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Feshbach resonances in an ultracold mixture of ^{87}Rb and ^{40}K*

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We report the experimental preparations of the absolute ground states of ^{87}Rb and ^{40}K atoms ($|F=1, m_{\mathrm{F}}=1\rangle + |F=9/2, m_{\mathrm{F}}=-9/2\rangle$) by means of the radio-frequency and microwave adiabatic rapid passages, and the observation of magnetic Feshbach resonances in an ultracold mixture of bosonic ^{87}Rb and fermionic ^{40}K atoms between 0 T and 6.0×10^{-2} T, including 7 homonuclear and 4 heteronuclear Feshbach resonances. The resonances are identified by the abrupt trap loss of atoms induced by the strong inelastic three-body collisions. These Feshbach resonances should enable the experimental control of interspecies interactions.

Keywords: adiabatic rapid passages, homonuclear Feshbach resonance, heteronuclear Feshbach resonances

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1. Introduction

Quantum degenerate gases in ultracold temperature offer new opportunities for studying novel macroscopical quantum phenomena. Since the observation of magnetic Feshbach resonances in ^{23}Na Bose–Einstein condensate (BEC)[1] and ^{85}Rb cold atom,[2] magnetic-field Feshbach resonances have been used as a versatile tool for manipulating quantum degenerate atomic gases, which enriches the field of the physics of degenerate matter. Simply by varying the strength of an applied uniform magnetic field, one can continuously tune the interaction between ultracold atoms in arbitrary values repulsive ($a > 0$), attractive ($a < 0$), non interacting ($a = 0$) or strongly interacting ($|a| \to \infty$). The unique tunability provided by Feshbach resonances has enabled the controlled collapse of a BEC,[3,4] the creation of bright matter wave solitons,[5,6] the formation of ultracold diatomic molecules,[7] the realization of the BCS–BEC crossover in dilute gases,[8] and the observation of the Efimov spectrum in ultracold gases.[9]

Alongside experimental efforts, substantial work has also been done on the theory of Feshbach resonances. Over last decade various models have been developed for ultracold collisions, the coupled channel calculation,[10,11] the variable phase theory,[12,13] the multichannel quantum defect theory (MQDT),[14] and the asymptotic bound state model (ABM).[15] Feshbach resonance depends crucially on the existence of an internal atomic structure, which can be modified by an external field. A magnetically tuned Feshbach resonance occurs when the bound molecular state in the closed channel energetically approaches the scattering state in the open channel where the atoms are prepared. This can be described by a simple expression, for the s-wave scattering length a as a function of the magnetic field B,

$$a(B) = a_{\mathrm{bg}}\left(1 - \frac{\varDelta}{B - B_0}\right), \tag{1}$$

where a_{bg} is the background scattering length, $\varDelta$ is the resonance field width, and B_0 is the resonance field strength, defined by the crossing of a bound state of a closed channel with the threshold of the open channel.

The mixture of K and Rb has aroused considerable interest, since there are several isotopic pairs that are easy to bring into ultracold and quantum degenerate regimes. The main isotopic combinations

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present several accessible Feshbach resonances and the ground-state dimmer has a relatively large electric-dipole moment.[16]

In this paper we report an extensive experimental study of the Feshbach resonances in an ultracold mixture of ^{87}Rb (boson) and ^{40}K (fermion) between 0 T and 6.0×10^{-2} T, including boson–boson, fermion–fermion and boson–fermion systems. The observed Feshbach resonances include 4 heteronuclear Feshbach resonances in the absolute ground states of ^{87}Rb $|1,1\rangle$ and ^{40}K $|9/2,-9/2\rangle$, 5 homonuclear Feshbach resonances of ^{87}Rb in $|1,1\rangle$. Moreover, 1 p-wave Feshbach resonance of ^{40}K in hyperfine state $|9/2,-7/2\rangle$ and 1 homonuclear Feshbach resonance of ^{40}K in hyperfine states mixture of $|9/2,-7/2\rangle$ and $|9/2,-9/2\rangle$ are also measured. We observe the heating of the gas due to the increased inelastic collision near Feshbach resonances and present the characteristic of p-wave Feshbach resonance in hyperfine state $|9/2,-7/2\rangle$ of ^{40}K at 1.988×10^{-2} T.

