

Photoemission Spectroscopy for Ultracold Atoms

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We perform momentum-resolved rf spectroscopy on a Fermi gas of ^{40}K atoms in the region of the the BCS-BEC crossover. This measurement is analogous to photoemission spectroscopy, which has proven to be a powerful probe of excitation gaps in superconductors. We measure the single-particle spectral function, which is a fundamental property of a strongly interacting system and is directly predicted by many-body theories. For a strongly interacting Fermi gas near the transition temperature for the superfluid state, we find evidence for a large pairing gap.

Keywords: ARPES; BCS-BEC crossover; fermions; superfluidity

We realize a powerful new technique to probe ultracold atoms and use this technique to probe the BCS-BEC crossover.¹ The phase diagram of the BCS-BEC crossover was first mapped out at JILA using observations of pair condensation.² Since then, there have been many experiments exploring this crossover. Many of these experiments have examined macroscopic quantities such as thermodynamics, collective excitations, and superfluidity. In this paper, we focus instead on probing microscopic behavior in the crossover. This allows direct access to the excitation gap, which is an essential feature of fermionic superfluidity.

In the BCS limit, the excitation gap Δ is the order parameter, which characterizes the onset of the new order at the superfluid (or superconductor) phase transition. The gap is zero above the transition temperature T_c and non-zero below T_c . This excitation gap arises because of the pairing of fermions, which results in a minimum energy, 2Δ , that must be added to

create excitations with fermionic character. In other words, 2Δ is the minimum energy required to break a pair. In the BCS-BEC crossover, things get even more interesting because an excitation gap is expected to exist above the superfluid phase transition temperature.³⁻⁸ Here, 2Δ is still the minimum energy to break a pair, but Δ is now referred to as the pseudogap and does not necessarily signal the onset of the superfluid phase transition. This concept of preformed pairs (pairing that occurs at temperatures above T_c) is perhaps easiest to see when thinking about the limit of a BEC of diatomic molecules. Here, clearly the pairing (molecule formation) can happen at temperatures well above the BEC transition temperature.

Clearly, one would like to probe the excitation gap in the BCS-BEC crossover and see the predicted pseudogap as well as the pairing that occurs in the superfluid phase. Previous experiments have used photoassociation⁹ or rf spectroscopy¹⁰⁻¹⁴ to probe microscopic behavior in the BCS-BEC crossover. Our new photoemission spectroscopy technique presented here is based on rf spectroscopy.

In 2003, our group used rf spectroscopy to measure the binding energy of potassium Feshbach molecules.¹⁰ The minimum energy to break a pair, 2Δ , is simply the binding energy in the BEC limit. In 2004, the Innsbruck group reported rf spectroscopy of the BCS-BEC crossover and the observation of a double-peak structure in the spectrum.¹² This was interpreted as observation of the gap.^{12,15} In 2007, the MIT group used this same interpretation of rf spectra for a strongly imbalanced Fermi gas mixture and came to the unlikely conclusion that this system had pairs without superfluidity in the $T = 0$ limit.¹⁴ This conclusion was difficult to believe because it meant that there exist bosons (the pairs) that do not Bose condense at $T = 0$. The problem lies with the rf spectroscopy and a number of theorists have pointed out problems with the simple interpretation of double-peaked rf spectra in terms of a pairing gap.¹⁶

Two issues can affect the interpretation of the rf spectroscopy results. The first issue is the fact that the density of the gas varies spatially because the atoms are confined in a harmonic potential. The gas density is highest in the center of the cloud and falls to zero at the edges of the cloud. This inhomogeneous density is important if one is probing many-body behavior, which of course depends on density. In particular, the size of the excitation gap in the BCS-BEC crossover depends on density (except in the BEC limit where the pairing becomes a two-body effect, namely molecules). A number of theory papers have pointed out that the two features in the double-peaked rf spectra come from different parts of the cloud.^{15,17-21} One

peak, which occurs near the single-atom Zeeman frequency, is due to atoms at low density at the edges of the cloud. The second peak, which is shifted in frequency with respect to the single-atom Zeeman frequency, comes from the center of the cloud where the density is high and many-body effects are important. Ignoring the unshifted feature due to atoms at the edges of the cloud, one is left with a single, frequency-shifted peak. This feature shows that there is a many-body (density-dependent) shift; this could be due to a pairing gap or could instead be simply a mean-field, or cold-collision, shift.

