Simultaneous Magneto-Optical Trapping of Fermionic ^{40}K and Bosonic ^{87}Rb Atoms *

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We report on simultaneous magneto-optical trapping of fermionic ^{40}K and bosonic ^{87}Rb atoms. This trap is the first step towards quantum degenerate fermi gas ^{40}K. Laser lights for the two-species magneto-optical trap (MOT) are generated from diode lasers and tapered amplifier. The enriched ^{40}K dispenser is utilized in the experimental setup. We obtain up to $10^7 \sim 10^8$ ^{40}K and $10^8 \sim 10^9$ ^{87}Rb atoms respectively in the steady-state single-species MOT.

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In the field of atomic physics, experimental and theoretical studies on quantum degenerate Fermi gas (DFG) and quantum degenerate boson–fermion mixtures (BFMs) have been acquiring much attention in the recent years. DFGs and BFMs present a new path for understanding high-T_c superconductivity and strong interaction, producing ultracold molecules as well as investigating crossover between Bardeen–Cooper–Schrieffer superfluidity and Bose–Einstein condensation (BEC) of molecules. Because of the Pauli exclusion principle, the S-wave collisions between fermions are prevented in a spin polarized Fermi gas, while higher order partial waves are suppressed at low temperature. Evaporative cooling which is successfully used in achieving BEC cannot be utilized in cooling fermions into quantum degeneracy. In order to circumvent this limitation, two methods were developed. One is to cool fermions by collisions between different spin polarized states. Two states, $\langle 9/2, 7/2\rangle$ and $\langle 9/2, 9/2\rangle$, of ^{40}K atoms were used in the first achieved DFG.[1] The other is called the 'sympathetic cooling' in which fermions are sympathetic cooled by inter-species collisions between boson and fermion. Boson and fermion may be two different isotopes of the same chemical element or two different chemical elements. Until now, many works focused on DFG and BFM have been realized in several combinations of boson and fermion: ^{40}K–^{87}Rb,[2,3] ^{6}Li–^{7}Li,[4–9] ^{6}Li–^{23}Na,[10] ^{6}Li–^{87}Rb.[11] ^{40}K and ^{87}Rb mixtures are selected in our laboratory. The goal of our experiment is to sympathetically cool a gas of fermions ^{40}K down below its Fermi temperature by bosons ^{87}Rb to obtain a DFG.

In this Letter, we report on the simultaneous magneto-optical trapping(MOT) of ^{40}K and ^{87}Rb atoms in the collection cell. The two-species MOT will be used as a precooling stage to obtain the starting conditions for forced evaporative cooling of ^{87}Rb and sympathetic cooling of ^{40}K.

Figure 1 shows the energy-level diagram for ^{40}K and ^{87}Rb atoms with the transitions used for cooling and repumping. All these transitions are within D_2 lines. As can be seen from Fig. 1, the potassium ground hyperfine splitting is within 1.3 GHz. Therefore, ^{40}K cooling and repumping light can be achieved from the same laser by means of AOMs to shift the frequencies. We have developed a relatively simple semiconductor laser system,[12] which is schematically shown in Fig. 2. They are based solely on external cavity diode lasers (ECDLs), injection-seeded diode lasers and tapered amplifier. Three grating-feedback ECDLs are used as master lasers: two of them at 780.246 nm are for the ^{87}Rb D_2 line and another at 766.702 nm is for the ^{40}K D_2 line. For each master, a small part of output light is used for frequency locking via saturated absorption spectroscopy (SAS). The frequency of the rest of light is then shifted via double-pass or quadruple-pass acousto-optic modulator (AOM). The generated four frequency components are coupled into four single-mode polarization-maintaining fibres respectively and transported to the neighbour optical table. A small part of light from the output of fibre is used for injecting slave laser and the remaining light is available for probing the atom cloud. Three of the slave lasers (except the Rb repumping light) are injected into a tapered amplifier (TA) to boost their

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power by a master oscillator-power configuration. The AOMs behind TA and Rb repumping slave laser are also used to offset the laser frequency. The zeroth light is then available for pushing the atomic sample to the science cell.

