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Radio-frequency spectroscopic measurement for pairing gap in an ultracold Fermi gas

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The study of ultracold Fermi gases has exploded a variety of experimental and theoretical research since the achievement of degenerate quantum gases in the lab, which expands the research range over atomic physics, condensed matter physics, astrophysics and particle physics. Using the Feshbach resonance, one can tune the attractive two-body interaction from weak to strong and thereby make a smooth crossover from the BCS superfluid of cooper pairs to the Bose Einstein condensate of bound molecules. In this crossover regime, the pairing effect plays a significant role in interpreting the interaction mechanism. Whenever the localized or delocalized pairing occurs at sufficiently low temperature, the single-particle energy will shift with respect to free atoms, due to the two-body or many-body interaction. Measuring the pairing gap can improve the understanding of the thermodynamics and hydrodynamics of the phase transition from the pseudogap to the superfluid, which will make an analogue to the high-temperature superconductivity in condensed matter. In this work, we will give a brief introduction to a novel radio-frequency (RF) spectroscopic measurement for pairing gap in an ultracold Fermi gas, which is currently widely used on the ultracold atomic table in the lab. In different interaction regimes of the BEC-BCS crossover, ultracold atoms are excited with a RF pulse and the characteristic behavior can be extracted from the spectrum.

degenerate Fermi gas, Feshbach resonance, Bose Einstein condensate, superfluid

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1 Introduction

Many-body problem in the strongly correlated system is a great challenge to the modern physics today. And also the two-body problem plays an important role and still becomes a research focus in ultracold atoms. After achieving degenerate Fermi gases in the lab [1], ultracold Fermi gas has become a versatile tabletop in quantum simulating many-body interactions, which generally happen in condensed matter, e.g., high temperature superconductivity [2]. The outstanding phase diagram for the fermionic interaction is the crossover from a BCS (Bardeen, Copper and Schrieffer) [3] superfluid of cooper pairs to a Bose Einstein condensate (BEC) of bound molecules, which is indicated in Figure 1 [4]. In different interaction regimes, the mechanism of the pairing and superfluidity is strongly dependent on the two-body or many-body interaction. For example, on the BCS interaction, pairing and superfluidity occur simultaneously at the same temperature and the many-body interaction dominates. On the BEC side, pairing occurs first and then superfluidity appears when temperature decreases,

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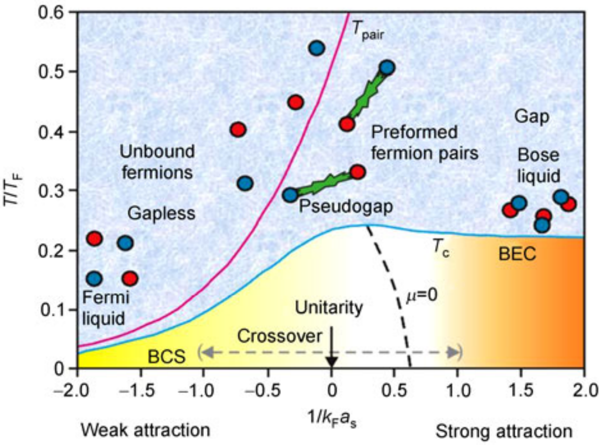

Figure 1 (Color online) Phase diagram for the fermionic interaction [4].

where the two-body interaction becomes significant. In the crossover between these two regimes, the scattering length diverges into infinitely big. In this case, the pairing mechanism shares the characters of both BCS and BEC sides, where pairing proceeds the superfluidity and the pair size is comparable to the atomic separation. Ultracold quantum gases pave a convenient way to understand this pairing mechanism due to its tunability and controllability using a magnetic Feshbach resonance, where the s-wave interaction can be tuned from the attrative to the repulsive [5]. When considering the interaction between fermionic atoms, the single-particle energy will shift with respect to free atoms more or less. Consequently, the pairing and superfluidity can result in an energy shift, which is terminologically called "energy gap". So getting the information about the pairing energy gap can greatly improve our understanding of the dynamics of pairs and superfluidity. The question is how to get the pairing information technically in the lab.

