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Direct evaporative cooling of ^{41}K into a Bose-Einstein condensate

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We have investigated the collisional properties of ^{41}K atoms at ultracold temperatures. To demonstrate the possibility of using ^{41}K as a coolant, a Bose-Einstein condensate of ^{41}K atoms in the stretched state ($F=2,m_F=2$) was created by direct evaporative cooling in a magnetic trap. An upper bound of the three-body loss coefficient for atoms in the condensate was determined to be $4(2)\times10^{-29}$ cm^{-6} s^{-1}. A Feshbach resonance in the $F=1$, $m_F=-1$, state was observed at 51.35(10) G, which is in good agreement with theoretical prediction.

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Quantum degenerate gases are attracting a great deal of interest recently as an ideal testbed for studying condensed-matter systems [1]. One of the biggest advantages of using cold atoms is the unprecedented flexibility. One cannot only choose the strength and symmetry of the confining potential, but also tune the strength of interatomic interactions. The availability of a rich variety of atomic species also brings considerable advantages. It enables researchers to choose the statistics and the mass ratio of atoms in a quantum mixture of gases. To date, a variety of quantum degenerate Bose-Bose, Bose-Fermi, and Fermi-Fermi mixtures has been realized and studied intensively.

However, there exist certain drawbacks in choosing an exotic combination of atomic species. For example, a large difference in mass can be problematic for systematic studies of a quantum degenerate mixture. The difference in the gravitational sag can result in an inhomogeneous spatial overlap between the two clouds. Common solutions to this problem are to increase the vertical trapping frequencies, make the trapping potential sensitive to atomic species [2], or use atomic species that are close in mass. The last solution favors "an isotopic degenerate gas mixture" since the mass difference is minimized. This scheme has been realized for He, Li, and Yb, but not for K.

Here we report our study on the collisional properties of ^{41}K. Our primary motivation was to establish ^{41}K as a coolant, enabling the production of an isotopic Bose-Fermi mixture of ^{41}K-^{40}K. Starting from a pure ^{41}K sample, we produced a pure Bose-Einstein condensate with more than 3×10^5 atoms. The evaporation trajectory quite remarkably resembled that of ^{87}Rb. We measured the efficiency of evaporative cooling of both the pure ^{41}K sample and the pure ^{87}Rb sample in the same environment and found that they differed by only 15%.

Potassium has another stable bosonic isotope (^{39}K), which is more abundant (93.3%) compared with ^{41}K (6.7%). We chose ^{41}K because the triplet scattering length of ^{39}K is negative, and a Feshbach resonance was needed for producing a large condensate [3]. To date, most of the collisional properties of ^{41}K have been inferred from measurements performed on other isotopes rather than by directly exploring ^{41}K. The current best estimate for the triplet scattering length of ^{41}K is $a_{41}=60.54(6)a_0$, where a_0 is the Bohr radius [4]. This value was obtained by combining the results from two-photon spectroscopy of ^{39}K$_2$ [4,5] and Feshbach spectroscopy of ^{39}K [6] and ^{40}K [7]. ^{41}K has been Bose condensed using Rb as a coolant [8].

For investigating the collisional properties of ^{41}K experimentally, we employed the standard method of producing a quantum degenerate gas in a trap, namely, laser cooling followed by evaporative cooling in a magnetic trap. The laser cooling of ^{41}K required extra attention, because the hyperfine splittings of ^{41}K were small. In particular, the hyperfine splitting in the 4 $^2P_{3/2}$ state was only about 14 MHz, which was on the same order as the natural linewidth of the D_2 line (6.2 MHz) (Fig. 1). Thus, it is practically impossible to form a closed transition since off-resonant excitation to the other excited states is not at all negligible. In fact, in order to increase the capture range of the magneto-optical trap (MOT), we had to detune the "cooling beam" to the red of the whole excited state hyperfine manifold [9]. By preparing almost the same amount of laser power for both "cooling" and "repumping" transitions, we overcame these problems and succeeded in capturing a large number of ^{41}K atoms in the MOT [10].

