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Experimental investigation of evaporative cooling mixture of bosonic ^{87}Rb and fermionic ^{40}K atoms with microwave and radio frequency radiation*

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We investigate sympathetic cooling fermions ^{40}K by evaporatively cooling bosonic ^{87}Rb atoms in a magnetic trap with microwave and radio frequency induced evaporations in detail. The mixture of bosonic and fermionic atoms is prepared in their polarized spin states $|F = 9/2, m_F = 9/2\rangle$ for ^{40}K and $|F = 2, m_F = 2\rangle$ for ^{87}Rb, which is trapped in Quadrupole–Ioffe–Configuration trap. Comparing microwave with radio frequency evaporatively cooling bosonic ^{87}Rb atoms with sympathetically cooling Fermi gas ^{40}K, we find that the presence of rubidium atoms in the $|2, 1\rangle$ Zeeman states, which are generated in the evaporative process, gives rise to a significant loss of ^{40}K due to inelastic collisions. Thus, the rubidium atoms populated in the $|2, 1\rangle$ Zeeman states should be removed in order to effectively perform sympathetically cooling ^{40}K with the evaporatively cooled ^{87}Rb atoms.

Keywords: microwave and radio frequency induced evaporation, sympathetically cooling, inelastic collisions

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1. Introduction

Since the fist realization of quantum degeneracy mixture of bosonic ^{7}Li and fermionic ^{6}Li atoms,[1,2] degenerate Bose–Fermi mixture, which rarely occurs in nature, has become one of the central topics of the physics of ultracold gases, and attracted much attention in experiment and theory in many body problem,[3] strongly interacting quantum regime,[4] production of ultracold heteronuclear molecules[5] and so on. In the most experiments on ultracold atoms and atomic mixtures, the atoms are trapped in conservative magnetic potentials and ultracold temperatures are reached through evaporative cooling, for instance, with radio frequency (RF) and microwave (MW).

The different evaporation methods have different applicabilities and efficiencies. The use of MW radiation in evaporative cooling has been explored by a number of groups and it has become a common technique in the field of ultracold atoms.[6−10] The utilization of MW radiation for evaporative cooling of ^{87}Rb in the $|2, 2\rangle$ state will induce the generation of ^{87}Rb atoms in the $|2, 1\rangle$ state, which was also reported in Refs. [6]–[9]. The impurity of ^{87}Rb atoms in the $|2, 1\rangle$ state will affect the efficient sympathetic cooling in ultracold Fermi–Bose atomic mixtures. For instance, in the sympathetic cooling of ^{41}K by ^{87}Rb,[6] it was observed that K atoms were lost in the first part of evaporation, which was attributed to the inelastic collisions with the impurity. Another group found that the evaporation efficiency for ^{40}K atoms could be improve significantly by continuously removing the ^{87}Rb atoms in the $|2, 1\rangle$ state.[8] For the sympathetic cooling of ^{133}Cs by ^{87}Rb,[9] it was found that the atoms in the $|2, 1\rangle$ state became significantly populated when evaporatively cooling ^{87}Rb. For the sympathetic cooling of ^{6}Li by ^{87}Rb,[7] the presence of $|2, 1\rangle$ or $|1, 1\rangle$ atoms leads to large inelastic ^{6}Li losses at high densities and prevents the achievement of Fermi degeneracy. In order to remove the $|2, 1\rangle$ state atom from the trap, the method was used in which the microwave carrier frequency tuned to the $|2, 1\rangle$–$|1, 0\rangle$ transition for atoms at the trap centre.[7−10]

In the sympathetic cooling of ^{40}K by ^{87}Rb, many

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groups adopted the RF radiation for evaporative cooling of ^{87}Rb, and some groups utilized the MW radiation. In the present paper, we study two ways in detail: RF and MW induced evaporative cooling, for a mixture of ultra-cold ^{87}Rb and ^{40}K atoms in a magnetic trap in order to explore sympathetic cooling and the collisional rethermalization between the two species. By the comparison, we present their difference clearly, which may be conducive to choosing and optimizing the evaporative cooling.

