Thermal Atom-Ion Collisions in K-Yb$^+$ Hybrid System

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We report experimental studies of atom-ion collisions in a temperature range of several hundred Kelvin (thermal regime) using trapped ytterbium (Yb$^+$) ions immersed in potassium (K) vapor. Various collisional rate coefficients of the Yb$^+$ ion per K-atom number density are measured. We find the isotopically dependent charge-exchange rate coefficients to be $\kappa_{ce} = (12.7 \pm 0.8) \times 10^{-14} \text{ cm}^3\text{s}^{-1}$ and $\kappa_{ce} = (5.3 \pm 0.3) \times 10^{-14} \text{ cm}^3\text{s}^{-1}$ for K$^{172}$Yb$^+$ and K$^{172}$Yb$^+$ respectively. The spin-destruction rate coefficient is $\kappa_{sd} = (1.46\pm0.29) \times 10^{-9} \text{ cm}^3\text{s}^{-1}$, and the spin-exchange rate coefficient is $\kappa_{se} = (1.64\pm0.24) \times 10^{-9} \text{ cm}^3\text{s}^{-1}$, which are isotopically independent. Unlike alkali-alkali atomic systems that normally have $\kappa_{se} \gg \kappa_{sd}$, this thermal K-Yb$^+$ system has $\kappa_{se} \sim \kappa_{sd}$, which is not fully understood with present theory. Similar results have also been reported previously from other cold atom-ion hybrid systems. It is important to investigate hybrid systems of different atom-ion species to achieve better understanding on the collisional physics for atom-ion based quantum applications.

While free thermal atoms, trapped neutral atoms, and trapped ions are well established platforms for atomic-physics research and applications, a hybrid system of neutral atoms and ions can offer new capabilities and opportunities that cannot be accomplished with only one atomic species. In 1960s and 1970s, the spin-dependent charge-exchange opportunities that cannot be accomplished with only one neutral atoms and ions can offer new capabilities and physics research and applications, a hybrid system of trapped ions are well established platforms for atomic-atom interactions. In this paper, we study the K-Yb$^+$ atom-ion system. Ideally, if the collisions follow the Langevin model, the rate coefficients are nearly independent of the collisional kinetic energy. While the previous experimental studies using hybrid ion-atom systems were in the ultra-cold regime, our experiment is carried out in the thermal regime. This would help further understanding of the collisional interactions of hybrid systems in a wider temperature range.

Our experimental apparatus comprises a vacuum chamber for the atom-ion hybrid environment, B-field coils, and various laser sources. Inside the vacuum chamber, there is a linear Paul trap with four 50-mm long rods (6-mm apart along each side) and two hollow end caps, and there are two Yb sources (natural abundance and isotopically enriched) and one K getter (dispenser) source (natural abundance). The chamber was baked out to achieve $10^{-10}$ torr level and then was back filled with $45 \times 10^{-6}$ torr of helium gas for buffer-gas cooling to the trapped Yb$^+$ ions. The K getter was driven by 2.5-A DC current during the bakeout to clean up the possible outgassing sources on the getter. The trap rods were driven by a 1.95-MHz RF source at 780 $V_{pk-pk}$ and the end caps were connected to a 15-V DC source. We trapped $> 10^{10}$ ions with an ion density on the order of $10^8 \text{ cm}^{-3}$ and the measured ion temperature $T_{Yb^+} \approx 600 - 700 \text{ K}$. The laser sources include 369-nm, 399-nm, and 935-nm lasers for ion loading, state preparation, and interrogation of Yb$^+$ ions; and 766-nm and 770-nm lasers for optical pumping and probing of K atoms. As illustrated in Fig. 1, the 369-nm laser is delivered to the ion cloud to provide state detection and optical pumping of the trapped ions, and the 935-nm laser clears the low-lying $D_{3/2}$ state. Fluorescence at 369 nm or 297 nm is collected with a photon multiplier tube (PMT). To study the interactions between Yb$^+$ ion and K atoms, the vacuum chamber is filled with K vapor released from a potassium getter. The K vapor density is controlled through the electrical current applied on the getter. The measured K-atom temperature is $T_K \approx 340 \text{ K}$. A linearly polarized 770-nm laser beam with a doughnut profile is used to interrogate the K atoms.
used as a probe to measure the K-vapor density and temperature. The same laser beam is used to optically spin-polarize K atoms with circular polarization. The dark center of the doughnut beam is aligned to the ion cloud axis. A linearly polarized 766-nm laser beam through the ion cloud is used for an optical rotation (Faraday effect) measurement [18, 19] to determine the degree of spin polarization of the K atoms inside the ion cloud. Both the number density and the temperature of the trapped Yb+ ions and K atoms can be determined by measuring the signal contrast and the Doppler profile of the optical resonances through scanning the frequency of the transmitting probe laser across the D1 resonances [18, 19]. We used B-field coils to compensate the ambient magnetic field and set the preferred magnetic-field direction for the experiment.