A second issue is final-state effects, which is relevant for the situation where the rf spectroscopy involves transfer of the strongly interacting atoms into a spin state that is also strongly interacting. This was the case for the ^6Li experiments.^{12–14} Even if one assumes that the shifted peak is due to pairing, extracting a value for the gap from the measured frequency shift is a difficult theoretical problem when there are final-state effects.^{22–27} These final-state effects can be avoided if the strongly interacting atoms are transferred into a spin-state where the atoms are only weakly interacting with the remaining cloud.

Our recent work¹ and also recent results from the MIT group²⁸ report rf spectroscopy of a strongly interacting Fermi gas without strong final-state effects. The MIT paper²⁸ directly contrasts data for ^6Li atoms with and without strong final-state effects. The rf spectra in the two cases are dramatically different, both qualitatively and quantitatively. These recent results show that density inhomogeneity and final-state effects are likely causes of the double-peak structure in previous rf spectra, which therefore can not be simply interpreted as evidence for pairing. In ^{40}K rf spectroscopy, final-state effects are easily avoided and in fact the final spin-state in the rf transfer is so weakly interacting that atoms transferred into this state can pass through the gas with a low probability of experiencing even one collision. Beyond just permitting rf spectroscopy without complicated final-state effects, this circumstance allows us to extract additional information and obtain a clear signature of a pairing gap.

We can now obtain momentum-resolved rf spectra, since the momenta of the atoms transferred into the new spin-state are not scrambled by collisions. This turns out to provide a very close analogue to photoemission spectroscopy (PES) of solids²⁹ (see Figure 1). For electronic systems, PES has proven to be a powerful probe of the excitation spectra.³⁰ In a typical photoemission experiment, a beam of photons ejects electrons from the sample via the photoelectric effect. These photons are counted as a function of their energy and momentum. Using conservation of energy, the energy of the

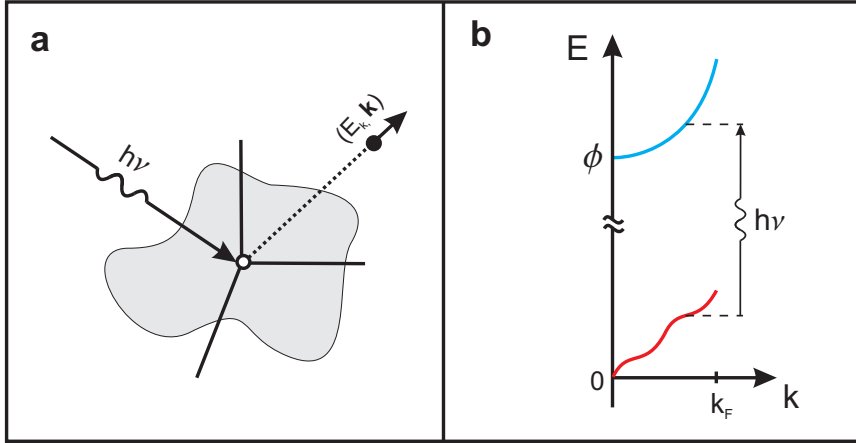


Fig. 1. **Photoemission spectroscopy for ultracold atom gases.** **a** In electron PES, one measures the energy of electrons emitted from solids, liquids, or gases by the photoelectric effect. Using energy conservation, the original energy of the electrons in the substance can be determined. Similarly, in photoemission spectroscopy for atoms, an rf photon with energy, $h\nu$, transfers atoms into a weakly interacting spin state. **b** The rf photon drives a vertical transition where the momentum $\hbar k$ is essentially unchanged. By measuring the energy and momentum of the out-coupled atoms (upper curve) we can determine the quasiparticle excitations and their dispersion relation (lower curve). Here ϕ is the Zeeman energy difference between the two different spin states of the atom.

single-particle states in the solid can be determined. Thus, PES reveals the density of states and the dispersion, E_S vs. k , for the single-particle states in a strongly interacting electron system. This technique has been used to probe the excitation gap in high- T_c superconductors and other strongly correlated materials. Note that in PES, as well as in our experiment, the photon momentum is negligible compared to the typical momentum of the strongly interacting particles.

The basic steps of our technique for atoms are (1) apply a short rf pulse, (2) turn off the trap, (3) selectively image the transferred atoms after a period of expansion from the trap, (4) obtain the three-dimensional number of atoms as a function of momentum $N(k)$ using an inverse Abel transform, and (5) repeat for different rf frequencies.¹ If we simply count the number of atoms vs. rf frequency, we obtain an rf spectra without final-state effects. If we use conservation of energy, we can extract the occupation of single-particle states as a function of energy E_s and momentum k in the strongly interacting atom gas.