The present paper is organized as follows. We present the experimental setup for the preparation of the cold Rb–K mixture, the generation of RF and MW radiations and their interactions with the atomic sample in Section 2. In Section 3 we observe the realization of a quantum degenerate mixture of bosonic ^{87}Rb and fermionic ^{40}K atoms by using the RF induced evaporative cooling and an obvious loss of the K atom number during the microwave induced evaporative cooling. The loss of the K atom number is due to the presence of the ^{87}Rb atoms in the $|2,1\rangle$ Zeeman states, which are pumped back into the trapping $|F=2,\ m_F=1\rangle$ state by the same MW radiation in the course of evaporation. Thus, the rubidium atoms populated in the $|2,1\rangle$ Zeeman states should be removed in order to effectively perform the sympathetic cooling of ^{40}K with the evaporatively cooled ^{87}Rb atoms. Finally, some conclusions are presented in Section 4.

2. Experimental setup

2.1. Mixtures of bosonic ^{87}Rb and fermionic ^{40}K atoms

Our experimental setup has been described in detail in Refs. [11] and [12]. Here we give it only a brief description. We use a double-chamber vacuum system, which is connected by a differential pumping tube, with a 3D collection magneto-optical-trap1 (MOT1) and six-beams MOT2. The mixture of bosonic ^{87}Rb and fermionic ^{40}K is loaded in MOT1 from the background vapour released by a reservoir, where ^{40}K vapour is produced by a home-made enriched ^{40}K dispensers.[13] Then we transfer the atoms of two species from MOT1 to MOT2 by pulse pushing beam. We can obtain about 10^9 ^{87}Rb atoms and 10^7 ^{40}K atoms in MOT2, respectively. Once MOT2 is filled, with brief compressed MOT and molasses phases, the trapping beams are switched off and the atoms are optically pumped into the $|F=2,\ m_F=2\rangle$ and $|F=9/2,\ m_F=9/2\rangle$ doubly polarized states of ^{87}Rb and ^{40}K, respectively. After that, the atoms are captured in a magnetic quadrupole field immediately, and then the current of these coils is increased from 15A to 25A in 600 ms, which compresses the cold ensemble. Subsequently, turn on the Ioffe coil and increase the current to 36 A, and at the same time the current in quadrupole coils is also increased to 36 A, which produce a magnetic trap in Quadrupole–Ioffe–Configuration (QUIC). This process converts the quadrupole potential into a harmonic trapping potential, in which the bias field is about 1.5 G and the ^{40}K axial (radial) trapping frequency is $2\pi\times 23.9$ Hz ($2\pi\times 236.6$ Hz). The corresponding ^{87}Rb trap frequencies are a factor of $\sqrt{m_{\rm Rb}/m_{\rm K}}\approx 1.47$ smaller, where $m_{\rm Rb}$ and $m_{\rm K}$ are the atomic masses of ^{87}Rb and ^{40}K, respectively.

Once the atoms are loaded into the QUIC trap, atom numbers and temperatures are extracted by absorption imaging of the atomic clouds after a variable time of free expansion. We use the two-species imaging detection technique for taking two absorption images for two different species respectively in a single experimental run. We divide the CCD into three areas. The first area is the image area (1024×340 chip) which is located at the top of CCD, the other two areas are used as the storage areas (1024×680 chip) blocked by a mask for two species respectively. In our experiment, one experimental run consists of three imaging sequences (three frames). The first frame consists of two absorption images, one is of the ^{40}K cloud and the other of ^{87}Rb cloud. The ^{40}K cloud is first imaged after 3–5 ms time of flight, before the beginning of the exposure. The exposure flash of probe light is typically 50 μs long and controlled by using an AOM. After recording ^{40}K cloud, the image of ^{40}K is shifted into storage area in a shift time of about 1.4 ms. Then the image area is exposed by Rb probe light to image the ^{87}Rb cloud after 20–30 ms time of flight. After an image of ^{87}Rb is captured, the image is also shifted into storage area. Then we allow for approximately 250 ms read-out time into computer for the two images. Then we perform the second frame, which consists of the two reference images taken in the same way, however without the atomic cloud. The last frame has the two dark images without probe lights. Afterwards, the optical density of two species is computed separately and displayed on the computer screen with the configurable false colour.

The probe beams for both species are overlapped with a polarizing beam splitter (PBS) and pass through the same imaging optics. Typical initial conditions in the QUIC trap for Rb are the atom number of 2–3×10^8 and the temperature of 200–300 μK. The corresponding parameter of K cannot be measured directly, as the optical density is too small to be accurately determined from absorption images. Now we have an excellent starting point to achieve runway evaporation.