Figure 1 illustrates different collisional interactions, such as charge exchange, spin destruction, and spin exchange. The charge-exchange interaction occurs when an electron migrates from a neutral K atom to a Yb+ ion during the collision (There could be an intermediate state (YbK)+ during the collision process):

\[
\text{charge exchange: } Yb^+ + K \rightarrow Yb + K^+. \]

After charge-exchange collisions, the neutral Yb can no longer be trapped. This leads to the main ion loss mechanism. We can measure the charge-exchange induced ion-loss rate to determine the charge-exchange rate coefficient via the following relation:

\[
\gamma_{ce} = \frac{1}{\tau_{ce}} = k_{ce} \cdot n_K, \quad (1)
\]

where \(\gamma_{ce}\) is the charge-exchange rate, \(\tau_{ce}\) is the exponential ion loss time constant, \(n_K\) is the number density of K atoms, and \(k_{ce}\) is the charge-exchange rate coefficient. Here, the rate coefficient \(k = \langle \sigma v \rangle\) is an ensemble average of all possible velocity-dependent cross section \(\sigma(v)\) and colliding relative velocity \(v\).

To measure \(\tau_{ce}\), we delivered a 1-mm diameter, 3-mW cw 935-nm laser beam overlapped with a 1-mm diameter 369-nm laser beam to the ion cloud. The 369-nm laser was at 1 \(\mu\)W, pulsed every 11 minutes for 0.4 s. \(^{171}\)Yb+ ions are kept in the dark for 99.94% of time to eliminate any possible laser associated ion-signal-loss effects, such as F-state trapping [17] and laser-enhanced charge exchange (will be explained later). For \(^{172}\)Yb+, we used a 0.2 \(\mu\)W 369-nm laser, 4-s pulsed repeated every 11 minutes for the same reasons. We carefully verified that the 369-nm laser power and its duty cycle were sufficiently low to make sure no noticeable effect to be seen from the presence of the 369-nm laser. The typical fluorescence signals of Yb+ ions are shown in Fig. 2a. To extract \(\tau_{ce}\), we fit the data to an exponential function. The data indicates that the \(^{171}\)Yb+ ions leave the trap about twice faster than \(^{172}\)Yb+ ions with the same K-atom density. The summary of experimental data of \(1/\tau_{ce}\) for \(^{171}\)Yb+ and \(^{172}\)Yb+ with different K-atom density \(n_K\) are shown in Fig 2b. With linear fits, we find the charge-exchange rate coefficient to be

\[
^{171}k_{ce} = (12.7 \pm 0.8) \times 10^{-14} \text{ cm}^3\text{s}^{-1}
\]

\[
^{172}k_{ce} = (5.3 \pm 0.3) \times 10^{-14} \text{ cm}^3\text{s}^{-1}.
\]

Since the charge-exchange efficiency is strongly related to the electronic structures of the two colliding species,
the different electronic energy-level structures of $^{171}$Yb$^+$ and $^{172}$Yb$^+$ ions may explain their significantly different rate coefficients. It is worth noting that the ion loss rate under the presence of K atoms increases rapidly when the Yb$^+$ ions are exposed to D1 resonant 369-nm laser, or the K atoms inside the ion cloud are exposed to D1 resonant 770-nm laser. We believe this is caused by the much stronger charge-exchange interaction when the colliding ion or atom is in the excited state. Based on our experimental parameters, we estimated the charge-exchange rate coefficient to be on the order of $10^{-9}$ to $10^{-8}$ cm$^3$s$^{-1}$ if one of the colliding species is in its excited state ($P_{1/2}$).

Atom-ion collisions can induce not only charge exchange but also spin flips, including random spin flips that destroy the spin polarization of the colliding atomic species, and spin exchange that swaps the electronic angular momentum between the ion and the atom. These spin-dependent collisional effects on the Yb$^+$ ion leads to these forms:

spin exchange: Yb$^+ \uparrow + K \downarrow \rightarrow$ Yb$^+ \downarrow + K \uparrow$,
spin destruction: Yb$^+ \downarrow \uparrow + K \rightarrow$ Yb$^+ \uparrow \downarrow + K$.