Details of our experimental setup can be found elsewhere [11]. We employed a double-MOT system. The first MOT was loaded from the background gas, which was released from a homemade dispenser [12]. The dispenser contained 98.7% ^{41}K enriched KCl. The glass cell was maintained at 50 °C in order to increase the loading rate of the first MOT. A beam of atoms was pushed from the first MOT to the second MOT using a resonant push beam. The frequency of the push beam was 6 MHz red detuned from $4S_{1/2}$ $F=1$ to $4P_{3/2}$ $F'=2$ transition. We loaded 1.4×10^9 ^{41}K atoms in the second MOT in 10 s. As the typical temperature of atoms in the ^{41}K MOT was about 5 mK, we introduced additional stages of spatial compression (40 ms) and Doppler cooling (12 ms) [13]. The typical number, density, and temperature

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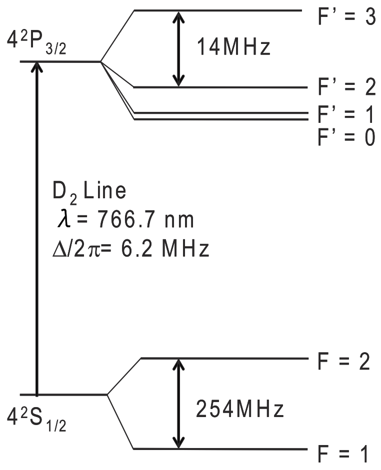

FIG. 1. The energy level diagram of ^{41}K atoms. Hyperfine splitting of the 4 $^2P_{3/2}$ state is comparable to the natural linewidth of the D_2 line (6.2 MHz).

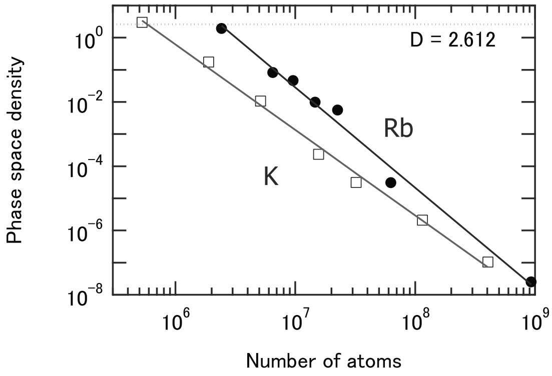

FIG. 2. The typical evaporative cooling trajectory for ^{41}K (squares) and ^{87}Rb (circles) atoms. The efficiency of evaporative cooling $\gamma \equiv -d(\ln D)/d(\ln N)$ was 2.7 for ^{41}K and 3.1 for ^{87}Rb. Here, D is the phase-space density of the gas.

of the cloud following the cooling were 1.0×10^9, 5.1×10^{10} cm^{-3}, and 100 μK, respectively. The obtained phase-space density was about 1.0×10^{-6}, which was sufficient to start evaporative cooling.

The efficiency of evaporative cooling is difficult to predict, since it is quite sensitive to small inelastic loss processes. In general, the efficiency depends sensitively on the ratio between "good" (elastic) and "bad" (inelastic) collisions, which is typically more than a factor of a few hundred for alkali metal atoms. Evaporative cooling of alkali metal atoms in the stretched state is often quite efficient, since one can expect a very tight confinement from the trap, and there should be no scattering resonances. A prominent exception has been ^{133}Cs, whose evaporative cooling in the stretched state is hindered by the strong dipolar relaxation process induced by the second-order spin-orbit interaction [14].

For loading ^{41}K atoms into a magnetic trap, we optically pumped the atoms into the stretched state ($|F,m_F\rangle = |2,2\rangle$). The weak-field seeking state in the lower hyperfine manifold ($|1,-1\rangle$) was not ideal for magnetic trapping, since the maximum trap depth for the $|1,-1\rangle$ state was limited to around 0.8 mK due to the Paschen-Back effect. Our magnetic trap was in the Ioffe-Pritchard configuration. In order to minimize heating during the transfer to the magnetic trap, we loaded atoms in a loose magnetic trap with a high bias field, and then atoms were adiabatically compressed by increasing the radial confinement and lowering the bias field. The trapping frequency after compression was $\nu_r = 325$ Hz ($\nu_z = 15.0$ Hz) in the radial (axial) direction. The typical initial condition following adiabatic compression was $N = 8.2\times 10^8$ and $T = 680$ μK, which gives the phase-space density of 4.5×10^{-7}.

Figure 2 shows a typical evaporation trajectory for ^{41}K atoms in the $|F,m_F\rangle = |2,2\rangle$ state. We first tried to evaporatively cool ^{41}K atoms by driving the rf transition between Zeeman sublevels. However, we found that it was necessary to actively remove atoms in the $|2,1\rangle$ and $|2,0\rangle$ states. We believed that this purification was necessary because a large second-order Zeeman shift increased the accumulation of atoms in the $|2,1\rangle$ and $|2,0\rangle$ states and also increased the energy release from $|2,1\rangle + |2,1\rangle \rightarrow |2,2\rangle + |2,0\rangle$ collisions [15,16]. To obtain a pure $|2,2\rangle$ sample, we first selectively removed atoms in the $|2,1\rangle$ and $|2,0\rangle$ states by driving rf transitions to the lower hyperfine manifold when the bias field was high. Then, we evaporatively cooled the cloud by driving the $|2,2\rangle \rightarrow |1,1\rangle$ transition, which was 254 MHz at zero magnetic field.

