Suppression of Penning ionization in a spin-polarized mixture of rubidium and He*

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Abstract. This paper presents the first study of the collision dynamics of an ultra-cold spin-polarized mixture of rubidium and metastable helium (He*) atoms. Our experiment monitors ion production from the mixture for both magnetically polarized and unpolarized cases. In the unpolarized case, we observe an increase in our background ion rate. However, in the completely polarized sample the ion production is below the sensitivity of our experiment. Nonetheless, we determine an upper limit of $5 \times 10^{-12}$ cm$^3$ s$^{-1}$ for the polarized rate constant ($\beta_{\text{Rb--He}^*}$), which is two orders of magnitude below the unpolarized rate constant. Such a suppression of the He*--$^{87}$Rb polarized rate was not apparent a priori and opens the intriguing possibility of creating a dual Bose–Einstein condensate comprising an alkali ground-state atom and an excited-state noble-gas atom.

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1. Introduction

Metastable triplet helium atoms (He*) exist in an excited state and carry 19.8 eV of internal energy, sufficient to Penning ionize almost any atom or molecule with which a He* atom might collide. This property was thought to preclude the possibility of a He* Bose–Einstein condensate (BEC) since the high densities required for condensate production would lead to large Penning losses. However, as predicted by Shlyapnikov et al [1], Penning losses are reduced by several orders of magnitude in a spin-polarized mixture of He*, compared to those in an unpolarized sample, and thus production of a He* BEC is possible [2]–[5].

In a mixture of He*–87Rb atoms inter-species Penning processes should also play an important role

\[ \text{He}(2^3S) + \text{Rb} \rightarrow \text{He}(1S) + \text{Rb}^+ + e. \]  

\(^{87}\text{Rb}\) atoms have an ionization energy of \(\sim 4\) eV; thus a collision with a He* atom is sufficient to ionize the \(^{87}\text{Rb}\) atom while transferring the He* atom to its ground state. As is the case for an ensemble of He* atoms, a spin-suppression argument can be made for a He*–\(^{87}\text{Rb}\) mixture. If the whole mixture is spin polarized (He* in \(m_J = +1\), and \(^{87}\text{Rb}\) in \(m_f = +2\)) there will be a reduction in Penning ionization as the total spin of the colliding particles in the final state will not exceed 2, while in the initial state it equals 3, and the spin conservation rule cannot be satisfied. While this argument is valid, the extent of the suppression that one might obtain for a He*–\(^{87}\text{Rb}\) mixture is unclear, since the interatomic potentials required for theoretical calculation of the Penning rate are not known.

Ultra-cold mixtures of atoms have been widely studied, due to their interesting collisional properties as well as their appropriateness for sympathetic cooling, e.g. of fermions [7]. However, there has only been one previous investigation of a cold alkali–noble gas mixture in which metastable argon (Ar*) atoms were simultaneously trapped with \(^{87}\text{Rb}\) atoms [8]. This study was conducted in a magneto-optic trap (MOT), where the atoms are essentially unpolarized, and an unpolarized Penning rate was measured. The additional step of determining the polarized rate by implementing magnetic trapping was not pursued, presumably because the production of an Ar* BEC is not feasible due to the large inelastic loss rates still present in spin-polarized Ar* [9].

In this paper, we present the results of experiments in which we probe the Penning ionization rates of a mixture of ultra-cold He*–\(^{87}\text{Rb}\) atoms. We are able to demonstrate that a high degree of suppression exists for the polarized case and to put an upper limit on the polarized Penning rate constant at \(5 \times 10^{-12} \text{ cm}^3\text{s}^{-1}\). Such a low rate constant might make a dual He*–\(^{87}\text{Rb}\) BEC possible, which would be an interesting environment in which to create exotic He*–\(^{87}\text{Rb}\) molecules, in a similar manner to that in which long-range He* dimers have been previously demonstrated [10].

Moreover, the mixture is interesting in terms of sympathetic cooling [11] of He* with \(^{87}\text{Rb}\). The large mass difference between the two species and the high magnetic moment of He* make the simultaneous magnetic trapping of He* and magneto-optic trapping of \(^{87}\text{Rb}\) possible. Inside such a trap, temperatures of \(\sim 10 \mu\text{K}\) for \(^{87}\text{Rb}\) should be possible using standard polarization gradient cooling techniques [12]. Sympathetic collisions within the He*–\(^{87}\text{Rb}\) mixture should efficiently thermalize the He* atoms to this temperature, which is only a factor of two above the highest condensation temperature reported for He* [3]. In this way it might be possible to create a He* BEC comprising a large number of atoms in a short period of time.
Figure 1. Experimental set-up used to produce dual He*–$^{87}$Rb MOTs. He* MOT beams are shown as transparent (yellow) beams, whereas the solid (pink) beams represent $^{87}$Rb laser beams.