Different experimental configurations have been proposed by theorists and experimentalists to probe the pairing gap. Far-off resonant light can interact with atoms and be scattered into different angles in normal and superfluid gases [6]. But in this way, signal-to-noise ratio (SNR) is limited by the scattered probing light and the laser linewidth. Another optical method is to use a resonant two-photon Raman process, getting the pairing energy by probing population loss [7]. But the limited laser linewidth and the population fluctuation will decrease SNR. The many-body dynamics will change when the gas goes through the phase transition into the superfluid. So one can probe the phase transition by measuring the low-energy collective oscillation in different population imbalances or interaction strengths [8]. But this method only can give qualitative characters on quantum gases, no detailed information about the phase transition. Recently, a more accurate and convenient experimental method is proposed to excite the single-particle energy using a novel radio-frequency (RF) pulse [9]. In this method, the narrow linewidth and high coupling efficiency with atoms will help us to extract the excitation energy shift with respect to free atoms, which is equivalent to the pairing gap. The profile of the RF spectrum will also give valuable information, such as the final state interaction and kinetic energy distribution.

In this work, we will briefly summarize applications of a RF excitation to probe the pairing gap. The paper is organized into five different sections. In sect. 2, we will describe the general schematics of a RF pulse coupling different spin states of atoms and explain the process of this probing method. Sect. 3 will give some examples in which we can extract pairing information when degenerate Fermi gases are excited with a RF pulse. In sect. 4, a recently developed RF spectroscopic method named "RF photoemission" will be briefly introduced to study the ultracold Fermi gas. And finally in sect. 5, we will give a conclusion and discussion.

2 Schematics of a RF pulse coupling atoms

When atoms are cooled into a quantum regime, the interaction between atoms will play a significant role compared to the kinetic motion. In this case, two-body or many-body interaction will impose an energy shift with respect to free atoms. Pairing mechanism is a crucial problem for the Fermi gas and in different interaction regimes, the paring energy shows different dependences. On the BEC side, the pairing energy is equivalent to the binding energy of two-body molecules, $E_{\text{pair}} = E_{\text{b}} = \hbar^2 / ma^2$, and in the unitary regime $E_{\text{pair}}=0.2E_{\text{F}}$, and on the BCS side $E_{\text{pair}}=\exp(-\pi / 2k_{\text{F}} |a|)E_{\text{F}}$, where E_{b} is the binding energy, E_{F} is the Fermi energy, a is the s-wave scattering length and k_{F} is the Fermi wave vector [10,11]. The energy shift due to the weak attractive interaction in the crossover is generally in the order of kHz. Measuring the interaction energy will improve our understanding of physical characters of ultracold quantum gases. The linewidth of the first exited state for alkali atoms is in the order of MHz, which is comparable to the laser linewidth that we can obtain with coventional frequency-stabilization methods. Narrowing the laser linewidth into sub-kHz is a great challenge for experimentalists. Therefore, using optical transition is difficult to get information about the energy shift. Coupling between the total angular moment of electron and the spin moment of nucleus results in hyperfine splitting, which is generally in the order from MHz to GHz. Also, the Zeeman splitting in a weak or intermediate external magnetic field is in the order of MHz. Fortunately, both RF wave and microwave have frequencies in this range and thus can couple different spin states efficiently in the atomic ground state. So the RF spectrum can be used to excite ultracold gases and one can obtain the single-particle energy including interaction. The basic schematics of this coupling is displayed as in Figure 2. The atomic energy including interaction will shift with respect to

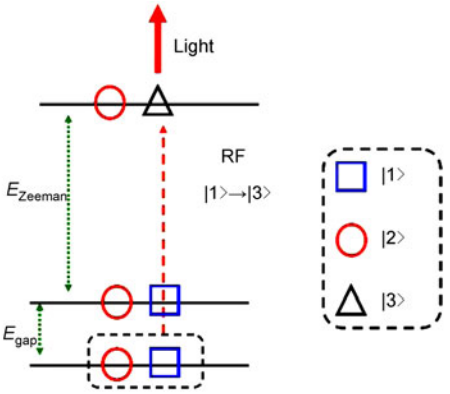

Figure 2 (Color online) Schematics of a RF pulse coupling atoms with interaction. The triangle, circle and rectangular signals denote different spin states. A RF pulse couples the transition from the spin state with interaction to the free atom. The light pulse is used to probe the population variation.