The efficiency of evaporative cooling is defined as $\gamma \equiv -d(\ln D)/d(\ln N)$, where D is the phase-space density of the gas [17]. We observed an efficiency of $\gamma_{\mathrm{K}} = 2.7$ in our system. This was comparable with or even better than some of the typical γ values for other alkali metal gases. For example, alkali metal gas γ values shown in "Overview of Evaporative Cooling Experiments" in Ref. [17] range from 1.5 to 2, with the prominent exception of ^{87}Rb, which shows $\gamma = 3.0$. In fact, by completing the rf sweep for evaporation, it was possible to pass the phase transition for the Bose condensation of ^{41}K and obtain a pure condensate (Fig. 3). A typical number of atoms in the pure condensate was 3×10^5.

For a more direct comparison, we prepared a gas of ^{87}Rb atoms in the $|F,m_F\rangle = |2,2\rangle$ state and performed rf-induced evaporative cooling in the same magnetic trap [18]. The typical evaporative cooling trajectory is shown by the filled circles in Fig. 2. The initial condition was $N_{\mathrm{Rb}} = 9.3\times 10^8$ and $T_{\mathrm{Rb}} = 1.2$ mK. The number of atoms in the pure ^{87}Rb condensate was 7×10^5. The obtained efficiency was $\gamma_{\mathrm{Rb}} = 3.1$, which was only $\sim 15\%$ higher than ^{41}K (Table I). This difference in efficiency can be partly attributed to the difference in the elastic cross section. The cross section for ^{87}Rb is a factor of about 2.8 larger than that for ^{41}K.

The three-body loss coefficient is important, since it practically limits the highest density one can achieve with a con-

TABLE I. A comparison between typical conditions before and after the evaporative cooling of ^{41}K and ^{87}Rb.

Species	Initial PSD	N_{BEC}	γ
^{41}K	4.5×10^{-7}	3×10^5	2.7
^{87}Rb	2.5×10^{-8}	7×10^5	3.1

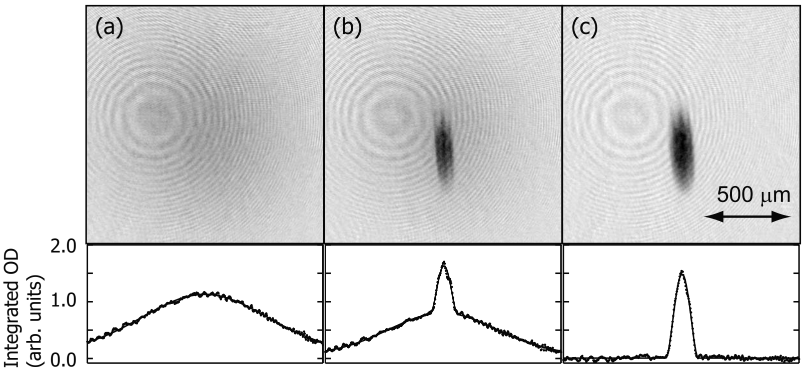

FIG. 3. A Bose-Einstein condensate of ^{41}K atoms obtained by direct evaporation in a magnetic trap. Absorption images of ^{41}K atoms after 40 ms expansion showed (a) a thermal distribution at $T=750$ nK, (b) a bimodal distribution at $T=580$ nK, and (c) an almost pure condensate of 3×10^5 atoms. The evaporative cooling was performed by driving an rf transition between hyperfine levels of ^{41}K atoms. No coolant was used in the experiment.

densate. By studying the decay of the condensate, we determined the upper bound for the three-body loss coefficient for ^{41}K atoms in the $|F,m_F\rangle=|2,2\rangle$ state. We took a decay curve for the number of atoms in a condensate and fitted the data assuming exponential decay accelerated by the three-body loss processes. The obtained three-body loss coefficient was $4(2)\times10^{-29}$ cm^{-6} s^{-1}. We must point out here that this value is merely an upper bound for the three-body loss, since we cannot rule out any contributions from the two-body loss processes. This coefficient was slightly larger than that of ^{23}Na (1.6×10^{-29} cm^{-6} s^{-1}) [19] or ^{87}Rb (1.8×10^{-29} cm^{-6} s^{-1}) [20] in the upper hyperfine state.