2.2. RF and MW radiation

The RF radiation is produced by function generator (SRS DS345), and the amplitude of the output RF radiation is controlled by using a voltage-controlled radio frequency attenuator. Then the RF radiation is amplified by a power amplifier (Mini-circuit ZHL-5W-1). We use a simple three-loop coil to deliver RF power to the atoms for their evaporation and connect a high power RF resistance of 50 Ω in series with RF coil in order to achieve the impedance matching for better coupling. The evaporative range of RF is 1–30 MHz. We place the coil directly inside the inner diameter of the quadrupole trap coil and just outside the glass cell as shown in Fig. 1.

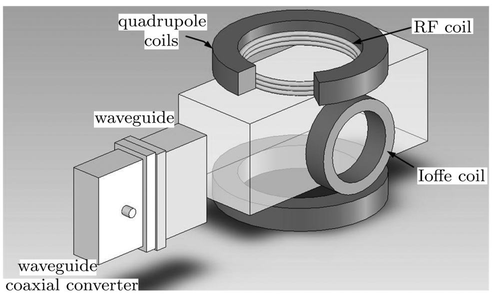

Fig. 1. Schematic of the experimental apparatus, including the magnetic trap setup, glass cell, radio frequency coil and microwave evaporation setup.

The RF induced evaporation can be described with the dressed atom formalism,[14] where the different Zeeman states $m_{F'}$ of the atoms are coupled to an RF field which is assumed to be linearly polarized

$$\boldsymbol{B}_{\mathrm{RF}}(t) = B_0 \cdot \cos(\omega t)\, \hat{e}_{\mathrm{RF}}. \tag{1}$$

The coupling matrix element between levels $|F, m_F\rangle$ and $|F, m_{\mathrm{F}}\rangle$ is

$$(1/4)\cdot g\mu_{\mathrm{B}} \cdot B_0 \left(\hat{e}_{\mathrm{rf}} \times \hat{e}_z\right) \sqrt{F(F+1) - m_F(m_F+1)}\,, \tag{2}$$

where g is the Landé factor and the trapping bias magnetic field is along the quantization axis $\hat{e}_z$. From Eq. (2), we know that the oscillating magnetic field which is used to drive different Zeeman transitions $\Delta m_F = \pm 1$ requires to be perpendicular to the axis of quantization (the bias magnetic field). The RF coupling between adjacent Zeeman sublevels results in an adiabatic multiphoton transition to a non-trapping state, leading to efficient RF induced evaporative coolings.

The details of our microwave apparatus are presented in Ref. [15]. The MW radiation is produced by microwave signal generator. The frequency sweep and the MW switch are computer-controlled and synchronized to the experimental cycle. The MW radiation delivered to atoms by waveguide which has a rectangular shape and produces an oscillating magnetic field perpendicular to the linear antenna inside the waveguide coaxial converter. The oscillating field which is used to drive these transitions is perpendicular to the axis of quantization.

3. Experimental results

Simultaneous quantum degeneracy of the mixture gases is achieved by evaporative cooling of ^{87}Rb and sympathetic cooling of ^{40}K. This scheme circumvents the problem of vanishing elastic cross section for only spin-polarized fermions at ultracold temperatures. Here, we investigate RF and MW induced evaporative coolings respectively for the mixture of ultracold ^{87}Rb and ^{40}K atoms in order to explore sympathetic cooling efficiency between the two species.

3.1. RF and MW evaporative coolings

First we investigate RF induced evaporative cooling. When only loading Rb atoms and by sweeping the RF from 30 MHz to 1 MHz over a period of 43 s, the most energetic Rb atoms are removed and the remaining atoms arrive at lower temperatures. The phase transition occurs at a temperature of $T_{\mathrm{c}} \approx 500$ nK. We can achieve pure Bose–Einstein condensate (BEC) of ^{87}Rb with the number of atoms about 2×10^5.

When Rb and K atoms are loaded simultaneously, sympathetic cooling of ^{40}K atoms to quantum degeneracy takes place by selectively evaporating ^{87}Rb, while ^{40}K is cooled in the bath of ^{87}Rb atoms. Both ^{40}K in the $|9/2, 9/2\rangle$ state and ^{87}Rb in the $|2, 2\rangle$ state have the same magnetic moments and are subjected to the same trapping potential, but have different Zeeman splittings at the same magnetic field (the energy splitting of ^{87}Rb is 2.25 times that of the ^{40}K. For a given cut-off RF, the magnetic field at which the ^{87}Rb in the $|2,2\rangle$ state satisfies the resonance condition for spin-flips is smaller than that for the ^{40}K in the $|9/2,9/2\rangle$ state, so the RF induced evaporative cooling does not cause a significant loss for the ^{40}K atoms.

