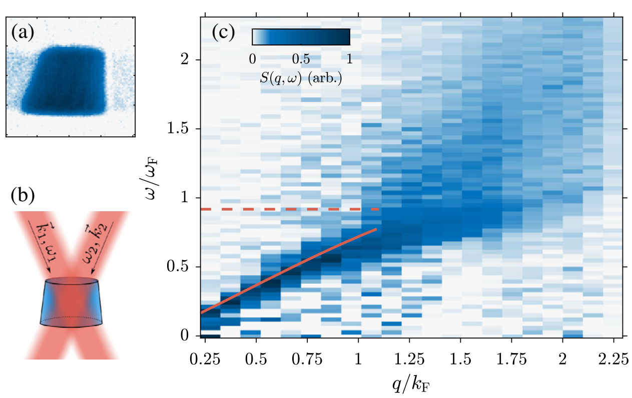

FIG. 1. Measuring the excitation spectrum of an ultracold Fermi gas using Bragg spectroscopy. (a) Absorption image of a homogeneous Fermi gas trapped in an approximately cylindrical box potential. (b) Sketch of the experimental setup. Two far-detuned laser beams with frequency and wave vector $(\omega_1, \vec{k}_1)$ and $(\omega_2, \vec{k}_2)$ are used to create excitations with energy and momentum transfer $\hbar\omega = \hbar\omega_1 - \hbar\omega_2$ and $\hbar q = |\hbar\vec{k}_1 - \hbar\vec{k}_2|$ through a two-photon process. (c) Measurement of the dynamic structure factor $S(q,\omega)$ of a unitary Fermi gas. At low energy and momentum transfer, the Goldstone mode of the superfluid manifests itself as a linear phononic mode with a slope that corresponds to the speed of sound v_s. Pair breaking excitations occur as a broad continuum, with a clear onset at an energy corresponding to twice the pairing gap Δ of the system. For comparison, the expected value of 2Δ on unitarity [33] is shown as a red dashed line, a numerical calculation of the center of the Goldstone mode is shown as a red solid line [34]. All data shown in this Letter are obtained by averaging over 7–40 individual measurements.

To measure the excitation spectrum of our system, we employ an experimental technique called Bragg spectroscopy [43–45]. This technique is based on applying two laser beams that are far detuned from the atomic transition so that single-photon scattering is strongly suppressed. However, stimulated scattering processes, where a photon from one beam is scattered into the other, can occur if the difference in energy and momentum between the absorbed and emitted photon is transferred to the atoms [Fig. 1(a)]. These two-photon scattering events therefore are only possible if the many-body system allows for the creation of excitations at this specific combination of transferred energy $\hbar\omega$ and momentum $\hbar q$. By applying such Bragg beams and measuring the resulting heating rate dE/dt, we obtain the dynamic structure factor $S(q,\omega) \propto \omega^{-1} dE/dt$ [46], which quantifies the probability for an excitation with energy $\hbar\omega$ and momentum $\hbar q$ to be created and therefore describes the excitation spectrum of the system [34].

For our first measurement, we prepare our gas at the so-called unitary point where the scattering length diverges and $1/k_F a = 0$. At this point, the only relevant length scale in the system is the inverse Fermi momentum $1/k_F$ and the system becomes scale invariant [8,47]. The gas is also very strongly interacting, with a collision rate that is comparable to the inverse Fermi time E_F/h of the system. This unitary Fermi gas is a canonical problem in many-body physics that was first posed in the context of neutron matter, and has come under intense experimental study with the development of ultracold Fermi gases.

Our measurement of the dynamic structure factor of the unitary Fermi gas is shown in Fig. 1(c). The two distinct types of excitations discussed above are immediately visible. First, there is a narrow, well-defined mode whose energy is approximately proportional to its momentum, which we identify as the sound mode of the Fermi gas. For very low energies, where collisions have time to restore local thermal equilibrium, it can be understood in terms of hydrodynamics [48], whereas for higher frequencies or weaker coupling strengths it is a Goldstone mode [26,27] that is driven by phase fluctuations of the superfluid order parameter.

