Determination of the Superfluid Gap in Atomic Fermi Gases by Quasiparticle Spectroscopy

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We present majority and minority radio frequency spectra of strongly interacting imbalanced Fermi gases of ^{6}Li. We observed a smooth evolution in the nature of pairing correlations from pairing in the superfluid region to polaron binding in the highly polarized normal region. The imbalance induces quasiparticles in the superfluid region even at very low temperature. This leads to a local bimodal spectral response, which allowed us to determine the superfluid gap Δ and the Hartree energy U.

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Pairing and superfluidity in fermionic systems are intricately related phenomena. In BCS theory [1], describing conventional superconductors, the emergence of superfluidity is accompanied by the opening of a gap in the excitation spectrum of the superfluid. This gap can be interpreted as the minimum energy required to break a Cooper pair or, equivalently, to create an elementary excitation, a so-called quasiparticle, inside the superfluid.

However, strongly correlated systems show a more complicated behavior. There are gapless fermionic superfluid systems, e.g., high temperature superconductors [2] or for superconductors with magnetic impurities [3]. On the other hand, there are numerous examples of systems with an excitation gap in the normal state, e.g., a high temperature superconductor above its superfluid transition temperature exhibiting a pseudogap [2].

Here, we use radio frequency (rf) spectroscopy to investigate the nature of pairing and the relation between pairing and superfluidity in a strongly interacting system of ultracold atomic Fermions.

We can spectroscopically distinguish the superfluid and the polarized normal fluid by introducing excess fermions into the system. In a superfluid phase described by BCS theory, the excess particles can be accommodated only as thermally excited quasiparticles. A local double-peaked spectrum reflects the coexistence of pairs and unpaired particles. In the normal phase, at large spin polarization, the limit of a single minority particle immersed into a Fermi sea is approached, which can be identified as a polaron [4–7]. Here the system can be described in the framework of Fermi liquid theory and no stable pairs exist. We find that these different kinds of pairing correlations are smoothly connected across the critical density imbalance [8], also called the Clogston-Chandrasekhar limit of superfluidity [9,10].

The rf spectrum of a superfluid containing quasiparticles shows two peaks, which, in the BCS limit, would be split by Δ, the superfluid gap. Therefore, rf spectroscopy of quasiparticles is a direct way to observe the superfluid gap Δ in close analogy with tunneling experiments in superconductors [11]. From the observed spectrum we can also determine a Hartree term, see Y. Castin in [12], whose inclusion turned out to be crucial.

For this study, we have combined several recently developed experimental techniques: The realization of superfluidity with population imbalance [13] leading to phase separation [8,13,14], tomographic rf spectroscopy [15], *in situ* phase-contrast imaging with 3D reconstruction of the density distributions [8]. In order to minimize final state effects [16] we have prepared an imbalanced mixture of states $|1\rangle$ and $|3\rangle$ of ^{6}Li (corresponding to $|F = 1/2, m_F = 1/2\rangle$ and $|F = 3/2, m_F = -3/2\rangle$ at low field) in an optical dipole trap at a magnetic field of $B =$ 690 G, at which there is a Feshbach scattering resonance between the states $|1\rangle$ and $|3\rangle$ [16,17]. Evaporative cooling at $B = 730$ G is performed by lowering the power of the trapping light. After equilibration an rf pulse was applied for 200 μs selectively driving a hyperfine transition from state $|1\rangle$ or $|3\rangle$ to state ($|2\rangle|F = 1/2, m_F = -1/2\rangle$ at low field). Immediately after the rf pulse an absorption image was taken of the atoms transferred into state $|2\rangle$.

The spectra were correlated to the local Fermi energy $\epsilon_{F\uparrow} = \frac{\hbar^2}{2m}(6\pi n_\uparrow)^{2/3}$ of the majority density $n_\uparrow$ and to the local polarization $\sigma_{\mathrm{loc}} = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$ which is a measure of the local excess fermion population. As in a previous publication [8] the local densities were measured using phase-contrast imaging and 3D reconstruction using the inverse Abel transformation.