2. Experimental setup

2.1. Mixture of ^{87}Rb and ^{40}K in an optical trap

The apparatus and cooling scheme in the experiment have been described in previous papers[16–18] and are briefly introduced here (see Fig. 1). We simultaneously cool ^{87}Rb and ^{40}K atoms by laser in an ultrahigh vacuum cell where the vacuum is kept at 3.0×10^{-9} Pa. The atoms are optically pumped to their doubly polarized spin states, $|F = 9/2,\ m_{\rm F} = 9/2\rangle$ for ^{40}K and $|F = 2,\ m_{\rm F} = 2\rangle$ for ^{87}Rb as shown in Figs. 2 and 3. Here F is the total spin, and $m_{\rm F}$ is the spin projection. Then the atoms are transferred over a distance of 12 mm from the quadrupole trap centre to a harmonic magnetic trap in quadrupole-Ioffe configuration (QUIC). In this configuration, all three coils (two quadrupole coils and one Ioffe coil) are driven by a single power supply at a current of 32.5 A, yielding a stable magnetic field trap. The corresponding harmonic trap frequencies are $\omega_z = 2\pi \times 16.3$ Hz in the axial direction and $\omega_r = 2\pi \times 179.3$ Hz in the radial direction for ^{87}Rb. The corresponding ^{40}K trap frequencies are a factor of $\sqrt{m_{\rm Rb}/m_{\rm K}} \approx 1.47$ bigger, where $m_{\rm Rb}$ and $m_{\rm K}$ are the atomic masses of ^{87}Rb and ^{40}K, respectively. After the ^{87}Rb and ^{40}K atoms are loaded into the trap, radio frequency (RF) evaporative cooling for 43 s resulted in an almost pure Bose–Einstein condensate of 2×10^5 ^{87}Rb atoms and a quantum degeneracy Fermi gas of 1×10^6 ^{40}K atoms.

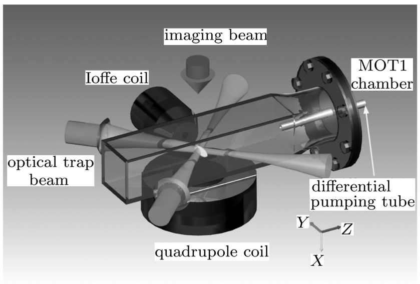

Fig. 1. Schematic drawing of the experimental setup where the Feshbach resonance of ^{87}Rb and ^{40}K mixture is studied using a homogeneous magnetic field created by the quadrupole coils in an optical trap.

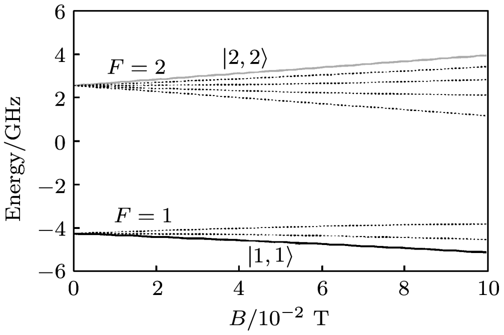

Fig. 2. Hyperfine states of ^{87}Rb with a nuclear spin $I = 3/2$ versus magnetic field B. The solid line in the upper ground state manifold represents the $|2,2\rangle$ state where we perform the evaporative cooling in the QUIC trap. The solid line in the lower manifold denotes the absolute ground state $|1,1\rangle$ state transferred from $|2,2\rangle$ by an MW adiabatic rapid passages, where we observe the Feshbach resonance in an optical trap.

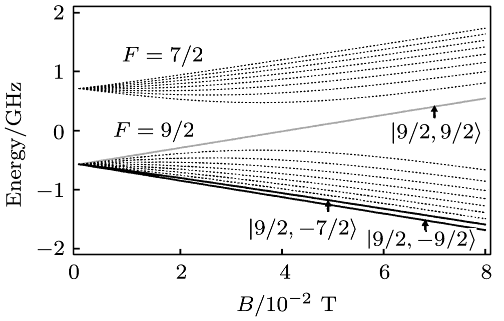

Fig. 3. Hyperfine states of ^{40}K with a nuclear spin $I = 4$ versus magnetic field B. The solid line in the upper ground state manifold represents the $|9/2,9/2\rangle$ state used for sympathetic cooling in the QUIC trap. The solid line in the lower manifold denotes the absolute ground state $|9/2,-9/2\rangle$ state transferred from $|9/2,9/2\rangle$ by an RF adiabatic rapid passages. The solid line in the lower manifold refers to $|9/2,-7/2\rangle$ state transferred from $|9/2,-9/2\rangle$ where we observe the Feshbach resonance in an optical trap.