The second type of excitations are single-particle excitations in which an atom is lifted out of the Fermi sea and a particle-hole excitation is created. These particle-hole excitations appear as a broad continuum in our spectra, as each particle inside the Fermi sea can be excited to any unoccupied state if it receives the proper combination of energy and momentum transfer. However, as the fermions are paired, this requires an energy of at least twice the pairing gap Δ, resulting in a well-defined onset of the continuum. The overall behavior of our measured dynamic structure factors is in excellent agreement with theoretical expectations [49]; a comparison to a quasiparticle random-phase approximation calculation of $S(q,\omega)$ is shown in the Supplemental Material [34].

While in the limits of small or large momentum transfer the response of the system can be clearly identified as either a collective or single-particle excitation, there is a range of intermediate momenta where this is not as straightforward. In particular, as the collective mode approaches the pair breaking continuum it no longer follows the linear slope given by the speed of sound and instead starts to bend down. This behavior is reminiscent of an avoided crossing with the onset of the pair breaking continuum, and indicates the existence of a coupling between the Goldstone mode and the excitation of single particles from the superfluid via pair breaking. Such a coupling has been predicted by theory [26,49–51], but had not yet been observed in experiments.

After examining the general structure of the excitation spectrum, we now proceed to measure the dynamic structure factor at interaction strengths ranging from the deep BEC to the BCS regime. The results are displayed in Fig. 2 and clearly show the evolution of the superfluid throughout the BEC-BCS crossover.

Our first observation is that the collective mode is present throughout the entire BEC-BCS crossover. This is a direct consequence of the fact that the presence of a well-defined Goldstone mode is a fundamental feature of any neutral superfluid [26,27,52]. In contrast, the nature of the single-particle excitations changes completely when going across the crossover. On the BCS side of the resonance [Figs. 2(e), 2(f)], the pairs are large and weakly bound and we observe a broad continuum of pair breaking excitations. This continuum becomes less pronounced as the pairs become more tightly bound in the crossover regime and completely disappears from our spectra in the BEC regime [Figs. 2(a), 2(b)]. This is caused by the pairs turning into deeply bound molecules, which are only broken at very high energy and momentum transfers. Consequently, when going toward the BEC regime, pair breaking is gradually replaced by a different single-particle excitation where a single unbroken molecule is ejected from the condensate.

This behavior directly shows the evolution of our system from a BCS superfluid of weakly bound Cooper pairs to a BEC of deeply bound molecules. In the following, we discuss the properties of the collective mode and the pair breaking continuum in more detail and use them to extract quantitative information about our system.

First, we consider the behavior of the collective mode, whose curvature has important consequences for the damping processes allowed in the system and has been a topic of intense theoretical discussion [53,54]. We follow [55–57] and fit the dispersion with an expression of the form $\omega(q) = v_s q(1+\zeta q^2)$, examples are shown in

