Radio-frequency spectroscopy of weakly bound molecules in ultracold Fermi gas*

Huang Liang-Hui(黄良辉), Wang Peng-Jun(王鹏军), Fu Zheng-Kun(付正坤), and Zhang Jing(张 靖)†

State Key Laboratory of Quantum Optics and Quantum Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, *China*

(Received 30 June 2013; revised manuscript received 6 August 2013; published 2 December 2013)

We create weakly bound Feshbach molecules in ultracold Fermi gas ^{40}K by sweeping a magnetic field across a broad Feshbach resonance point 202.2 G with a rate of 20 ms/G and perform the dissociation process using radio-frequency (RF) technology. From RF spectroscopy, we obtain the binding energy of the weakly bound molecules in the vicinity of Feshbach resonance. Our measurement also shows that the number of atoms generated from the dissociation process is different at various magnetic fields with the same RF amplitude, which gives us a deeper understanding of weakly bound Feshbach molecules.

Keywords: Feshbach resonance, scattering length, weakly bound molecules

PACS: 34.20.Cf, 67.85.Hj, 03.75.Lm **DOI:** 10.1088/1674-1056/23/1/013402

1. Introduction

Ultracold Fermi gas is a versatile and flexible platform to study strongly interacting fermionic systems with regard to artificial optical potential and Feshbach resonance. Since the Feshbach resonance was first explored in the Bose–Einstein condensate (BEC) of ^{23}Na[1] and ^{85}Rb[2] atoms in 1998, this technique has become an important tool to control the interaction between atoms in ultracold quantum gases. Therefore, an effective way to produce the weakly bound Feshbach molecules is linearly sweeping a magnetic field across a Feshbach scattering resonance in ultracold atomic gas.[3] Scattering resonance, known as Feshbach resonance, occurs when the collision energy of two free atoms in an open channel equals that of a bound molecular state in one closed channel. By varying the strength of an external magnetic field, we can tune the relative atom–molecule energy through the Zeeman effect and arbitrarily controlling the strength of interactions between two atoms.[4–6] On the BEC side of the Feshbach resonance, the interaction is strong and repulsive ($a > 0$), and there is a weakly bound molecular state. On the Bardeen–Cooper–Schreiffer (BCS) side of the resonance, the gas has strongly attractive interaction ($a < 0$), where no two-body bound molecular state exists and many-body effects can give rise to pairing.[7] Close to the Feshbach resonance, the interaction can be described by a simple expression,[4] in which the s-wave scattering length varies dispersively as a function of the external magnetic field B

$$a(B) = a_{\rm bg}(1 - \frac{\Delta}{B - B_0}), \tag{1}$$

where Δ is the resonance width which is determined by the strength of coupling between the quasi-bound state and the free-particle state of the incoming atoms, $a_{\rm bg}$ is the background scattering length away from the resonance, and B_0 is the resonance position. The scattering length diverges, in the vicinity of which the two channels are strongly coupled and the scattering length goes to infinite. The other physical quality of interest here is the binding energy of Feshbach molecules near the resonance. It is well approximated by[8]

$$E_{\rm b} = \frac{\hbar^2}{m(a - r_0)^2}, \tag{2}$$

where $r_0 \approx 60a_0$ is the range of the van der Waals potential in our experiment,[7] and m is the mass of the ^{40}K atom.

The condensations of molecules on the BEC side of the Feshbach resonance and pairs on the BCS side of resonance have been observed in gas of ^{40}K and ^{6}Li atoms.[9–11] The binding energy is an important parameter for the weakly bound molecules associated via magnetically tunable Feshbach resonances. To precisely calibrate this parameter, many methods have been developed to dissociate the molecules and probe the properties of converted atoms, for example, through a powerful and effective tool of RF technology, which is similar to angle-resolved photoemission spectroscopy (ARPES).[12] In 2003, Jin's group measured the dissociation spectra and binding energies of weakly bound molecules by RF spectroscopy.[5,13] In this dissociation process, the RF-stimulated photoemission drives a vertical transition where the momentum is essentially unchanged. In 2012, our group successfully used momentum-resolved Raman spectroscopy to measure the binding energy of Feshbach molecules ^{40}K$_2$. In the Raman dissociation process, the dissociated atoms are transferred into another internal state with a different momentum.[14,15] By running one single experiment, we obtained the signals of unpaired (free) atoms and the bound molecules, and directly determined the binding energy.[16,17] From different dissociation processes, it is easy to see that the RF spectroscopy is a special case of Raman.