To manipulate the interaction of cold atoms via Feshbach resonance in a homogeneous magnetic field created by the quadrupole coils with a better optical and mechanical access, it is necessary to transport the ultracold atom samples from QUIC trap to the centre of the quadrupole coils (glass cell). In our experiment we transport nonadiabaticly the atom sample at about 2 μk over a distance of 12 mm in horizontal direction to the centre of the quadrupole coils. Then the atomic sample is transferred into an optical trap created by two off-resonance laser beams, at a wavelength of 1064 nm, crossing in the horizontal plane.[19] The atoms are further evaporatively cooled in the optical trap by reducing the power of the infrared beam in 800 ms, while the common temperature of the two gases was about 1 μk. At this temperature, the two samples are near the point of quantum degenerate.

2.2. The preparation of Zeeman states

The spin states of atoms are then transferred into the selected states by means of a series of radio frequency (RF) and microwave (MW) adiabatic rapid passages. In this process, the frequency tuning must be fast enough compared with the relaxation time of the atomic spin states and slow enough so that the transfer of the spin states can be produced adiabatically. The electromagnetic field intensity is chosen for optimizing the strength of adiabatic coupling to maximize the transferring efficiency. A horizontal homogeneous magnetic field is raised to about 4.0×10^{-4} T to transfer the ^{87}Rb atoms from the $|2,2\rangle$ state to the $|1,1\rangle$ state through a microwave rapid adiabatic passage. The typical MW frequency ramp is from 6843.535 MHz to 6842.535 MHz in 50 ms. The transfer efficiency is better than 95% and the remaining atoms in the $|2,2\rangle$ state are removed by a resonant light pulse in 30 μs.

In order to prepare the ^{40}K atoms in $|9/2,-9/2\rangle$ state, we ramp the magnetic field to about 2.0×10^{-3} T, where the quadratic energy splitting between the sublevels of the ground state in ^{40}K and ^{87}Rb allows the separate addressing of individual transitions. In our experiment the horizontal field is raised to 1.96×10^{-3} T to transfer ^{40}K from the $|9/2,9/2\rangle$ state to the $|9/2,-9/2\rangle$ state via a rapid adiabatic passage induced by an RF field sweeping across the ten magnetic sublevels in 50 ms. Here, it is noticed that the magnetic component of the RF or MW electromagnetic field should be perpendicular to the quantization axis of the atoms to maximize the transfer efficiency. To prepare a spin mixture of ^{40}K in $|9/2,-9/2\rangle$ and $|9/2,-7/2\rangle$ states, a homogeneous magnetic field, produced by the quadrupole coils operating in Helmholtz configuration, is raised to about 1.2×10^{-2} T. The ^{40}K atoms are transferred from the $|9/2,-9/2\rangle$ to the $|9/2,-7/2\rangle$ state by using RF sweep within 200 ms. The final Bose–Fermi mixture, Bose–Bose mixture or Fermi–Fermi mixture is stable against spin-exchange collisions: when one of the components is in the lowest energy spin state and the other is in any magnetic sublevel of its ground hyperfine state.

3. Experimental results

Once the atomic sample has been prepared in the spin mixture of interest, the magnetic field, produced by the quadrupole coils operated in Helmholtz configuration, is quickly increased to a certain value. In order to control the magnetic field precisely, the power supply (Delta SM70-45D) operates in the constant voltage mode and the current through the coils is controlled by the external controller relying on a precision current transducer (Danfysik ultastable 867-60I). The magnetic field is calibrated between 3.0×10^{-2} and 6.0×10^{-2} T using the ^{87}Rb $|1,1\rangle \rightarrow |2,2\rangle$ RF transition.