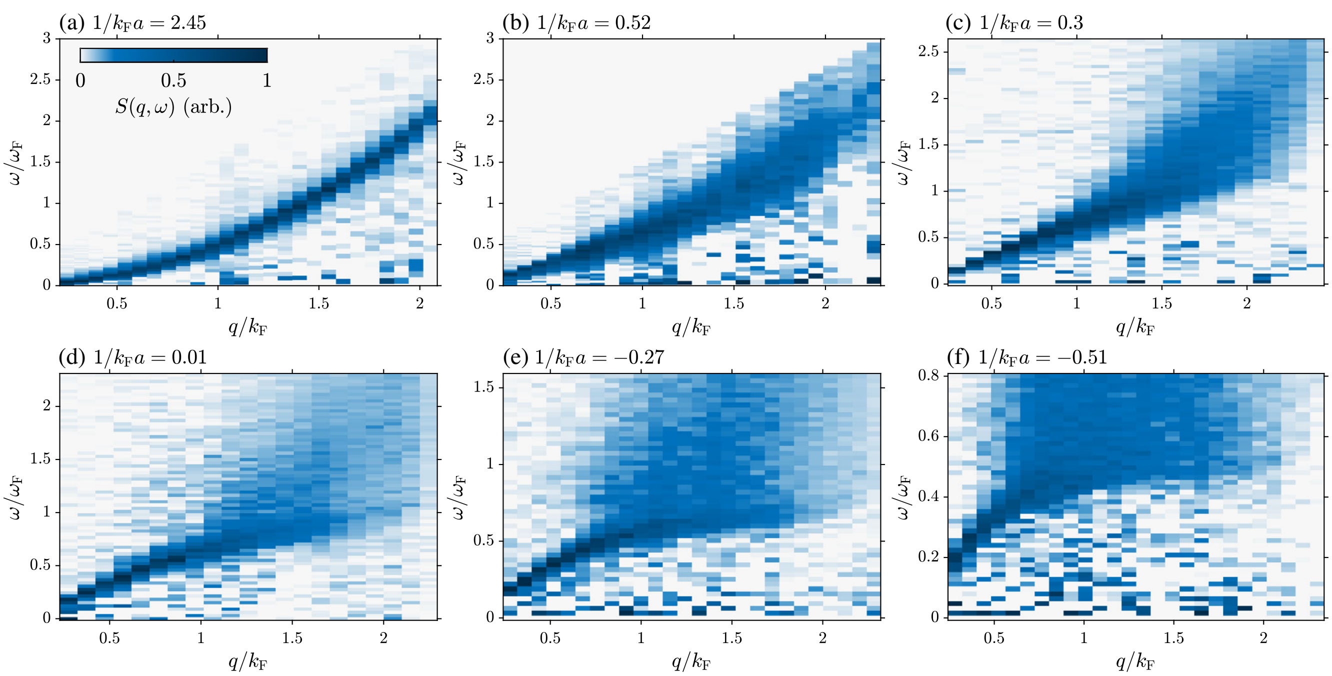

FIG. 2. Evolution of the excitation spectrum in the BEC-BCS crossover. (a) In the deep BEC regime, the excitation spectrum follows the Bogoliubov dispersion of an interacting Bose gas, with a linear sound mode at low momenta and a quadratic dispersion of single-molecule excitations at high momenta. (b),(c) When moving into the crossover regime, the compressibility of the system decreases, and consequently the linear branch has a steeper slope and persists to higher momenta. At the same time, the high-momentum part of the dispersion shows a strongly reduced curvature and starts to broaden, which indicates the transition to pair breaking excitations. (d) At the unitary point, there is already a strong pair breaking continuum, which becomes even more pronounced when going further into the BCS regime (e),(f).