*Project supported by the National Basic Research Program of China (Grant No. 2011CB921601), the National Natural Science Foundation of China (Grant No. 11234008), the Project for Excellent Research Team of China (Grant No. 61121064), and the Doctoral Program Foundation of Ministry of Education, China (Grant No. 20111401130001).

†Corresponding author. E-mail: jzhang74@aliyun.com

© 2014 Chinese Physical Society and IOP Publishing Ltd

In this letter, we report on the production of the homonuclear, weakly bound Feshbach molecules of $^{40}K_2$ near an s-wave broad Feshbach resonance by ramping the magnetic field from the BCS side to pass the Feshbach resonance point $B_0 = 202.2$ G at a rate of 20 ms/G. The experiment is performed with a balanced two component mixture of a quantum Fermi gas of ^{40}K. First, the atoms are prepared in two magnetic sublevels $|1\rangle = |F = 9/2, m_F = -9/2\rangle$ and $|2\rangle = |F = 9/2, m_F = -7/2\rangle$ states. When producing Feshbach molecules in the highest vibrational state, we apply a Gaussian-shaped RF pulse to dissociate Feshbach molecules into free atom states $|1\rangle$ and $|3\rangle = |F = 9/2, m_F = -5/2\rangle$. Finally, we obtain the RF spectroscopy by recording the atomic number of $|3\rangle$ versus the RF frequency. Two features are observed in the spectroscopy: a symmetric atomic peak near the hyperfine transition of free atoms, and an asymmetric molecular peak, which means that the RF pulse dissociates $^{40}K_2$ molecules. The distance between the atomic peak and the onset of the molecular peak corresponds to the binding energy E_b. Furthermore, we compare the number of Feshbach molecules at different external magnetic fields using identical RF amplitudes.

2. Experimental setup and sequence

In our experiment, the mixture of ^{87}Rb atoms ($\sim 1 \times 10^7$) at the spin state $|F = 2, m_F = 2\rangle$ and ^{40}K atoms ($\sim 4 \times 10^6$) at the spin state $|F = 9/2, m_F = 9/2\rangle$ are precooled to 1.5 μK by radio-frequency evaporation cooling in configuration (QUIC) trap,[18–21] and then are transported to the center of the glass cell[22,23] to enable optical observation, where F is the quantum number of atomic total angular momentum, and m_F is the projection along the magnetic direction. Both species are loaded into the optical dipole trap, and we obtain the degenerate Fermi gas of 2×10^6 ^{40}K atoms in the lowest hyperfine Zeeman state $|9/2, 9/2\rangle$ by decreasing the depth of the optical trap. The optical dipole trap is created by two far-resonance laser beams, at a wavelength of 1064 nm, crossing in the horizontal plane. The temperature of the Fermi gas is $0.3T_F$–$0.4T_F$, where the Fermi temperature is defined by $T_F = \hbar\varpi(6N)^{1/3}/k_B$. Here $\varpi = (\omega_x\omega_y\omega_z)^{1/3}$ is the geometric mean of the optical trap frequency, N is the number of ^{40}K atoms, and k_B is the Boltzmann constant. In the region of degenerate Fermi gas, the optical trap frequency is $2\pi \times (116, 116, 164)$ Hz along the (x, y, z) direction. At the same time, we use a resonant laser beam for 30 μs to remove the ^{87}Rb atoms without losing and heating ^{40}K atoms.[14,15] Finally, we transfer ^{40}K atoms from the $|F = 9/2, m_F = 9/2\rangle$ state to the $|1\rangle = |F = 9/2, m_F = -9/2\rangle$ state in a rapid adiabatic passage induced by sweeping an RF field across all the magnetic Zeeman states in $F = 9/2$ manifold in 50 ms, where the horizontal external magnetic field is about 19.6 G.[24]