The rf spectra shown in Fig. 1 reveal a gradual change in the nature of the pairing correlations. The balanced superfluid is characterized by identical spectral responses of majority and minority particles and has been the subject of previous studies, see Zwierlein, Grimm, and Regal in [12] and references therein. In the polarized superfluid region [8,18] (and references therein) the minority spectrum perfectly matches the pairing peak of the majority spectrum, locally coexisting with the quasiparticle spectral contribution, resulting in a local double-peak structure of the majority spectrum, see Fig. 1(b). The spectrum suggests that the majority population can be divided into two distinct parts: One part consisting of pairs forming the superfluid, the other part consisting of quasiparticle exci-

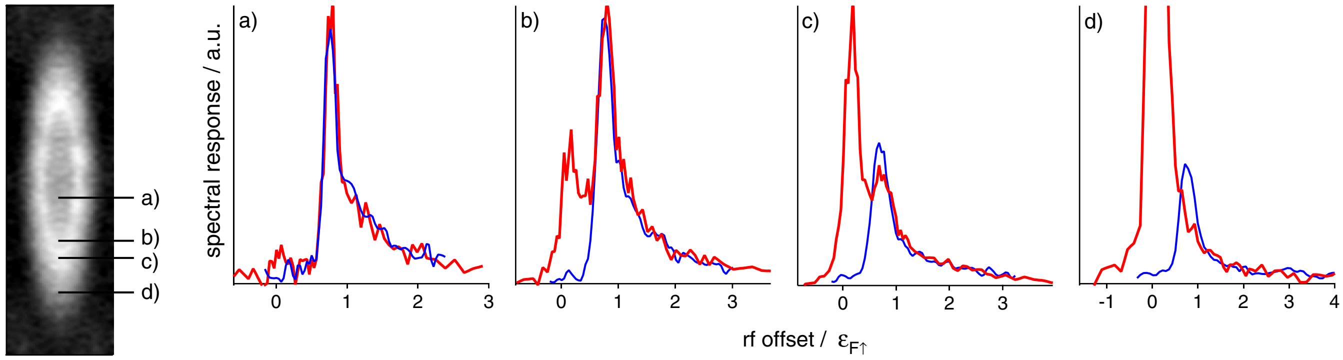

FIG. 1 (color online). Tomographically reconstructed rf spectra for various regions of the atomic sample at unitarity. (a) Balanced superfluid, (b) polarized superfluid, (c) moderately polarized transition region, and (d) highly polarized normal region. The panel on the left shows a phase-contrast image of the atomic cloud before rf excitation. The positions of the spectra (a) to (d) are marked in the phase-contrast image and by the arrows in Fig. 2. Red: Majority spectrum, blue: Minority spectrum. Local polarizations σ_{loc} and local temperature T/T_F, respectively: (a) $-0.04(2)$, 0.05(1); (b) 0.03(1), 0.06(1); (c) 0.19(1), 0.06(2); (d) 0.64(4), 0.10(2). The negative value in (a) implies that the local polarization as inferred from phase-contrast imaging underestimates σ_{loc} by up to 0.05.

tations in the form of excess fermions. Therefore, a natural interpretation of the rf spectrum is to identify one peak as a Stokes process (rf creates a quasiparticle excitation) giving rise to the dissociation part of the rf spectrum and the other as an anti-Stokes process (rf destroys a quasiparticle excitation).

As the local imbalance is further increased beyond the superfluid to normal (SF-N) transition [8,19], see Fig. 1(d), the majority spectrum no longer shows a local double-peak structure. This is consistent with theoretical work [20,21] attributing the double-peak structure in the normal phase in previously reported rf spectra [22,23] to the inhomogeneous density distribution. For increasing spin polarization the majority and minority pairing peaks lose spectral overlap. We interpret the missing overlap as indication that the minority atoms are no longer bound in pairs, each of them interacting with more than one majority atom, a situation we refer to as polaronic binding. We have seen [19] that on the Bose-Einstein condensation (BEC) side of the Feshbach resonance the overlap between minority and majority spectra does not depend strongly on the presence of excess fermions as is expected in a molecular picture. At unitarity, within our experimental resolution, the overlap starts to decrease at the SF-N interface, see Fig. 1(c).