Figure 2 shows the intensity map (proportional to number of atoms as

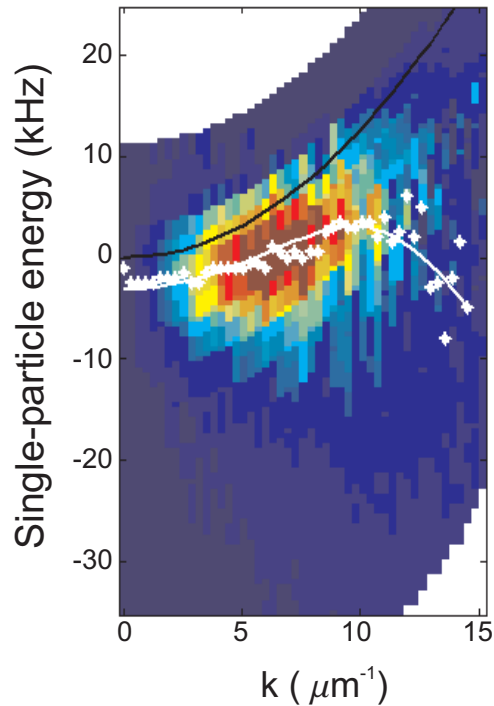


Fig. 2. **Single-particle excitation spectrum obtained using photoemission spectroscopy for ultracold atoms.** Data is for a strongly interacting Fermi gas where $1/k_F^0 a = 0$ and $T \approx T_c$. Plotted is an intensity map of the number of atoms out coupled to a weakly-interacting spin state as a function of the single-particle energy E_s and wave vector k . The black line is the expected dispersion curve for an ideal Fermi gas. The white points (*) mark the center of each fixed energy distribution curve. The Fermi wave vector k_F^0 is $8.6 \pm 0.3 \mu\text{m}^{-1}$. The white line is a fit of the centers to a BCS-like dispersion.

a function of E_s and k) measured for the strongly interacting Fermi gas. In the intensity map, the observed energy width of the data is larger than the measurement resolution and can be caused by a finite lifetime of the single-particle excitations. The black line shows the dispersion for free particles, $E = \hbar^2 k^2 / 2m$. The white points show the measured dispersion curve, which was obtained by fitting a Gaussian to the intensity vs E_s for each value of k . This dispersion curve shows a back-bending behavior that is characteristic of a pairing gap.

One of the aspects of PES that makes it a useful probe of microscopic behavior is that it measures the spectral function, which is a quantity that is directly predicted by many-body theories.³⁰ The spectral function for the

BCS-BEC crossover has been discussed in many theory papers. The peaks of the spectral function are predicted to follow a “BCS-like” dispersion curve where the BCS gap is replaced by the pseudogap.³⁻⁸ This dispersion has two branches, with one corresponding to the occupied part of the excitation spectrum while the other corresponds to the Bogoliubov excitations. With our technique, as in PES of solids, we only measure the states that are occupied and so would not expect to see the excited branch when probing a low temperature gas.

The white points in Fig. 2, fit well to the BCS-type dispersion with the chemical potential and the gap Δ as fit parameters. It should be noted that these best fit values can be influenced by the density inhomogeneity of the trapped gas and by the fact we use Gaussian fits to extract the peak (white points) for each value of k . Our photoemission spectroscopy for ultracold atoms reveals the dispersion curve $E_s(k)$ and we are able to see the back-bending behavior characteristic of an excitation gap due to pairing of fermions. (Note also that one can easily discriminate against atoms at very low density at the edges of the cloud, which would give a signal that follows the simple quadratic dispersion shown by the black line.)

In conclusion, we have used photoemission spectroscopy, accomplished by momentum resolving the out-coupled atoms in rf spectroscopy, to probe the occupied single-particle density of states and energy dispersion through the BCS-BEC crossover. In the future, it may be possible to use spatially resolved photoemission spectroscopy to probe the local pairing gap. Another extension of this work will be to study the BCS-BEC crossover as a function of temperature and/or unbalanced spin population. Photoemission spectroscopy for ultracold atoms is a powerful and conceptually simple probe of strongly correlated atom gases that could be applied to many other atom gas systems. In the studies presented here, the atoms are interacting via isotropic s-wave interactions and therefore considering different directions of the out-coupled atoms’ momenta was not necessary. However, like angle-resolved photoemission spectroscopy (ARPES) for solids, this technique could also be applied to non-isotropic systems such as atoms in an optical lattice, low dimensional systems, or higher partial wave pairing of atoms.³¹

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