free atoms with a value of E_{gap}, due to the binding or pairing effect. The transition frequency is corresponding to the Zeeman splitting, which is coupled with a RF pulse $h\nu_{rf}=E_{Zeeman}+E_{gap}$, where E_{Zeeman} is the Zeeman spitting in the external applied magnetic field with an additional energy of hyperfine splitting if the two spin states belong to different electronic ground states, h is the Planck constant. When an RF pulse excites atoms from the ground state to the exited one, the energy shift is positive. Due to the low probing efficiency of the RF pulse, one generally uses a light excitation to probe the population variation of the ground or excited states. By analyzing the RF spectrum, one can get useful information on whether the two-body or many-body problem dominates in the interaction, or distinguish different pairing phases, such as the gapless, pseudogap or superfluid phase.

Figure 3 is a typical RF spectrum for an interacting Fermi gas, which comes from refs. [12]. The left large peak corresponds to the transition of the ideal gas without interaction. The right weak peak has a nearly 162 kHz positive energy shift with respect to free atoms due to the pairing effect. The narrow linewidth of the RF wave affords an accurate spectroscopic tool for measuring the pairing energy, which results in a double-peak structure in the spectrum. Also, other physical parameters can affect the profile of the RF spectrum. For example, different ro-vibrational energies of the two-body molecule, the inhomogeneous atomic density distribution or continuous kinetic energy of excited atoms would cause asymmetry in the RF spectrum [12]. In addition, the scattering length of excited atoms is generally not zero and then in this case, the final state interaction should be included to analyze the RF spectrum. As shown in Figure 4 for ground states of fermionic atom lithium6, the final state interaction is comparable to that of initial states. The RF spectrum implies the interaction information about initial and final spin states.

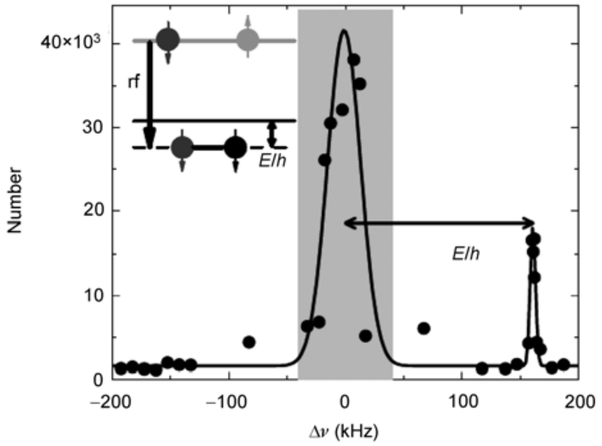

Figure 3 RF spectrum for an interacting Fermi gas [12].

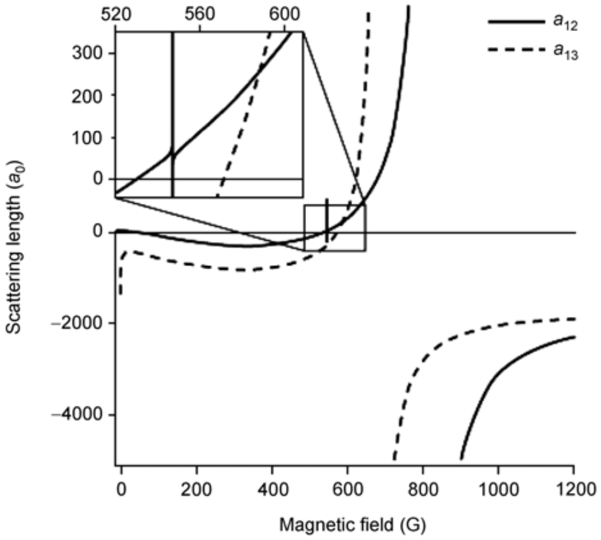

Figure 4 Scattering length for the three ground states of lithium6 [9]. a_{12} has a narrow Feshbach resonance on 543 G and a wide resonance on 834 G. a_{13} has a wide resonance on 690 G [5]. The two strong interactions of initial and final states have a big overlap around 750 G, where the final state interaction should be included to analyze the RF spectrum.