We also performed “Feshbach spectroscopy” for ^{41}K atoms in the $F=1$ state. By determining the position of Feshbach resonances, it was possible to check the validity of assumptions used for calculations of interatomic potential. A Feshbach resonance of 300 mG wide has been predicted for ^{41}K atoms in the $|F,m_F\rangle=|1,-1\rangle$ state at 51.4 G [6]. That was the only *s*-wave Feshbach resonance predicted for ^{41}K atoms in the $F=1$ manifold below 100 G. Here, resonances wider than 1 mG only were considered.

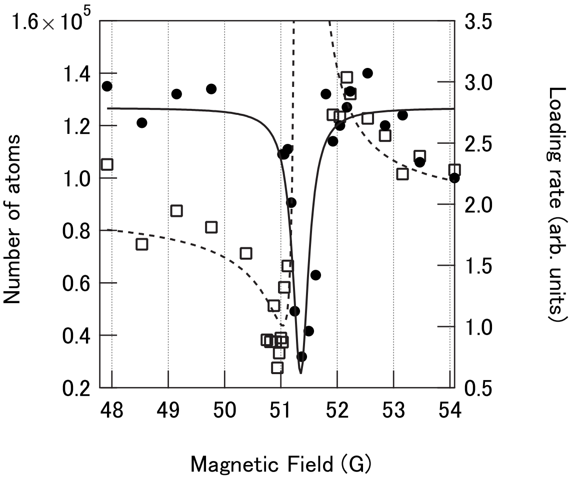

FIG. 4. A Feshbach resonance of ^{41}K in the $|F,m_F\rangle=|1,-1\rangle$ state. The number of trapped atoms after 500 ms hold time (circles) showed a pronounced dip at a Feshbach resonance because of an enhanced three-body loss. The typical number density at the center of the cloud was about 1×10^{13} cm^{-3}. In a separate experiment, the loading rate of a crossed-beam dipole trap from a single-beam dipole trap was measured as a function of the bias magnetic field (squares). In order to determine the position and width of the resonance, the loss data were fitted with a Lorentzian curve centered at the resonance (solid line), and the loading rate data were fitted assuming that the loading rate is proportional to the elastic cross section [21]. The extracted center and the width of the resonance were 51.35(10) G and −0.3(1) G, respectively, which are in good agreement with theoretical predictions of Ref. [6] (51.4 and −0.3 G, respectively).

For identifying the position and width of the Feshbach resonance, we performed two measurements using a crossed-beam optical dipole trap ($\lambda=820$ nm). In the first experiment, we measured the trap loss rate as a function of the bias magnetic field. A pronounced loss feature was observed for atoms in the $|1,-1\rangle$ state near 51.4 G. In the second experiment, we measured the loading rate of the crossed-beam optical dipole trap. For this, atoms were first confined in a single-beam optical dipole trap and the second beam was then switched on suddenly. Atoms were accumulated to the crossed region and the rate was determined as a function of the bias magnetic field (Fig. 4). The data were analyzed by assuming a symmetric loss feature around the resonance and proportionality between the loading rate and the elastic cross section. The observed center and width of the Feshbach resonance were 51.35(10) G and −0.3(1) G, respectively, which are in good agreement with theory (51.4 and −0.3 G, respectively) [6].

In conclusion, we studied the collisional properties of ^{41}K atoms. A Bose-Einstein condensate of ^{41}K atoms in the $|F,m_F\rangle=|2,2\rangle$ state was created by direct evaporation in a magnetic trap. The efficiency of evaporative cooling was $\gamma=2.7$, which was only ~15% lower than ^{87}Rb under the same condition. By measuring the lifetime of a condensate, the upper bound of the three-body loss coefficient was determined to be $4(2)\times10^{-29}$ cm^{-6} s^{-1}. A Feshbach resonance in the $|F,m_F\rangle=|1,-1\rangle$ state was observed at 51.35(10) G, which is in good agreement with the theory. The observed high efficiency of evaporative cooling makes ^{41}K a good candidate for a coolant. We can also expect good thermalization between ^{40}K and ^{41}K, since the interspecies scattering length is relatively large and positive ($a_{40-41}=97a_0$) [4]. This opens up the possibility of performing Bose-Fermi mixture experiments using a mixture of ^{41}K and ^{40}K, which should display negligible difference in sag due to gravity. Furthermore, ^{41}K can be a good substitute for ^{87}Rb. This is especially true when one wants to cool atomic species that have a poor elastic cross section with ^{87}Rb [22].

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