2. Experiment

Our experiments are performed in an ultra-high vacuum chamber that allows access for the six separate beams required to produce a dual He*–$^{87}$Rb MOT (see figure 1). The set-up consists of a cryogenically cooled dc discharge used as a source of He*. The design and performance of this source have been reported elsewhere [6]. The He* atomic beam is first collimated in two-dimensional optical molasses and then slowed to $\sim 70$ m s$^{-1}$ using a Zeeman slower. A three-beam retro-reflected geometry is used to capture $\sim 3 \times 10^8$ He* atoms from this beam in a MOT. The MOT vacuum chamber can be isolated from the low-vacuum source (and the incident background of ground-state helium atoms) by use of an in vacuo valve. This allows us to reach the low pressures required to achieve an $\sim 18$ s lifetime in our magnetic trap. In order to create a large $^{87}$Rb MOT we use a low-velocity intense source (LVIS) to create a cold beam of $^{87}$Rb atoms. The flux of this source into the main chamber is $\sim 10^8$ a s$^{-1}$. Because of access constraints, we only use a three-beam retro-reflected MOT geometry to trap atoms from this beam. Moreover, the three sets of beams are not orthogonal, but rather intersect at an angle of $60^\circ$ as shown in figure 1. Nonetheless, with a total intensity of $I = 21$ mW cm$^2$ and a detuning of $\delta = -2\Gamma$ (from the $F = 2 \rightarrow F' = 3$ transition) for the trapping laser beams and a repumping laser locked to the $F = 1 \rightarrow F' = 2$ transition, we are able to load $\sim 10^8$ $^{87}$Rb atoms into a MOT.

Efficient transfer of the mixture into the magnetic trap is nontrivial due to the disparate nature of the two species. The $^{87}$Rb MOT is loaded for $\sim 5$ s, at which point the He* atomic beam is unblocked, via an in vacuo valve, and the He* MOT is fully loaded in approximately half a second. This procedure is necessary since the helium beam greatly attenuates the number of $^{87}$Rb atoms we can trap. An $\sim 4$ ms period of polarization gradient cooling, in which we
detune the $^{87}$Rb MOT beams $-4.4\Gamma$ from resonance, is used to minimize the temperature of the $^{87}$Rb atoms. The $^{87}$Rb cloud is then spin polarized using a 500 $\mu$s laser pulse tuned to the $F = 2$ to $F' = 2$ transition. At approximately the same time we initiate Doppler cooling of the He$^+$ by reducing both the detuning and intensity of the He$^+$ MOT beams for a period of a few milliseconds. The magnetic trap uses the same quadrupole field as our MOTs; however, at transfer we increase the field gradient from 5 to 20 G cm$^{-1}$ in the weak-trapping axis so that the field is able to support $^{87}$Rb atoms in the $F = 2$ ground state against gravity. Using this procedure, we are able to transfer $6 \times 10^7$ He$^+$ atoms at a temperature of 200 $\mu$K and $3 \times 10^6$ $^{87}$Rb atoms at a temperature of 80 $\mu$K into the magnetic trap.

Determining the Penning rate coefficient from our experiments requires a knowledge of the number and temperature of $^{87}$Rb atoms ($N_{\text{Rb}}$ and $T_{\text{Rb}}$, respectively) and the number and temperature of He$^+$ atoms ($N_{\text{He}}$, $T_{\text{He}}$, respectively). We use a saturated fluorescence method [5] to determine the atom number. The method relies on ramping our MOT laser beams to resonance with full power. In such a case, the scattering rate of photons is simply $R = N \times \Gamma/2$, and one needs only to take into account the collection efficiency of the imaging system to determine the number of atoms. Separate photodiodes are used for the He$^+$ and $^{87}$Rb measurements, and filters are used to stop He$^+$ light from interfering with the $^{87}$Rb measurement and vice versa. The temperature measurements are obtained via time-of-flight (TOF) expansion techniques. In the case of $^{87}$Rb, the size of the cloud for various TOF expansion times is used, whereas for He$^+$ the cloud is dropped on an electron multiplier located 27 cm below with the ensuing TOF distribution yielding a temperature.

3. Results

To demonstrate our sensitivity to $^{87}$Rb ion production, we first produce an unpolarized mixture of He$^+$–$^{87}$Rb and monitor the ions produced by the sample. This is achieved by first loading a He$^+$ MOT and then subsequently turning off the He$^+$ MOT light so that the He$^+$ atoms are confined in the MOT magnetic field. The $^{87}$Rb trapping light is then turned on and an $^{87}$Rb MOT is loaded. Figure 2 shows the resulting experimental traces from such an experiment. At just after 1.5 s, we turn on an electron multiplier that has a direct line of sight to the atom clouds and monitors the ion production of the sample. The dotted (black) line shows the background He$^+$ ion production, which primarily results from inelastic background collisions when no $^{87}$Rb is present. At approximately 2 s the $^{87}$Rb MOT starts loading and the resulting fluorescence detected on the $^{87}$Rb photodiode is shown as a solid (blue) trace. The presence of $^{87}$Rb atoms increases the ion production rate, resulting in the ion trace shown by the dashed (red) curve. While this experiment proves our sensitivity to $^{87}$Rb ions, it is difficult to produce a realistic unpolarized rate coefficient for the mixture since the overlap between the two clouds is difficult to determine. Our experience is that radiation light forces can displace the centre of the $^{87}$Rb MOT significantly from the magnetic trap zero, which can dramatically reduce the number of ions produced.