3 Characteristic behaviors of degenerate Fermi gases extracted by using a RF excitation

When the Fermi gas is cooled into a degenerate regime, Fermi quantum statistics will emerge, which is fundamentally different from that in the quantum Bose gas [2]. In the quantum Fermi gas, atoms couldn't condensate into a ground state due to Pauli exclusion, where the pairing mechanism plays a central role in explaining the atomic interaction. If temperature is decreased sufficiently so that the kinetic energy is less than the interaction energy, paring begins to occur when the atomic energy is smaller than a value relevant to the pairing gap. When different pairs have a phase coherence with a small fluctuation in the background reservoir, the superfluid begins to form. The RF spectrum is strongly related to the pairing process and improves the understanding of interactions in ultracold Fermi gases.

In the weak interaction regime, the mean-field approximation is well suitable to describe the quantum system. The many-body interaction will cause an energy shift which is both dependent on the atomic density and s-wave scattering length at low temperature, $\Delta\nu = 2\hbar n(a_{13} - a_{12})/m$, where $\Delta\nu$ is the energy shift with respect to free atoms, $\hbar$ is the Planck constant divided by 2π, m is the atomic mass, n is the atomic density, a_{13} and a_{12} are scattering lengths of final and initial states, respectively. Thus the RF spectrum implies the mean-field effect and the scattering length can be experimentally deduced with this method [9,13]. As shown in Figure 5, the s-wave scattering length can be mapped out by using a RF spectrum across the Feshbach resonance. But when the interaction approaches the unitary regime, the mean-field approximation doesn't work any more. Here, many macroscopic physical properties don't depend on microscopic parameters and only the atomic distance and Fermi energy are the scaled length and energy parameter. This character is indicated obviously in Figure 6, where the frequency shift of the RF spectrum remains unchanged when the interaction arrives at the resonance.

When the s-wave scattering length is negative, atoms have an attractive interaction and Cooper pairs form due to the many-body effect. But when the interaction goes to the BEC side with a positive scattering length, bound molecules will form where the two-body interaction plays a significant role. The RF pulse should first breakdown the bound molecule and then excite the transition between ground spin states of free atoms, with an energy $h\nu_{\rm rf} = h\nu_{\rm atom} - E_{\rm binding} - \Delta E$, where $h\nu_{\rm atom}$ is the transition energy of free atoms, $E_{\rm binding}$ is the binding energy of molecules with a value of $E_{\rm b} = \hbar^2/ma^2$ and ΔE is the kinetic energy which is imparted to the dissociated pairs. As shown in Figure 7, the RF spectrum of ultracold molecules shows an asymmetry on dissociating bound molecules and imposes a kinetic energy on free atoms with different driving frequencies [11]. Using the Fourier transformation between wave functions in spatial and momentum representations, one can use a RF spectrum to determine the pair size [14], which is a very important microscopic parameter in the high temperature su-

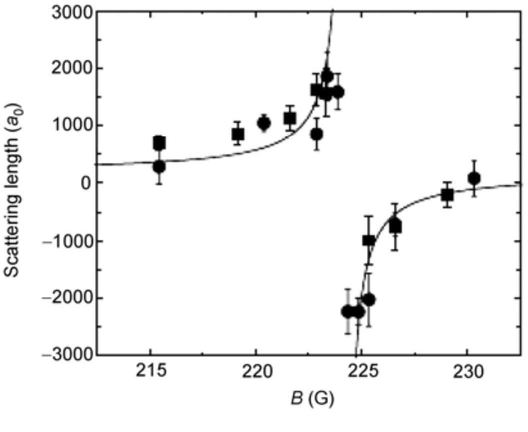

Figure 5 S-wave scattering length obtained from the RF spectrum of fermionic pottasium40 atoms [13].