To look for Feshbach resonances, we record the fraction of atoms lost through inelastic collisions after a hold time between 0.2 s and 2 s in a fixed magnetic field. The hold time is chosen such that the maximum loss of atoms is approximately 20%. After the hold time, the magnetic field is lowered to a small bias field and turned off. Simultaneously the atoms are released from the optical trap, then the absorption images are taken after 5-ms expansion time for ^{40}K and 15 ms for ^{87}Rb. We search the magnetic field for Feshbach resonances in a range between 0 T and 6.0×10^{-2} T by observing the abrupt trap loss of the heteronuclear or homonuclear mixtures. To avoid any possible confusion with other resonances, we also check the absence of loss after one component of the mixture has been removed before the magnetic field is applied. Strong inelastic losses from optically trapped pure ^{87}Rb atoms in $|1,1\rangle$ state are observed at the resonance positions of 3.193×10^{-2}, 3.8725×10^{-2}, 3.9149×10^{-2}, 4.0623×10^{-2}, and 5.5147×10^{-2} T, separately as shown in Fig. 4 and Table 1. For each resonance, a Gaussian fit is used to extract the central position and the width of the resonance. The resonance at 4.0623×10^{-2} T is an s-wave Feshbach resonance, the others are d-wave resonances. The two-^{87}Rb atom boson–boson system is now well characterized experimentally[20,21] and understood theoretically through both continuum and bound-state calculations.[22] The loss of trapped atoms in the vicinity of a Feshbach resonance is treated as a two-stage reaction, using the Breit–Wigner theory.[23] The first stage is the formation of a resonant diatomic molecule, and the second one is its deactivation by inelastic collisions with other atoms.

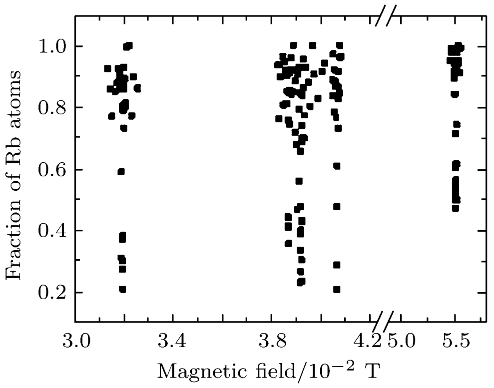

Fig. 4. The atom number of ^{87}Rb as a function of the magnetic field in the absolute ground state $|1,1\rangle$ for homonuclear Feshbach resonances. The feature near 4.06×10^{-2} T shows s-wave resonances, the others indicate d-wave resonances.

Table 1. Experimental observed magnetic field positions of the Feshbach resonances in ultracold atoms ^{87}Rb, ^{40}K and the mixtures. l is the orbital angular momentum of the molecular state associated with each resonance.

$\vert F_1, m_{F1}\rangle + \vert F_2, m_{F2}\rangle$	$B_{\text{expt}}/10^{-2}$ T	l
$\vert 1,1\rangle + \vert 1,1\rangle$	3.193	2
	3.8725	2
	3.9149	2
	4.0623	0
	5.5147	2
$\vert 1,1\rangle + \vert 9/2,-9/2\rangle$	4.6245	0
	4.9571	0
	5.1575	1
	5.4689	0
$\vert 9/2,-9/2\rangle + \vert 9/2,-7/2\rangle$	2.021	0
$\vert 9/2,-7/2\rangle + \vert 9/2,-7/2\rangle$	1.988	1

We also observe 4 heteronuclear Feshbach resonances in the absolute ground states of ^{87}Rb $|1,1\rangle$ and ^{40}K $|9/2,-9/2\rangle$ as shown in Fig. 5 and Table 1. The resonance at 5.5175×10^{-2} T is a p-wave Feshbach resonance, the others are s-wave resonances. Our measured resonances of the K–Rb system are consistent with the experimental observation[24–27] and the theoretical prediction.[28,29] The isotropic singlet $X^1\Sigma^+$ and triplet $a^1\Sigma^+$ interaction potentials are parameterized in terms of the scattering lengths a_s and a_t, respectively. In the above Feshbach resonances, the s-wave resonances ($l = 0$) are the simplest type of pairing. In this case, the pairing is isotropic in space and does not involve orbital angular momentum. The s-wave Feshbah resonance at 5.467×10^{-2} T with a width of 3.0×10^{-4} T has been widely used to produce heteronuclear molecule in an optical dipole trap or a three-dimensional (3D) optical lattice. Figure 6 shows the relative inelastic losses of potassium atoms and the heating induced by the inelastic collision near 4.9571×10^{-2} T.