Quantum degeneracy for the ^{87}Rb gas is characterized by the emergence of a bimodal distribution in the absorption image taken after time-of-flight expansion. The effect of quantum degeneracy on fermions is more subtle. The density distribution in the period of time of flight becomes more 'flat topped' than that for a classical gas due to the Pauli pressure. We fit the two-dimensional density distribution of a spin-polarized Fermi gas after time-of-flight expansion by using a semiclassical expression[16] to extract the ^{40}K atoms number, Fermi temperature and the actual temperature of the gas. In our experiment, we can obtain up to 8×10^5 degenerate fermions ^{40}K with the degeneracy parameter $T/T_F = 0.48$.[12]

With loading only Rb atoms, microwave forced evaporative cooling of ^{87}Rb is performed on the ground state hyperfine transition between $|F=2, m_F=2\rangle$ and $|F=1, m_F=1\rangle$ as shown in Fig. 2.

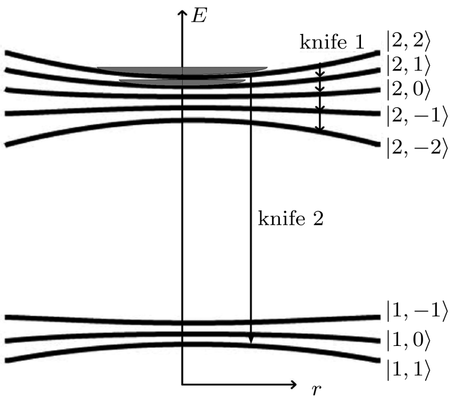

Fig. 2. Microwave and Radio frequency induced transitions for evaporating the ^{87}Rb cloud in $F=2, m_F=2\rangle$ state. The knife 1 indicates Radio frequency induced transitions, and the knife 2 shows microwave induced transitions.

The MW frequency is swept from 6.9 GHz to a final value 6.8372 GHz in about 37.4 s. By optimizing the MW power and sweeping frequency, we find that the pure BEC is hard to achieve at the end of the evaporation stage. Finally we may achieved ^{87}Rb Bose–Einstein condensate including the condensate and thermal atoms with the total atomic number of 2.03×10^5.[15] This phenomenon is caused by the presence of the ^{87}Rb atoms in the $|2,1\rangle$ Zeeman states, which are pumped back into the trapping $|F=2, m_F=1\rangle$ state by the same MW radiation in the course of evaporation. We observe lots of Rb atoms populated in the $|F=2, m_F=1\rangle$ state shown below in Fig. 4(b), which is separated in space with a new method reported in Ref. [17]. The atoms in different trapped spin states will have a large separation due to the gravity sag and different trap frequencies when the quadrupole current in the QUIC trap is reduced. This method needs neither an additional bias magnetic field to produce the magnetic gradient for separating the spin states nor long time flight, thus may check very a small number of atoms in different trapped spin states.

When Rb and K atoms are loaded simultaneously, the sympathetic cooling of ^{40}K atoms in MW forced evaporative cooling is performed. We notice dramatic loss for the ^{40}K cloud. At the end of each stage of the evaporation ramp, we let the clouds equilibrate for 10 ms inside the trap and take the absorption image after 1 ms expansion time, which is compared with the image for the pure radio frequency induced evaporative cooling as shown in Fig. 3. As we see, the optical density of ^{40}K at the beginning of the two different evaporative methods is increased and there is not significant loss of ^{40}K atom number, which indicates the two different sympathetic coolings are effective at high temperature. When the mixture is cooled down to about a temperature of 10 μK, the quick decreases of the ^{40}K atom number and the optical density occur when microwave forced evaporative cooling is used, however, the optical density of ^{40}K samplestill increases with using the RF evaporative cooling. At the end of the last stage of RF induced evaporation, the ^{40}K sample can enter the quantum degeneracy regime. This harmful effect in MW forced evaporative cooling is induced by $|F=2, m_F=1\rangle$ Rb atoms, which can be trapped in the QUIC trap and will induce a significant loss of the K atom number due to inelastic collisions and prevent ^{40}K atoms from entering the quantum degenerate regime. The Rb atoms transferred to the $|F=1, m_F=1\rangle$ state by the MW radiation can be pumped back to the $|F=2, m_F=1\rangle$ state after traveling some distance to become again resonant with the same microwave radiation, which was also reported in Ref. [7]. The atoms are kept in the state and accumulated in the trap when MW forced evaporative cooling is used, and then elastically