To create the bound molecules, the atoms in $|1\rangle$ state are transferred to a 50/50 mixture of $|1\rangle$ and $|2\rangle$ in higher magnetic field $B = 203.6$ G by RF of $\pi/2$ pulse. Then, we adiabatically ramp the external magnetic field from $B_1 = 204$ G at the BCS side to various final magnetic field values B_2 (201.1–201.6 G) at the BEC side of the resonance in 20 ms, and associate two free atoms into Feshbach molecules (see Fig. 1(a)). To measure the binding energy, after a waiting time $t_w = 30$ ms we apply an RF pulse with Gaussian amplitude envelop and width of 50 μs or 500 μs at the center frequency about $\nu_{RF} \approx 47$ MHz close to the hyperfine transition of $|2\rangle$ and $|3\rangle$ states, which will transfer free atoms in state $|2\rangle$ or dissociate bound molecules to the free atom states $|3\rangle$ and $|1\rangle$, as shown in Fig. 1(c). In this process, we assumed that the $|3\rangle$ state is an ideal probe state which is empty and has weak interactions with atoms in $|1\rangle$ and $|2\rangle$ states. The two-body s-wave scattering lengths $a_{13} = 250a_0$ and $a_{23} = 170a_0$ are much smaller than the scattering length $a_{12} \approx 2000a_0$,[25] so the interaction effect of atoms in $|3\rangle$ state in probe process can be neglected, as shown in Fig. 1(b). Subsequently, we immediately turn off the optical trap and the magnetic field, let the atoms ballistically expand in 12 ms and take the time-of-flight (TOF) absorption image. For the final readout, we apply a magnetic field gradient in the first 10 ms during free expansion, which creates a spatial separation of different Zeeman states in a Stern–Gerlach effect. Then the number of atoms in each state is independently measured from the TOF image, as shown in Fig. 1(a).

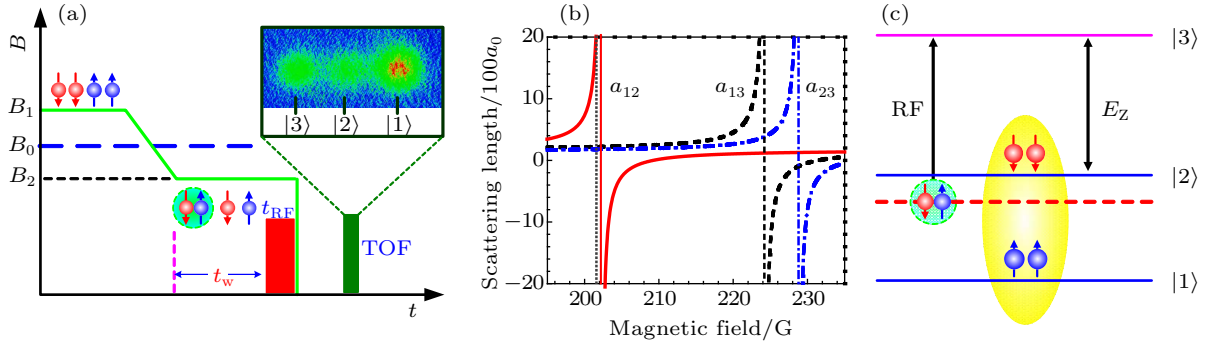


Fig. 1. (color online) (a) Time sequence of the external magnetic field to associate free atoms into Feshbach molecules, where $B_1 = 204$ G and B_2 are the initial and final external magnetic field, and $B_0 = 202.2$ G is the resonant point, respectively. Inset is a typical absorption image of three hyperfine states after 12-ms TOF. (b) Plot of the scattering lengths a_{12} (solid red line), a_{13} (dashed black line), and a_{23} (dash-dotted blue line) as functions of magnetic field. In the range of magnetic field (vertical dotted thick line), a_{12} is much bigger than the other two. (c) Schematic of the RF spectra measurement. We apply an RF pulse to transfer free atomic state $|2\rangle$ to the empty state $|3\rangle$ or dissociate molecular state (dashed red line) into free atom states $|3\rangle$ and $|1\rangle$.