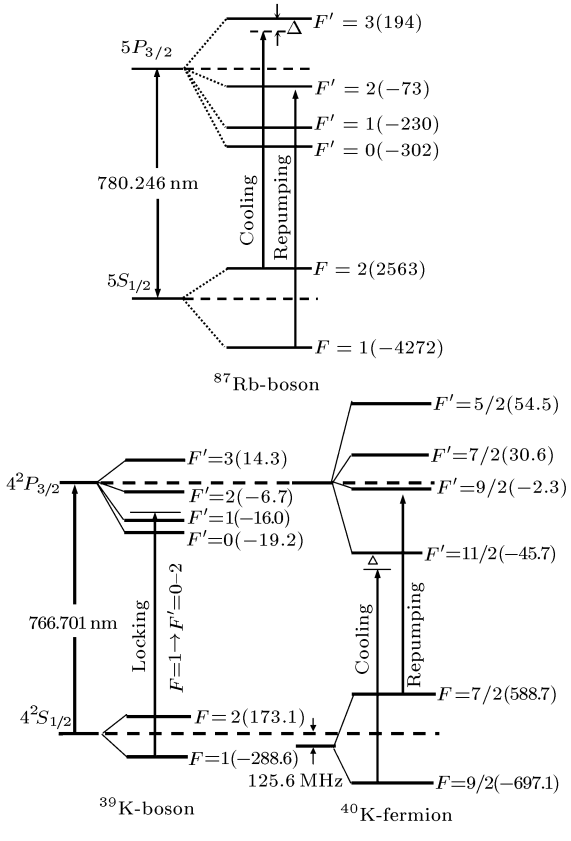

Fig. 1. Relevant energy levels for cooling and trapping ^{40}K and ^{87}Rb. All the transitions are within the D_2 lines, respectively. Numbers in parentheses are the hyperfine frequency shifts in MHz. For K isotopes, the ground-state frequencies are referenced to ^{39}K.

The frequencies of three master lasers are locked by the modulation transfer spectrum (MTS) technology,[13] in which the modulation of the pump beam can be transferred to the counterpropagating probe beam (originally unmodulated). The frequency of the pump beam is dithered (in our case, at 30 kHz) by a single-pass AOM and the resultant modulation of the probe is demodulate to achieve the error signal by phase-sensitive detection. The error signal is sent to control the piezo of grating-feedback and the current of the master laser to lock to the maximum of the peak of SAS. This method can eliminate the frequency jitter because of modulation-free to the master laser. Thus we achieve long term stability of laser frequency. Note that the laser frequency shift must be concerned for trapping and repumping light, since the single-pass AOMs are used in SAS for providing the pump-beam modulation.