Here the $\uparrow, \downarrow$ arrows represent the spin state. The dynamic of the Yb$^+$ spin polarization is described by

$$P_{Yb^+} = R_{op}(1 - P_{Yb^+}) + n_K [\kappa_{se}(P_K - P_{Yb^+}) - \kappa_{sd} P_{Yb^+}],$$

(2)

where $R_{op}$ is the optical pumping rate on the ions, $P_{Yb^+}$ and $P_K$, ranging from -1 to 1, are the spin polarization for the Yb$^+$ ions and K atoms, and $\kappa_{sd}$ and $\kappa_{se}$ are the rate coefficients for the spin-destruction and spin-exchange interactions. From Eq. [2] with $R_{op} = 0$ and $P_K = 0$, we find the total spin-relaxation time constant to be $\tau_{spin} = \gamma_{spin}^{-1} = [(\kappa_{sd} + \kappa_{se})n_K]^{-1}$. To measure the total spin-relaxation rate $\gamma_{spin}$, we keep the K atoms unpolarized (i.e. $P_K = 0$), and we spin-polarize the $^{172}$Yb$^+$ ions by applying a circularly polarized 369-nm laser to pump the $^{172}$Yb$^+$ ion into the $|m = 1/2\rangle = |\uparrow\rangle$ or $|m = -1/2\rangle = |\downarrow\rangle$ state in its Zeeman sublevels as illustrated in Fig. 4. As shown in Fig. 5, when the unpolarized $^{172}$Yb$^+$ ions are illuminated by the 369-nm laser light, fluorescence appears at the beginning and then decays as most of the ions are spin polarized ($P_{Yb^+} \sim 1$), where ions are in the dark state of the pump light and the photon scattering is minimized. During the “OFF” period of the pump light (i.e. $R_{op} = 0$), the spin relaxation process reduces $P_{Yb^+}$ and therefore recovers the fluorescence signal when the pump light turns on again.
and negative K-atom spin polarization at the ion cloud inside the dark volume is ±0.24 using the optical rotation method with a weak and optically detuned 766-nm beam. With these experimental conditions, Fig. 1 summarizes the results of $P_{Yb^+}$ versus $P_K$, where $P_{Yb^+}$ can be well calibrated by measuring the signal levels the ion fluorescence with conditions of $P_{Yb^+} = 0$ and $P_{Yb^+} = 1$. Using Eq. 3, we find $\kappa_{se} = (1.64 \pm 0.24) \times 10^{-9}$ cm$^3$s$^{-1}$, and $\kappa_{sd} = (1.46 \pm 0.29) \times 10^{-9}$ cm$^3$s$^{-1}$. Since the K vapor density is controlled by the electric current through the K-getter (dispenser), one may wonder if some gas background was also produced when the K-getter temperature increased. Based on some previously reported spin-destruction cross section data[17], this would required the gas pressure to be $\geq 10^{-9}$ torr to affect our spin-destruction measurements, which can be easily detected by the residual gas analyzer (RGA) in our vacuum system. But we found no detectable, additional gas background during the production of the K vapor.

With the relative collisional velocity $\vec{v} = 4.6 \times 10^4$ cm/s determined by the temperatures of $Yb^+$ ions and K atoms, we find the effective spin-exchange cross section $\Sigma_{se} = \kappa_{se}/\vec{v} = 3.6 \times 10^{-14}$ cm$^2$, which is similar to that of many alkali-alkali pairs[19] in the thermal regime. For most applications using the atom-ion hybrid platform, $\kappa_{se} \gg \kappa_{sd}$ and $\kappa_{se} \gg \kappa_{se}$ will be the preferred conditions[20]. Under these conditions, the interactions of the quantum states between the neutral atom and the ion via spin-exchange would be stronger than the decoherence mechanism due to spin destruction, and atoms and ions would not change their original forms via charge exchange for sufficiently long period. A recent cold Rb Yb$^+$ experiment[14] and this thermal K-Yb$^+$ work have both shown $\kappa_{se} \sim \kappa_{sd}$. The cold regime results may be explained by the theoretical work of Tscherbul et. al [21]. But there is still no good theoretical explanation for thermal regime. The relatively large $\kappa_{sd}$ may be understood by further detailed modeling of the spin-orbit interactions[21, 22] in the future. In conclusion, we have studied the collisional effects in a thermal K-Yb$^+$ system. Our work may provide further insight to help establish ion clocks that do not use a UV light source and help study the quantum physics of atom-ion hybrid platforms.

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