3. Experimental results

Typical RF spectra at magnetic field on the BEC side of the Feshbach resonance are shown in Fig. 2. Analyzing the RF spectrum, we can obtain the binding energy of the weakly bound molecules by recording the atomic number peaks in the probe state as a function of the RF frequency $\nu_{\rm RF}$ and extracting the RF line-shapes in Fig. 2. Two features are apparent: the left narrow and symmetrical peak at low frequency corresponds to the Zeeman transition from state $|2\rangle$ to state $|3\rangle$, which can be used to precisely determine the magnetic field and noise using the Breit–Rabi formula.[26] The second right broader and asymmetrical peak at higher frequency is ascribed to the Feshbach molecules. The distance between the atomic peak and the onset of the molecular feature yields the binding energy $E_{\rm b}$. In Fig. 2 the dots are experimental data and the solid line is the combination of Gaussian fitting for the atomic feature and analytic formula fitting for the molecular tail,[27]

$$I(\nu_{\rm rf}) \propto \sqrt{h\nu_{\rm rf} - E_{\rm b}}/(h\nu_{\rm rf})^2, \tag{3}$$

where $\nu_{\rm rf}$ indicates $\nu_{\rm RF} - \nu_{\rm atom}$ and $\nu_{\rm atom}$ is the resonant frequency between the spin states $|2\rangle$ and $|3\rangle$. Recently, there is a new deep understanding of the bound-free spectrum: the tail is determined by the overlap between the wave functions of the initial molecular state and the free atomic final state in the trap.[28,29] In the RF-induced dissociation of weakly bound molecules, there is no net transferred momentum to the system, just an effect on the relative motion of the two atoms. In Ref. [28], Zürn *et al.* resolved the discrete trap levels in the radio-frequency dissociation spectra.

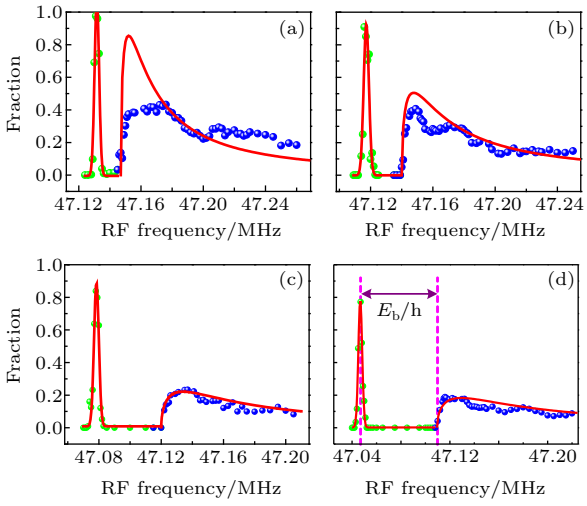


Fig. 2. (color online) Comparison of the experimental spectroscopy on the BEC side of the Feshbach resonance ($a > 0$). The dots are the experimental results, and the solid line is the fitting curve of an analytic formula (Eq. 3).

Comparing the four cases under different final magnetic fields B_2 in Fig. 2, we can see that with the external magnetic field decreasing, the distances between the two peaks (considered as the binding energy of molecules) becomes larger, revealing that the binding energy is dependent on the detuning of magnetic field from the Feshbach resonance. In Fig. 3, we plot the binding energy values versus the external field in the four measurements. The measurement results (blue points) is in good agreement with the theoretical ones using Eq. (2) (solid red line).

Having insight into the spectra in Fig. 2, we can also find that the magnitude of the tail varies at different magnetic field values, and the amplitude decreases as the magnetic field deviates more and more from the Feshbach resonance point. This is mostly attributable to the difference of transition strength between the bound molecules' states and free atoms' states in different external magnetic fields.

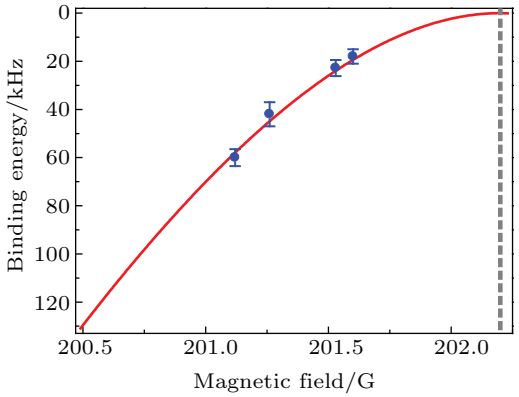


Fig. 3. (color online) Binding energy of weakly bound molecules versus the external magnetic field. The blue error bars are the binding energies of the molecules in experiment, and the red solid line is the theoretical calculation.