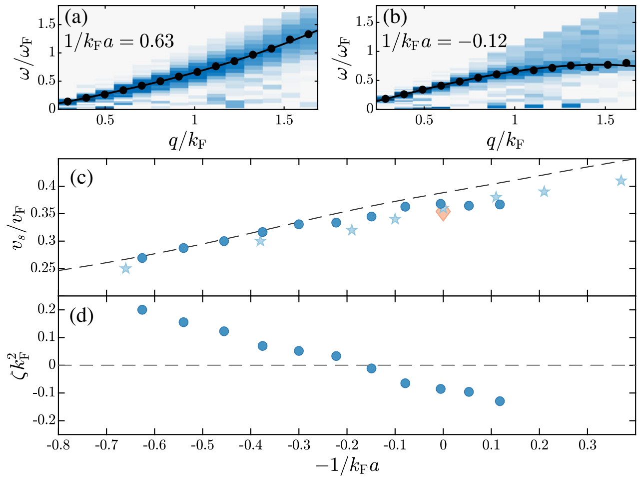

FIG. 3. Measurements of the collective mode on the BEC (a) and BCS (b) side of the resonance. The black dots show the fitted center of the collective mode for each momentum slice; the black line is a fit according to the equation $\omega = v_s q(1 + \zeta q^2)$. (c) Speed of sound v_s across the BEC-BCS crossover (blue dots) extracted from the fit to the collective mode. We find good agreement with a previous measurement of the speed of sound performed via fixed-momentum Bragg spectroscopy [26] (light blue stars), a measurement of the Bertsch parameter at unitarity [21] (orange diamond), and a quantum Monte Carlo calculation of the equation of state [58] (dashed line). (d) Prefactor ζ of the q^3 correction to the collective mode. In the BEC regime, the dispersion bends upward and $\zeta > 0$. When moving toward the crossover regime, the value of ζ decreases until it changes sign at an interaction strength of $1/k_F a \approx 0.2$. For interaction parameters $1/k_F a \lesssim 0.2$, the collective mode bends down and $\zeta < 0$. The statistical uncertainties of the data points shown in (c) and (d) are smaller than the marker size.

Figs. 3(a) and 3(b). This captures both the change of the linear slope due to the changing speed of sound [Fig. 3(c)] and the change in the curvature of the dispersion [Fig. 3(d)]. We find that the dispersion is convex ($\zeta > 0$) in the BEC regime, but when going toward the resonance ζ smoothly decreases until it changes sign at an interaction strength of $1/k_F a \approx 0.2$ and the dispersion becomes concave ($\zeta < 0$). At unitarity, we obtain a value of $\zeta = -0.085(8)/k_F^2$, which is in good agreement with [55,57] and provides a quantitative experimental benchmark.

Next, we consider the properties of the pair breaking continuum. We find that the continuum shows a clear dependence on both the energy and momentum transfer [see, e.g., Fig. 2(e)]. On the energy axis, there is a sharp threshold of the continuum at a well-defined energy, whereas the momentum axis shows a more gradual onset of pair breaking excitations. Both of these observations are directly related to important properties of the pairs.

The existence of an onset on the momentum axis can be understood by comparing the wavelength of the excitation to the size of the pairs. If the size of the pairs is large compared to the wavelength of the excitation, a single particle can be excited and the pair can be broken. However, if the pair is smaller than the wavelength of the Bragg lattice, the excitation exerts almost no differential force on the atoms and they are preferentially excited as an unbroken pair. Therefore, as the size of the pairs changes in the BEC-BCS crossover, the onset of the continuum changes with the interaction strength. In the BCS regime, the pairs are large and we observe a broad pair breaking continuum [Fig. 2(f)]. Going through the crossover, the pairs become more tightly bound and the onset of the continuum correspondingly moves to higher momenta, until we reach the deep BEC regime of tightly bound molecules, where pair breaking excitations are strongly suppressed and no continuum is visible [Fig. 2(a)]. In this regime, the gas has essentially become a strongly interacting Bose gas and pair breaking excitations only occur at very high momenta and energies.

The threshold on the energy axis is caused by the existence of the pairing gap Δ, which describes the energy cost associated with breaking a Cooper pair. We can therefore determine the evolution of the pairing gap by fitting the threshold of the pair breaking continuum in the dynamic structure factor, as shown in Fig. 4(a). This method works well in the BCS regime, but in the crossover the onset of the continuum is masked by the Goldstone mode [see Figs. 2(c), 2(d)]. In this regime, we therefore employ the method developed in Ref. [26] and separate the pair breaking excitations from the Goldstone mode by strong driving at low momentum transfer. An example of such a strongly driven spectrum can be seen in Fig. 4(b). We estimate that the systematic uncertainty for the pairing gap arising from the different fit functions used for the two methods is $0.03E_F$ [34].