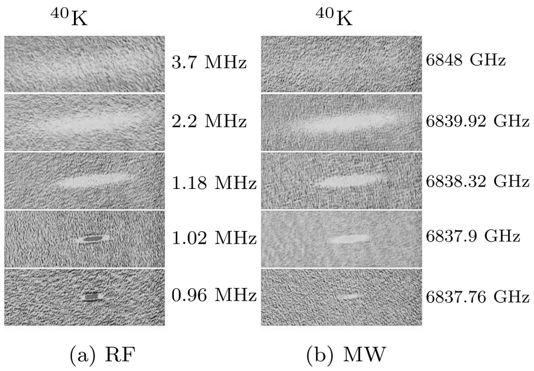

Fig. 3. False colour absorption images of ^{40}K in QUIC trap at four different stages of the sympathetic cooling. Panel (a) shows the ^{40}K atoms in the RF induced evaporative cooling stage, and panel (b) displays the ^{40}K atoms in the MW induced evaporative cooling stage.

collide with $|F = 9/2,\ m_F = 9/2\rangle$ doubly polarized states of ^{40}K.

We also find that there is an impurity of ^{87}Rb in the $|F = 2,\ m_F = 1\rangle$ state at the last stage of the pure RF induced evaporation as shown in Fig. 4(a). There are two possible processes to make the atoms populated in the $|F = 2,\ m_F = 1\rangle$ state: one is the process in which the initial spin-polarizing pulse fails to transfer all atoms into the fully stretched state, the other is the process in which the RF radiation transfers atoms into $|F = 1,\ m_F = 1\rangle$ state. The atom number in the $|F = 2,\ m_F = 1\rangle$ state is much smaller than that when the MW forced evaporation is used, so that there is no obvious harmful effect for the K atoms with using the RF forced evaporation.

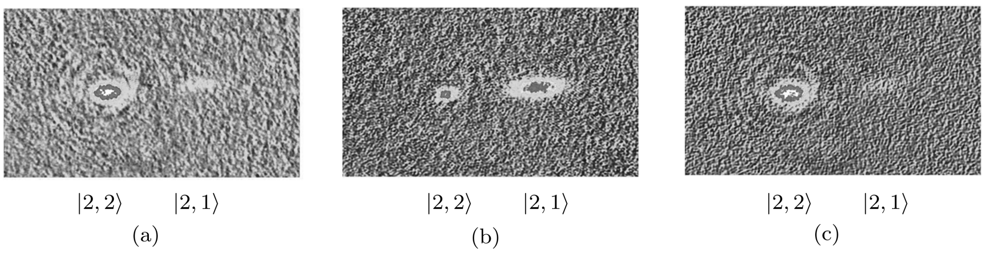

Fig. 4. Image of two atomic clouds, with Stern–Gerlach field used to separate ^{87}Rb atoms in $|F = 2, m_F = 1\rangle$ state (left) from atoms in $|F = 2, m_F = 24\rangle$ (right). Panel (a) shows the image after the RF induced evaporative cooling, panel (b) exhibits the image after the MW induced evaporative cooling and panel (c) displays the image after the modified evaporative cooling.

3.2. Improved evaporative cooling

In order to remove atoms in $|F = 2, m_F = 1\rangle$ state, we choose the fixed microwave frequency to transfer $|F = 2, m_F = 1\rangle$ atoms to the $|F = 1, m_F = 0\rangle$ untrapped state at the bottom of QUIC trap. Using the RF evaporation ramp and fixing the MW during evaporation, we may obtain up to degenerate fermions ^{40}K, in which the number of ^{40}K fermions reaches 10^6 and degeneracy parameter $T/T_F = 0.30$. The ^{40}K atom number is increased by 20% compared with that with using only the RF induced evaporative cooling. From Fig. 4(c), we can find that the atoms in the $|F = 2, m_F = 1\rangle$ state are not removed completely, with the fixed microwave frequency used. Possibly this needs a very accurate turning of the microwave frequency.

4. Conclusions

We have investigated the sympathetic cooling of ^{40}K by ^{87}Rb that is evaporatively cooled with RF radiation and MW radiation on the ground-state hyperfine transition. We find that the presence of rubidium atoms in the $|2,1\rangle$ Zeeman states during evaporative cooling gives rise to a large loss of the K samples due to inelastic collisions. Thus, the rubidium atoms populated in the $|2,1\rangle$ Zeeman states should be removed in order to effectively perform sympathetically cooling ^{40}K with the evaporatively cooled ^{87}Rb atoms.

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