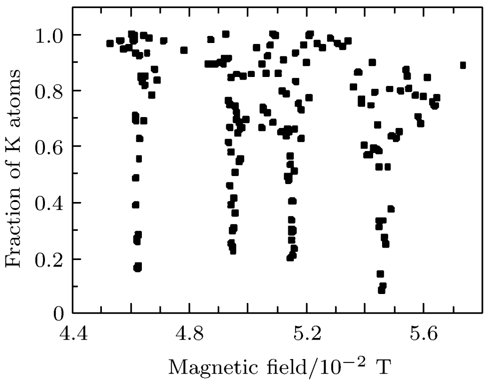

Fig. 5. The atom number of ^{40}K as a function of the magnetic field in a ^{40}K–^{87}Rb mixture in its absolute ground state for interspecies Feshbach resonances. The feature near 5.1575×10^{-2} T is for p-wave resonances, the others are for s-wave resonances.

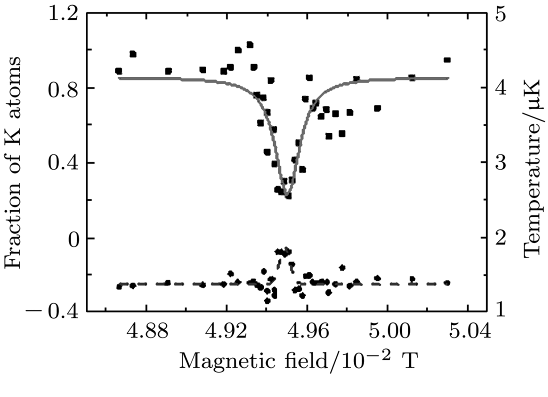

Fig. 6. Loss of atom number (black square) and an increase in the temperature (black circles) of ^{40}K observed near the interspecies Feshbach resonance at 4.9571×10^{-2} T. A Gaussian fitting (solid line) of the atom number is used to extract the central position and the width of the resonance.

We also measure 1 s-wave homonuclear Feshbach resonance of ^{40}K in hyperfine state mixture of $|9/2,-9/2\rangle$ and $|9/2,-7/2\rangle$ at 2.021×10^{-2} T and

1 p-wave Feshbach resonance of ^{40}K in $|9/2,-7/2\rangle$ at 1.988×10^{-2} T, as shown in Fig. 7, which have been reported in Refs. [30] and [31]. In the case of p-wave Feshbach resonance, the resonance is distinct from the s-wave resonance, in which the atoms must overcome a centrifugal barrier to couple to the bound state. Since the atoms need to tunnel through the centrifugal barrier to couple to the bound state, the position as well as the width of the p-wave Feshbach resonance is energy-dependent. The p-wave Feshbach resonance ($l=1$) corresponds to the different projections of the orbital angular momentum of the atomic pair, including the projection, $m_l=-1,0$, or 1. The difference between the m_l projections can be understood intuitively by considering the dipole–dipole interaction between the two atoms, which is detailed in Ref. [32]. The resonances are split into two components, depending on the magnitude of the resonant state projection of orbital angular momentum onto the field axis. Figure 7 shows clearly the doublet feature of the p-wave resonance through heating of the gas. This interesting resonant behaviour will represent distinct features depending on the dimensionality and the symmetry of the trap system.[33]

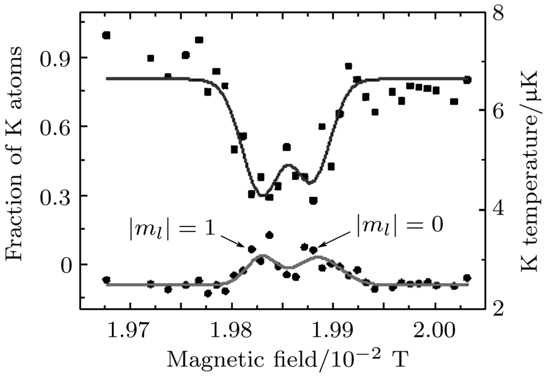

Fig. 7. Atom loss (black square) and heating (black circles) measurements of ^{40}K in $|9/2,-7/2\rangle$ near the p-wave Feshbach resonance at 1.988×10^{-2} T. The solid (dashed) line is for two-peak Gaussian fitting to the temperature (atom number) from which we can clearly observe the doublet feature of the p-wave resonance.

4. Conclusions

We have observed ten Feshbach resonances of an ultracold ^{87}Rb–^{40}K mixture between 0 T and 6.0×10^{-2} T by recording the fraction of atoms lost through inelastic collisions after a hold time in a fixed magnetic field. We also presented the heating of gas due to the inelastic processe near the Feshbach resonance and an interesting characteristic with the doublet feature for the p-eave Feshbach resonance. The Feshbach resonance provides a versatile tool for manipulating the interaction between ultracold atoms in order to study various quantum phenomena.

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