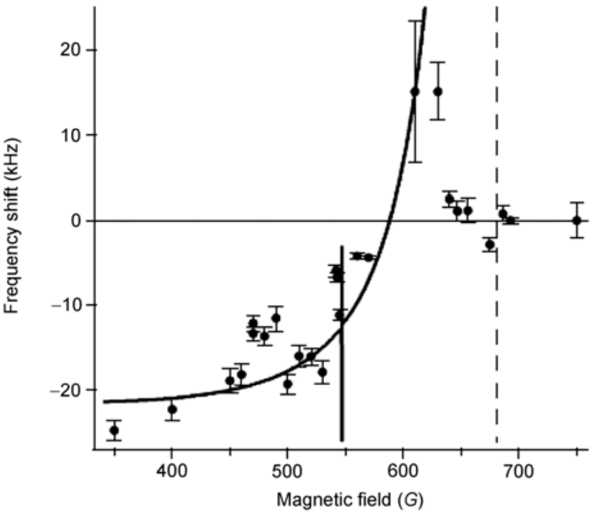

Figure 6 Frequency shift in the RF spectrum as a function of the external magnetic field [9].

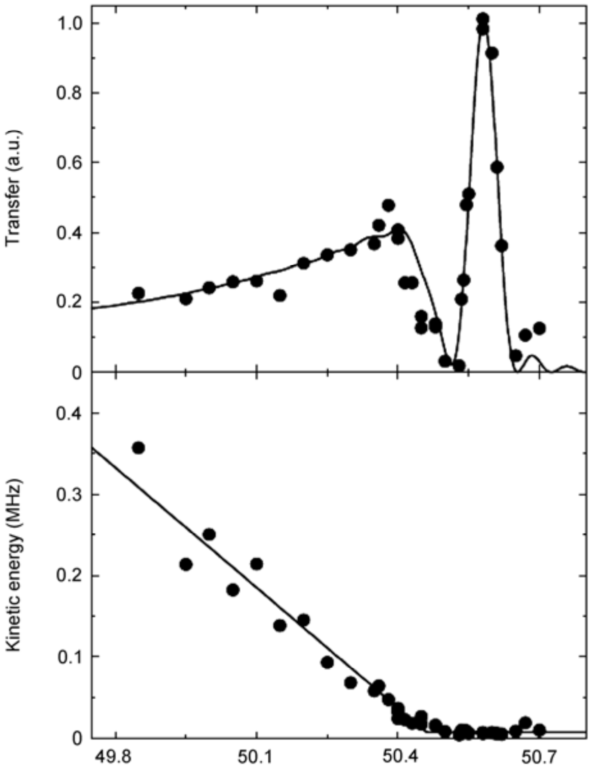

Figure 7 RF photodissociation spectrum of ultracold molecules and the dissociated kinetic energy per atom [11].

perconductivity. Also, combined with the *in-situ* imaging and 3D reconstruction, the spatially resolved RF spectrum can be used to probe the locally homogenous pairing gap [15] and phase transition from the normal state to the superfluid with a population imbalance [16].

For the population-balanced Fermi gas with sufficiently low temperature, all the atoms are bound into pairs and form a macroscopic supeufluid quantum state. But for the imbalanced Fermi gas with different populations or masses, Fermi energies of the two components are not equivalent and consequently, the Fermi surface will be deformed due to the attractive interaction. This imbalanced Fermi system shows many exotic quantum states, for example FFLO state [17], where pairing and superfluidity are greatly affected due to the mismatched Fermi surfaces [18]. This new pairing process is considered to have potential applications in understanding interaction mechanism in the high temperature superconductivity and other strongly correlated systems [19].