Even when the spectral overlap decreases, there is still equal response to the rf excitation in the high frequency tails, see Figs. 1(c) and 1(d). These tails correspond to large momentum components in the interparticle wave function and hence address the short range physics. We expect this part of the spectrum to be insensitive to changes in the binding at large distances.

The direct comparison between majority and minority spectra clarifies our previous experimental results on minority rf spectra in the $|1\rangle - |2\rangle$ mixture [23], in which we concluded that there is strong pairing in the normal phase. Although the previous results suffered from final state interactions [16], we confirm that the change in pairing correlations is indiscernible in the minority spectrum alone, but shows up in the spectral overlap with the majority spectrum. As a result, the observed spectral gap in the normal phase should not be interpreted as a signature of pairing but rather as strong pairing correlations in the form of a polaron as suggested in [24–26]. Figure 2 summarizes our data in the unitary regime.

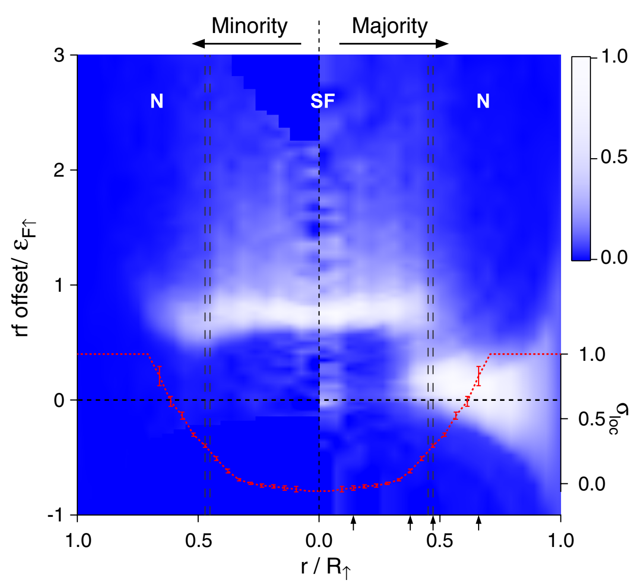

FIG. 2 (color online). Spatially resolved rf spectra of an imbalanced Fermi gas at unitarity. (a) The right half shows the majority spectra as a function of position in the trap expressed in terms of the majority Fermi radius $R_\uparrow$, the left half displays the minority spectra. The superfluid to normal transition region is marked by the gray vertical lines. The local polarization σ_{loc} is given by the short-dashed red line. The error bars are the standard deviation of the mean value. The arrows indicate the position of the four spectra shown in Fig. 1. The image is a bilinear interpolation of 2500 data points, each plotted data point in the image is the average of three measured data points. The spatial resolution of the image is $0.045 \cdot R_\uparrow$.

We now turn to a quantitative analysis of the spectral peaks in the superfluid phase for small density imbalance, and to the determination of the superfluid gap. Earlier work [15,22] tried to determine the gap from the onset of the pair dissociation spectrum. However, the rf spectrum is not only sensitive to final state interactions, it is also shifted by Hartree energies, as we show here. Furthermore, rf spectroscopy can excite all fermions, even deep in the Fermi sea, see M. Zwierlein in [12]. Therefore, the onset of the pair dissociation spectrum occurs for atoms with momentum $k = 0$ and, in the BCS limit depends quadratically on the gap parameter ($\omega_{\mathrm{th}} = \frac{\Delta^2}{2\epsilon_F}$). The excitation gap can be directly observed if quasiparticles near the dispersion minimum are *selectively* excited, as in tunneling experiments.