The frequencies of the three master lasers are locked as follows: For rubidium, the cooling master laser is locked to the $5^2S_{1/2}$ $F = 2 \rightarrow 5^2P_{3/2}$ $F' = 3$ transition of the D_2 line of ^{87}Rb. The repumping master laser is locked to $5^2S_{1/2}$ F=1$\rightarrow$ $5^2P_{3/2}$ $F' = 1$–2 crossover signal. For potassium, direct locking to a ^{40}K transition is not accessible due to the very low natural abundance of ^{40}K in the vapour of the spectroscopy cell. The laser frequency is locked to $4^2S_{1/2}$ $F = 1 \rightarrow 4^2P_{3/2}$ $F' = 0$–2 transition of the D_2 line of ^{39}K. The $4^2S_{1/2}$ $F = 9/2 \rightarrow 4^2P_{3/2}$ $F' = 11/2$ transition of ^{40}K and the $4^2S_{1/2}$ $F = 7/2 \rightarrow 4^2P_{3/2}$ $F' = 9/2$ transition of ^{40}K are 375.8 MHz blue and 866.6 MHz red of the $4^2S_{1/2}$ $F = 1 \rightarrow 4^2P_{3/2}$ $F' = 0$–2 signal of ^{39}K respectively. The frequencies of the required cooling and repumping light can be derived by means of AOMs. The ^{87}Rb cooling frequency is $\nu = \nu_{2\rightarrow3} - 55 + 75 * 2 - 110 = \nu_{2\rightarrow3} - 15$ MHz. The ^{87}Rb repumping frequency is $\nu = \nu_{1\rightarrow2} - 40 - 157/2 + 110 \times 2 - 110 = \nu_{1\rightarrow2} - 8.5$ MHz. The ^{40}K cooling frequency is $\nu = \nu_{1\rightarrow0-2}(^{39}\mathrm{K}) + 55 + 210 \times 2 - 110 = \upsilon_{9/2\rightarrow11/2}(^{40}\mathrm{K}) - 375.8 + 365 = \nu_{9/2\rightarrow11/2}(^{40}\mathrm{K}) - 10.8$ MHz. The ^{40}K repumping frequency is $\nu = \nu_{1\rightarrow0-2}(^{39}\mathrm{K}) + 55 - 205 \times 4 - 110 = \nu_{7/2\rightarrow9/2}(^{40}\mathrm{K}) + 866.6 - 875 = \nu_{7/2\rightarrow9/2}(^{40}\mathrm{K}) - 8.4$ MHz.

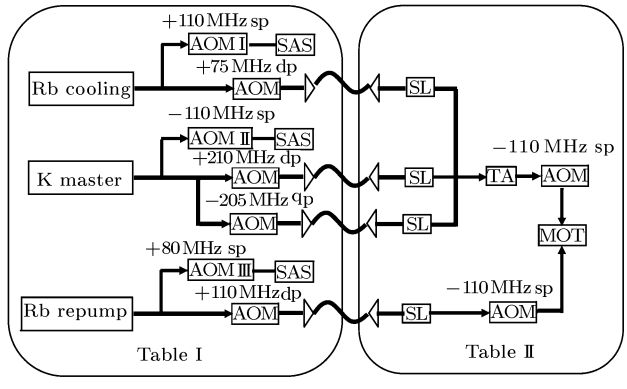

Fig. 2. Laser systems based on semiconductor lasers and tapered amplifier for potassium and rubidium magneto-optical trapping. The frequency are offset with single pass (sp), double pass (dp) and quadruple pass (qp) AOM. Note that the single-pass AOMs(I II III) are used in saturated absorption spectroscopy for providing the pump-beam modulation.

In our setup, the Rubidium source is a reservoir containing 5 g pure rubidium metal (natural abundance 72.17% ^{85}Rb and 27.83% ^{87}Rb), which is sealed in a vacuum system and separated from the MOT chamber by a valve. The naturally Potassium source is unaccessible for the experiment because the low abundance of the isotope ^{40}K (natural abundance are 93.26% ^{39}K, 0.012% ^{40}K and 6.73% ^{41}K) limits the collected atom number in the MOT. Using natural source, only 10^3 ^{40}K atoms were trapped in MOT in the past.[14,15] In the first DFG experiment, DeMarco

et al.[16] developed an enriched potassium source and collected 10^8 ^{40}K atoms in a vapour cell MOT. This method has been used in many groups. Enriched ^{40}K is available in the form of KCl rather than pure metal. We develop an enriched ^{40}K dispenser based on SAES getters and Refs. [16,17]. The device uses the following reaction mechanism to supply potassium:

$$2\mathrm{KCl} + \mathrm{Ca} \xrightarrow{\text{heat}} 2\mathrm{K} + \mathrm{CaCl_2}. \quad (1)$$

The reservoir of our dispenser is made of 0.125-mm-thin nichrome (80% nickel, 20% chrome). The nichrome is chemically inert and behaves well at high temperatures. The design of our reservoir has several advantages such as having more space, loading easily and preventing escape of the reactants. In our dispenser,[18] calcium (dendritic, purity 99.99%) and enriched potassium chloride (^{40}K abundance 6.2%) are used. They are converted into powder and mixed uniformly according to 2:1 volume ratio of Ca to KCl. This dispenser is demonstrated to be efficient. Figure 3 shows the saturated absorption spectroscopy, in which the ^{40}K atomic D_2 transition line can be seen clearly.