Free Fermi atoms require an additional energy to be bound into pairs, namely the pairing gap. But if the chemical potential difference between two components is larger than the pairing gap, pairing couldn't occur due to energy mismatching. A research group in MIT has measured the transition from the superfluid to the normal state by increasing the population imbalance [16]. Chandrasekhar Clogston limit (CC limit) is an important parameter to determine the population imbalance limit at which the superfluid couldn't form even at zero temperature, but it is difficult to be experimentally measured in metals due to Meissner effect. Ultracold atoms can afford an experimental platform to measure this parameter which couldn't be determined in solid materials. As indicated in Figure 8, the RF spectrum can be introduced to probe the minority and majority in Fermi gases, and then molecules and ferminonic polarons can be distinguished in various interaction strengths and population imbalances [20]. With this method, CC limit can be experimentally determined as expected.

4 RF photoemission spectroscopy in ultracold Fermi gases

In the conventional RF spectroscopy, the single-particle energy is only a function of the RF frequency, where the momentum of dissociated atoms is integrated. But the dispersion relation is critically dependent on the momentum distribution. So the energy and momentum resolved spectrum is necessary to probe the interacting system. As an analogue of the electron photoemission technique in condensed matter, the RF photoemission in Fermi gases is a combination of the RF excitation and 3D reconstruction of the TOF signal to extract the momentum distribution [21]. As indicated in Figure 9, for electrons scattered by an optical field, the single particle energy can be described as $E_{\mathrm{s}} = \varepsilon_k + \phi - h\nu$, , where $h\nu$ is the photon energy and φ is the surface potential. In ultracold atoms with a pairing gap, the single particle energy is $E_{\mathrm{s}} = \mu - \sqrt{(\mu - \hbar^2 k^2 / 2m)^2 + \Delta^2}$, where μ is the chemical potential, k is the wave vector and Δ is the pairing gap. If there is no pairing gap, the single particle energy is a quadratic function of the wave vector. However when the pairing process takes place in the Fermi gas, the dispersion will show a back-bending behavior. As indicated in Figure 10, back-bending of a strongly interacting Fermi gas in the large wave vector implies the existence of the pairing process. Also the binding energy of molecules can result in the back-bending behavior.

Pairing process involves important characters of the superfluid. With temperature being reduced, different spin states begin to pair at T^* under the many-body interaction. When the system reaches the threshold temperature T_{C}, all the pairs have a phase coherence and result in superfluidity. The pairing mechanism still remains controversial at the temperature above the superfluid transition [22,23]. Using the RF spectrum in strongly interacting Fermi gases at a finite temperature, the back-bending behavior indicates a pairing effect without superfluid, which is called the "pseudogap" [23].

5 Conclusion and discussion

The pairing effect plays a crucial role in interpreting the interaction mechanism in the BEC-BCS crossover of ultracold Fermi gases. RF spectroscopy is a powerful tool for measuring the pairing energy shift with respect to free at-

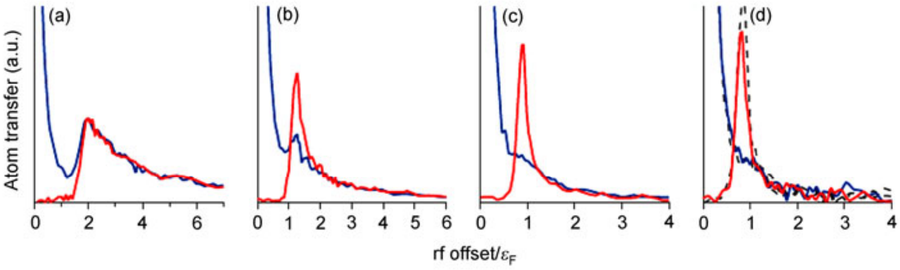

Figure 8 (Color online) RF spectrum of the majority and minority in Fermi gases with various interactions [20]. (a) is for the molecular limit, (b) and (c) for the Fermi polaron and (d) for the unitary regime.