4. Conclusions

In conclusion, we have created weakly bound ultracold Feshbach molecules from two spin components of Fermi gas by ramping the external magnetic field across the resonance, slowly enough to follow the avoided crossing adiabatically and convert pairs of trapped atoms into trapped molecules. In the association process, there is essentially no kinetic energy created, and the molecules have the same energy as the converted atoms. We also used RF technology to obtain RF spectra, which can be used to measure and investigate the magnetic field-dependent binding energy of weakly bound molecules. The results are in good agreement with the theoretical function. Moreover, the dependence of transition strength on external magnetic field has also been observed. In the future, RF dissociation spectroscopy of weakly bound molecules could be used to study ultracold molecule–molecule or molecule–atom collisions or used in the presence of spin-orbit coupling.

References

[1] Inouye S, Andrews M R, Stenger J, Miesner H J, Stamper-Kurn D M and Ketterle W 1998 *Nature* **392** 151
[2] Courteille Ph, Freeland R S, Heinzen D J, van Abeelen F A and Verhaar B J 1998 *Phys. Rev. Lett.* **81** 69
[3] Köhler T, Góral K and Julienne P S 2006 *Rev. Mod. Phys.* **78** 1311

[4] Chin C, Grimm R, Julienne P and Tiesinga 2010 *Rev. Mod. Phys.* **82** 1225
[5] Regal C A, Ticknor C, Bohn J L and Jin D S 2003 *Nature* **424** 47
[6] Regal C A, Greiner M and Jin D S 2004 *Phys. Rev. Lett.* **92** 083201
[7] Greiner M, Regal C A and Jin D S 2005 *Phys. Rev. Lett.* **94** 070403
[8] Szymańska M H, Góral K, Köhler T and Burnett K 2005 *Phy. Rev. A* **72** 013610
[9] Stewart J T, Gaebler J P and Jin D S 2008 *Nature* **454** 744
[10] Gaebler J P, Stewart J T, Drake T E, Jin D S, Perali A, Pieri P and Strinati C 2010 *Nat. Phys.* **569** 1709
[11] Zwierlein M W, Stan C A, Schunck C H, Raupach S M F, Kerman A J and Ketterle W 2004 *Phys. Rev. Lett.* **92** 120403
[12] Damascelli A 2004 *Phys. Scr.* **T109** 61
[13] Greiner M, Regal C A and Jin D S 2005 *Phys. Rev. Lett.* **94** 070403
[14] Dao T L, Georges A, Dalibard J, Scalomon C and Carusotto I 2007 *Phys. Rev. Lett.* **98** 240402
[15] Dao T L, Carusotto I and Georges A 2009 *Phys. Rev. A* **80** 023627
[16] Wang P J, Fu Z K, Huang L H and Zhang J 2012 *Phys. Rev. A* **85** 053626
[17] Fu Z K, Wang P J, Huang L H, Meng Z M and Zhang J 2012 *Phys. Rev. A* **86** 033607
[18] Wei D, Xiong D Z, Chen H X and Zhang J 2007 *Chin. Phys. Lett.* **24** 679
[19] Wang P J, Xiong D Z, Fu Z K and Zhang J 2011 *Chin. Phys. B* **20** 016701
[20] Wei D, Xiong D Z, Chen H X, Wang P J, Guo L and Zhang J 2007 *Chin. Phys. Lett.* **24** 1541
[21] Xiong D Z, Chen H X, Wang P J, Yu X D, Gao F and Zhang J 2008 *Chin. Phys. Lett.* **25** 843
[22] Xiong D Z, Wang P J, Fu Z K and Zhang J 2010 *Opt. Express* **18** 1649
[23] Wang P J, Chen H X, Xiong D Z, Yu X D, Gao F and Zhang J 2008 *Acta Phys. Sin.* **57** 4840 (in Chinese)
[24] Wang P J, Fu Z K, Chai S J and Zhang J 2011 *Chin. Phy. B* **20** 103401
[25] Ludewig A 2012 *Feshbach Resonance in* ^{40}K (Ph.D. disseration) (Amsterdam: Universiteit van Amsterdam)
[26] Daniel A 2010 *Rubidum* 87 *D Line Data*
[27] Schunck C H, Shin Y I, Schirotzek A and Ketterle W 2008 *Nature* **454** 739
[28] Chin C and Julienne P S 2005 *Phys. Rev. A* **71** 012713
[29] Zürn G, Lompe T, Wenz A N, Jochim S, Julienne P S and Hutson J M 2013 *Phys. Rev. Lett.* **110** 135301