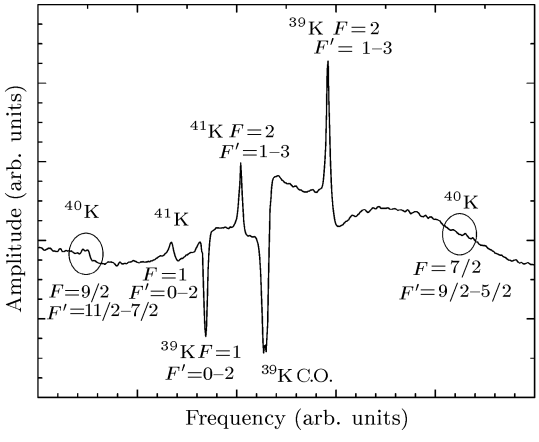

Fig. 3. Experimental results of saturated absorption spectroscopy for ^{40}K enriched dispenser. The positions labelled by circles are two absorption lines for the fermion isotope ^{40}K.

Our experimental vacuum system employs a double-cell structure. The collection cell is a compact octagonal chamber with eight CF35 viewports in the horizontal plane, and two CF100 viewports for the vertical laser beams. A 40 L/s ion pump maintains the pressure at about 2×10^{-7} Pa. When the dispenser is used, the pressure is dropped to 2×10^{-6} Pa.

Two external coils in anti-Helmholtz configuration create a quadrupole field at the MOT position. The laser beams for MOT utilize three retroreflect configurations as shown in Fig. 4. The atomic clouds are imaged both on a charge-coupled device (CCD) camera and a photodiode (PD). We monitor the number of atoms and the size of the atomic cloud by the PD and CCD.

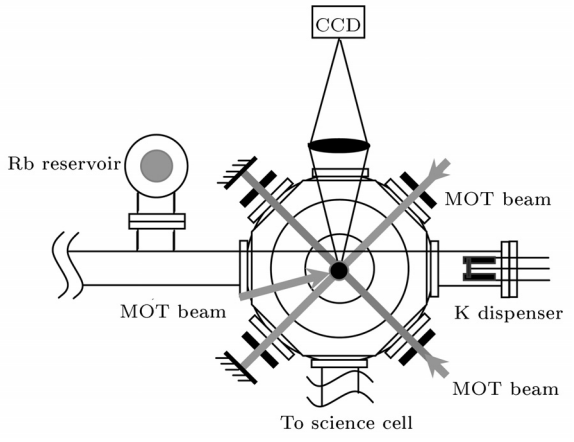

Fig. 4. Schematic diagram of the collection chamber showing the MOT beams, the rubidium and potassium source, and the MOT fluorescence detection.

As the first step, we cool and trap ^{87}Rb atoms in collection chamber from the background vapour released by a reservoir under room temperature. The potassium cooling and repumping light injected into TA are blocked. Each of the rubidium trapping beams has 15 mW laser power and combined with the repumping light by a polarization beam splitter cube. A telescope expands the beam to the $1/e^2$ radii of about 12.5 mm. The gradient magnetic field is 9 Gcm^{-1}. We obtain the information of the atom cloud with the MOT fluorescence measured by PD, taking into account the collection solid angle of the imaging lens. We also obtain the atom number to be approximately 10^8–10^9. Figure 5 shows a typical loading course for ^{87}Rb MOT.