The gaps determined by our fits to the excitation spectra are shown in Fig. 4(c). We find excellent agreement with previous experiments [24,26] that were performed in the BEC and crossover regimes. Next, we compare our data to T-matrix calculations that self-consistently include strong pairing correlations (black line in Fig. 4(c) [33]). Taking the zero-temperature result, this theory is in excellent agreement with our data in the BEC and crossover regimes, but lies significantly above our measurements in the BCS regime. While such a reduction of the gap could in principle be explained by finite temperature effects, the finite temperature results of the T-matrix calculation are inconsistent with our experimental observation that the system remains at almost constant entropy while ramping through the BEC-BCS crossover [34]. Another possible explanation could be that the size of the gap is influenced by particle-hole fluctuations. These fluctuations are not expected to be important at unitarity, but lead to the famous Gor'kov-Melik-Barkhudarov correction [60,61] in the BCS limit. This effect is taken into account in a recent strong coupling calculation [59], which is in good agreement with our data in the BCS regime, but lies significantly above our measurements on the BEC side of the resonance.

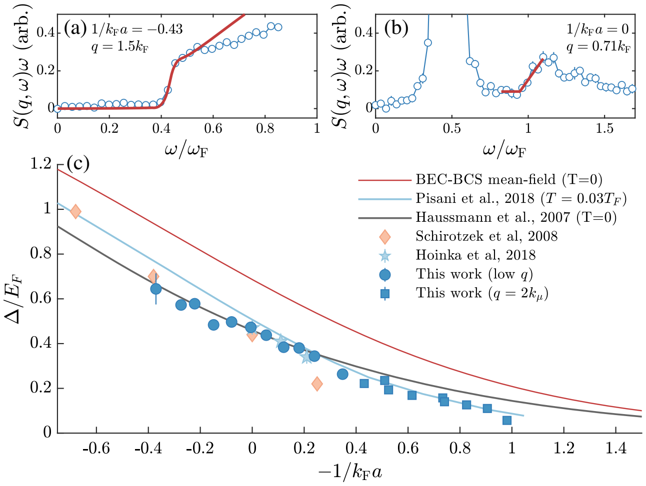

FIG. 4. Measurement of the pairing gap in the BEC-BCS crossover. (a) Heating rate $S(q,\omega)\omega$ on the BCS side of the resonance ($1/k_F a = -0.43$) measured at a fixed-momentum transfer of $\hbar q = 1.5\hbar k_F$. The onset of the pair breaking continuum is clearly visible in the data; the red line shows a fit of a line shape from quasiparticle random-phase approximation calculations used to extract the value of the pairing gap Δ [blue squares in panel (c)] [34]. (b) Close to resonance, we perform measurements at low momentum to separate the onset of the pair breaking continuum from the collective mode. The resulting onset determined from a bilinear fit (red) is shown in panel (c) as blue dots [34]. (c) Pairing gap Δ across the BEC-BCS crossover. The error bars denote the 1σ confidence interval of the fit and are (mostly) smaller than the symbol size. Our data is in good agreement with previous measurements (orange diamonds [24], blue stars [26]). When comparing to theory, we find excellent agreement with self-consistent T-matrix calculations [33] close to resonance and in the BEC regime (black solid line), but toward the BCS regime calculations including Gor'kov-Melik-Barkhudarov corrections [59] (light blue line) are closer to our data.

In conclusion, we have presented momentum- and energy-resolved measurements of the excitation spectrum of a homogenous ultracold Fermi gas. These measurements directly reveal the transformation from tightly bound molecules to weakly bound Cooper pairs that takes place in the BEC-BCS crossover. Moreover, we have determined the evolution of both the slope and curvature of the Goldstone mode as well as the pairing gap in the BEC-BCS crossover, which provides quantitative benchmarks for theory. These measurements are an excellent starting point for performing precision measurements of other key properties of strongly interacting Fermi gases, such as the critical temperature for superfluidity throughout the BEC-BCS crossover. Our setup is also ideally suited to create imbalanced Fermi gases and study their excitation spectrum to search for exotic phases such as the elusive Fulde-Ferrell-Larkin-Ovchinnikov state [62]. Looking beyond our system, the combination of a homogeneous sample and momentum-resolved Bragg spectroscopy established in this work is a powerful tool that can be used to measure the excitation spectrum of a wide variety of systems, ranging from dipolar gases to ultracold atoms trapped in optical lattices.

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