Our solution is to study not the ground state of a superfluid, but excited states where quasiparticles are present. In a simple BCS description, quasiparticles are in pure momentum states, but increase the total energy of the system because their momentum state is no longer available to the other particles for pairing. Consequently, in an excitation spectrum, quasiparticles appear at negative frequencies relative to the bare atomic transition frequency. The lowest energy quasiparticle appears at frequency $-\Delta$, see Fig. 3.

Final state interactions and Hartree terms can also create line shifts, and two peaks are needed for analysis, the dissociation peak and the quasiparticle peak in our case. In essence, it is the separation between the peaks in spectra like Fig. 1(b), which allows us to determine Δ.

Thermal population of quasiparticles requires a temperature on the order of the excitation gap Δ. At unitarity, this temperature can be estimated to be 95% of the critical temperature, away from the low temperature limit addressed in this Letter. Indeed, in samples of equal population of the spin states we were not able to spectroscopically resolve any local double-peak structures [19]. This problem can be overcome by introducing density imbalance between the constituents: The chemical potential difference between majority and minority components ($\mu_\uparrow > \mu_\downarrow$) forces a finite quasiparticle occupation into the superfluid region already at very low temperature [27]. This allows us to selectively populate quasiparticles at the minimum of the dispersion curve, see Fig. 3(a).

In Fig. 4(a) the position of the peaks of majority and minority spectra are plotted normalized by $\epsilon_{F\uparrow}$ as a function of position in the trap in the unitary limit [19]. The peak positions are proportional to the local Fermi energy inside the superfluid region within our experimental resolution. In the region of superfluidity with finite polarization the spectra show local double peaks. The position of the two peaks in the limit of small polarization is depicted in Fig. 4(b) for various interaction strengths.

It was unexpected that the quasiparticles appear at positive frequencies (relative to the atomic transition frequency). This is caused by the presence of Hartree terms, resulting in an overall shift of the systems energy and the rf spectrum [19]. In the weakly interacting limits, the Hartree term reduces to a simple mean-field shift. In the strongly interacting regime one has to resort to quantum Monte Carlo (QMC) calculations [28–30] for a numerical value of U.

In a mean-field description of the balanced superfluid starting from the BCS-Leggett ansatz for the BEC-BCS crossover, see Zwierlein in [12] taking into account the Hartree term U, the dispersion relation of the quasiparticles can be expressed as $E_k = \sqrt{\Delta^2 + (\epsilon_k + U - \mu)^2}$, see Y. Castin in [12] where $\epsilon_k = \frac{\hbar^2 k^2}{2m}$ is free particle kinetic energy and μ is the chemical potential. This mean-field formalism gives the analytic expression for the two peak positions. A quasiparticle at the minimum of the dispersion

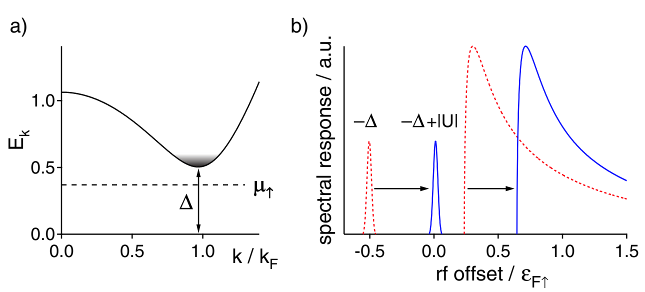

FIG. 3 (color online). Creation and spectroscopy of quasiparticles. (a) Population imbalance thermally generates quasiparticles even at low temperatures comparable to $\Delta - \mu_\uparrow$. $\mu_\uparrow$ is the chemical potential of the majority component. (b) The rf spectrum consists of a quasiparticle peak at negative frequencies and the pair dissociation spectrum at positive frequencies (dotted line). On resonance, the Hartree contribution U acts as an effective attraction and hence shifts the entire spectrum into the positive direction.