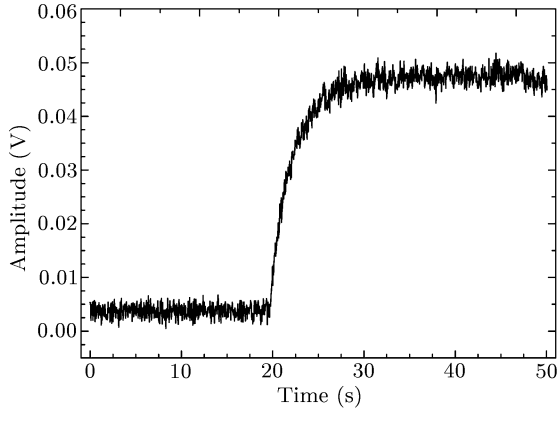

Fig. 5. A typical loading course for ^{87}Rb MOT.

Cooling and trapping ^{40}K in an MOT is similar with ^{87}Rb. The main difference is that ^{40}K MOT requires more repumping light than ^{87}Rb MOT due to the small excited-state hyperfine splitting. Each of the trapping beams carries 15 mW laser power and is red-detuned 10.8 MHz from the $4^2S_{1/2}$ $F = 9/2 \rightarrow 4^2P_{3/2}$

$F' = 11/2$ cycling transition of D_2 line of ^{40}K. The repumping beam is red-detuned 8.4 MHz from the $4^2S_{1/2}$ $F = 7/2 \rightarrow 4^2P_{3/2}$ $F' = 9/2$. The gradient magnetic field is 9 Gcm^{-1}. We obtain the atom number to be approximately 10^7–10^8. Figure 6 presents the images of single-species MOT for ^{87}Rb and ^{40}K.

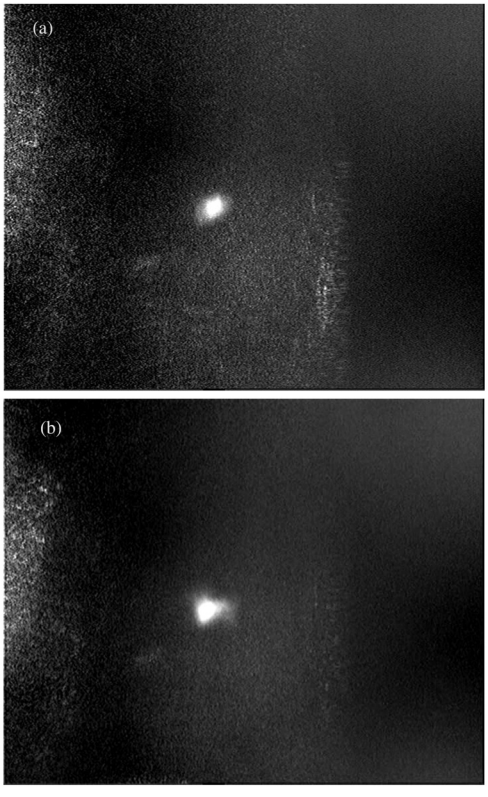

Fig. 6. A photograph for single-species (a) ^{40}K and (b) ^{87}Rb MOT.

In the case of two-species MOT, the steady state atom numbers of ^{40}K and ^{87}Rb simultaneously trapped are decreased largely compared to single MOT operation. There are some reasons: (1) The laser power output from TA is shared by ^{40}K and ^{87}Rb cooling and repumping light and thus lower for each atom species. (2) The collection chamber vacuum pressure is increased when the K dispenser is operated, which increases the atom losses due to collisions with the background gases. (3) An additional losses take place due to collisions between trapped ^{40}K and ^{87}Rb atoms. The two-species superimposed MOT are imaged onto a same photodiode so we cannot observe the atom numbers by means of this method.

In summary, we have demonstrated simultaneous trapping of fermionic ^{40}K and bosonic ^{87}Rb in a two-species MOT. The apparatus which have several advantages in the laser systems and ^{40}K atomic sources are presented. This two-species MOT is a first step towards achieved DFG ^{40}K, which provides a precooled atomic sample for being transported into a UHV chamber and subsequently evaporated into quantum degeneracy by sympathetic cooling.

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