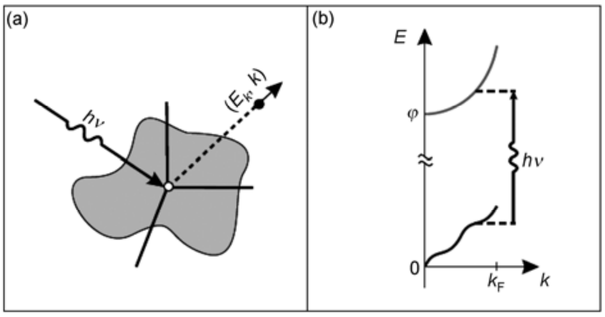

Figure 9 (a) Electron photoemission spectroscopy in solid materials where the original energy can be determined; (b) RF photoemission in ultracold atoms where a RF pulse drives a vertical transition with an unchanged momentum.

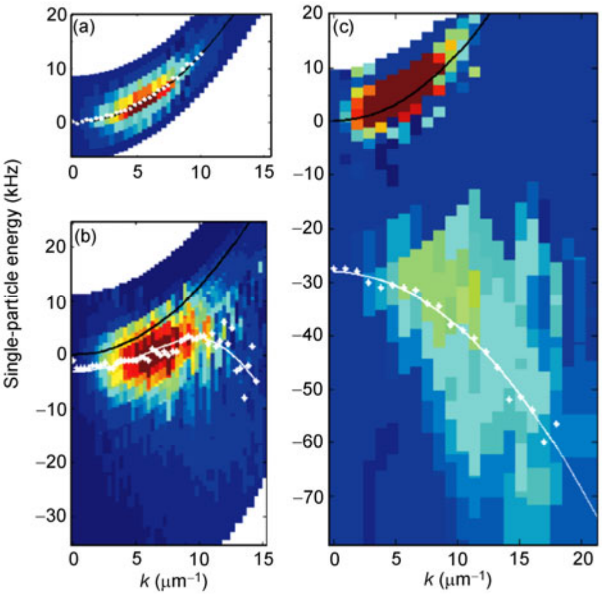

Figure 10 (Color online) RF photoemission spectroscopy in ultracold atoms [21]. (a) Data for weak interacting Fermi gases; (b) data for strong interacting Femi gases with back-bending which indicates the pairing gap; (c) on the BEC side of Fermi gases, free atoms and bound molecules can be distinguished in the RF spectrum.

oms. In this work, we just briefly summarize the applications of the RF spectroscopic method in probing the pairing gap in the ultracold quantum Fermi gas. Many-body or two-body interaction dominates in different regimes of ultracold atoms and both of them can result in an energy shift. Due to its narrow linewidth and high coupling efficiency, RF spectroscopy can be used to measure the mean-field interaction and unitary effect in different interactions. From the profile of the RF spectrum, one can get the information about the many-body and two-body pairing. For the population imbalanced Fermi gas, Fermi surface will be distorted because of the attractive interaction between different spin components. This imbalanced Fermi gas will show many exotic quantum states, and RF spectroscopy can be used to probe these quantum effects, such as CC limit and FFLO state, which are still research challenges in condensed-matter physics.

Combined with 3D reconstruction of a TOF signal, RF spectroscopy can give the dispersion relation which involves the kinetic energy and momentum distribution. As an analogue to the electron photoemission method in solid states, RF photoemission can provide us detailed information about the pairing effect in both momentum and frequency domains.

Ultracold Fermi gases with a tunable interaction provide a testbed to explore many-body and few-body physics in different interaction regimes. RF spectroscopy nowadays becomes an accurate probing and manipulating method to study an ultracold quantum gas. The narrow spectral linewidth and efficient coupling of an RF pulse can afford us the possibility to measure the slight but characteristic features caused by different interaction mechanisms in quantum gases. For example, the reduction of dimensions will have a big effect on the atomic interaction when atoms are confined in an optical dipole trap by using optical lattices [24]. Also, contrary to the broad Feshbach resonance, the kinetic energy should contribute to the scattering process on the narrow Feshbach resonance, which shows different phase diagrams in the strong interaction regime [25]. In addition, the spin-orbit-coupling [26] and imbalanced Fermi gas [27] will show us new quantum phases, which have recently become hot topics in research. RF spectroscopy can be used to probe these exotic quantum effects in the ultracold Femi gas and other measurement methods will be combined as a supplement.

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