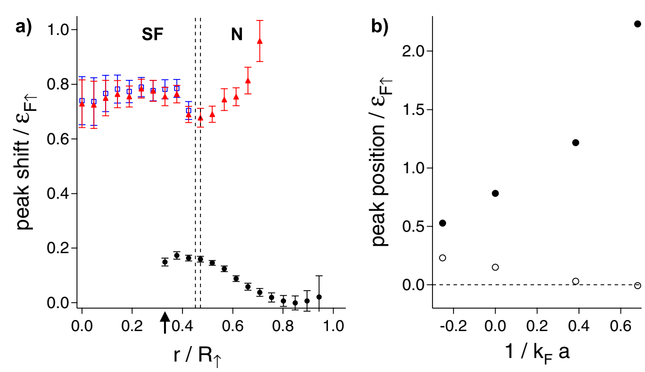

FIG. 4 (color online). (a) Normalized peak positions of pairing peaks and quasiparticle peak at unitarity as a function of position in the trap. The SF-N boundary (cusp in column density difference [19]) is marked by the dashed vertical lines. The arrow indicates the limit of low quasiparticle population relevant for (b). Majority: blue open squares (pairing peak) and solid black circles (quasiparticle peak). Minority: solid red triangles. (b) Pairing peak and quasiparticle peak positions as a function of the local interaction strength $1/k_F a$ in the limit of small local imbalance [see arrow in (a)]. Pairing peak: solid circles; quasiparticles peaks: open circles.

TABLE I. Superfluid gap Δ, Hartree term U, and final state interaction E_{final} in terms of the Fermi energy $\epsilon_{F\uparrow}$ for various interaction strengths $1/k_F a$.

$1/k_F a$	Δ	U	E_{final}
−0.25	0.22	−0.22	0.22
0	**0.44**	**−0.43**	**0.16**
0.38	0.7	−0.59	0.14
0.68	0.99	−0.87	0.12

curve will respond at an rf offset of $\omega_{\mathrm{rf}} = -E_{k_{\min}} - \mu + \epsilon_{k_{\min}} = -\Delta - U$, and the maximum of the pair dissociation spectrum occurs at $\hbar\omega_{\max} = \frac{4}{3}(\sqrt{\mu'^2 + \frac{15}{16}\Delta^2} - \mu') - U \simeq \frac{4}{3}\omega_{\mathrm{th}} - U$, where $\mu' = \mu - U$ and ω_{th} is the dissociation threshold (which is at momentum $k = 0$).

We determined the superfluid gap Δ and the Hartree energy U from the peak positions in the limit of small density imbalance ($\sigma_{\mathrm{loc}} \simeq 0.03$). At unitarity with the chemical potential $\mu = 0.42\epsilon_{F\uparrow}$, confirmed in previous experiments and theory, see [31] and references therein, we obtained $\Delta = 0.44(3)\epsilon_{F\uparrow}$ and $U = -0.43(3)\epsilon_{F\uparrow}$, in excellent agreement with the predicted values $\Delta_t = 0.45\epsilon_{F\uparrow}$ and $U_t = -0.43\epsilon_{F\uparrow}$ from QMC calculations [32]. Our determined values for Δ and U values suggest the minimum of the quasiparticle dispersion curve to occur at $k_{\min} \simeq 0.9k_F$. Table I shows the gap and Hartree energy for various interaction strengths. Away from unitarity we relied on QMC calculations for the chemical potential μ [33].

For an accurate quantitative comparison [19] final state interactions, also listed in Table I, had to be taken into account. The effect of final state interactions is an overall mean-field shift of $E_{\mathrm{final}} = \frac{4\pi\hbar^2 a}{m} n$. This shift affects both the quasiparticle peak and the pairing peak equally.

In conclusion, in crossing the superfluid to normal boundary we observed a gradual crossover in the pairing mechanism by comparing majority and minority spectra. The majority spectrum shows a local double-peak spectrum in the polarized superfluid region which allowed us to determine the superfluid gap Δ and the Hartree terms U. The spectra in the normal phase are consistent with a polaron picture.

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