Thus, we rely on a separate measurement of the unpolarized rate coefficient performed by overlapping the two MOTs. In this measurement, great care was taken to optimize the overlap between the two MOTs by imaging the clouds from two orthogonal directions. The resulting unpolarized Penning rate coefficient was found to be $6 \pm 2 \times 10^{-10}$ cm$^3$ s$^{-1}$ [13]. The rate determined by this method is consistent with an approximate rate calculated from the increase in ion production observed in figure 2. Note that these two rates, although both unpolarized, are
Figure 2. Rubidium ion production when an $^{87}$Rb MOT is overlapped with a He$^*$ magnetic trap.

not exactly the same since in the magnetically trapped case there is no population in the He$^*$ $2^3P_2$ excited state. For heteronuclear collisions the potential energy curves associated with S–S$'$ and S–P collisions are van der Waals in nature ($1/R^6$), whereas for P–P$'$ collisions the potential is quadrupole ($1/R^5$) in shape [14]. However, in a He$^*$ MOT the excited-state population is generally small, $\sim 5\%$, and thus we expect only a small difference between the rates.

Suppression of Penning ions should occur in the case of a spin-polarized mixture. We probe this suppression by loading both clouds of atoms into a magnetic trap. In such a case both the He$^*$ and $^{87}$Rb atoms are spin polarized (He$^*$ in $m_j = +1$, and $^{87}$Rb in $m_f = +2$). Figure 3 shows the fluorescence and ion traces that result from such an experiment. The fluorescence traces show the loading of both MOTs ($^{87}$Rb, solid (red) curve, He$^*$, dotted (blue curve)) until the laser beams are turned off at $\sim 5.7 \text{s}^{-1}$ and the atoms are transferred into the magnetic trap. At this point, an ion detector is turned on and the ion production for the mixture is measured, shown in the inset of figure 3 (solid red curve). This trace is compared to an identical run of the experiment without the $^{87}$Rb atoms present (dashed blue curve). Within the noise levels of our experiment, we observe no increase in ion production due to the presence of $^{87}$Rb in the spin-polarized mixture. While this means we cannot determine a spin-polarized Penning rate coefficient for the mixture, it allows an upper limit to be determined.

To analyse the inelastic Penning rate of the magnetically trapped He$^*$–$^{87}$Rb mixture, we need to evaluate the relationship between ion production and the loss rate coefficient $\beta_{\text{Rb–He}^*}$, given by

$$\phi = \beta_{\text{Rb–He}^*} \int n_{\text{Rb}}(x, y, z)n_{\text{He}^*}(x, y, z)\,dV$$

(2)
where \( n \) is the density of each cloud. In our experiment, the atoms are confined in an anti-Helmholtz quadrupole magnetic trap with a generalized density distribution given by

\[
    n(r, z) = \frac{N}{4\pi} \left( \frac{\mu}{k_b T} \right)^3 \alpha_1^2 \alpha_2^2 e^{-\left(\mu \alpha_1 r / k_b T\right)} e^{-\left(\mu \alpha_2 z / k_b T\right)}
\]

(3)

where \( \alpha_1 \) and \( \alpha_2 \) are the weak and strong magnetic field gradients of the trap, respectively, and \( \mu \) is the magnetic moment of the atom. The inclusion of gravity into the analysis is important because of the large mass difference between the two atomic species. This large difference causes the centre of the \(^{87}\text{Rb} \) trap to be displaced in the direction of gravity, whereas the \( \text{He}^* \) trap is almost unaffected and centred on the B-field zero, reducing the overlap of the two traps and therefore the expected ion production. Substituting equation (3) for \( \text{He}^* \) density and a modified equation (3) that includes gravity for \(^{87}\text{Rb} \) density into equation (2) and evaluating the numerical integral yields the expected ion rate. The \( \text{He}^* \) and \(^{87}\text{Rb} \) peak densities in the magnetic trap are \( 2 \times 10^{10} \text{ cm}^{-3} \) and \( 5 \times 10^9 \text{ cm}^{-3} \), respectively.

Producing an upper limit to the inelastic Penning rate requires a knowledge of absolute ion production. To determine our ion extraction efficiency, we calibrate our detector using the known unpolarized \( \text{He}^* \) Penning rate of \( 2.6 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1} \) [15]. The procedure involves loading a magnetic trap with \( \text{He}^* \) atoms of a known number and temperature. The trap is then illuminated with a short (\( \sim 100 \mu\text{s} \)) laser pulse that depolarizes the sample. The ion rate in the ensuing 50 \( \mu\text{s} \) combined with the known unpolarized rate is then used to determine the ion extraction efficiency. For all our experiments we use the same extraction voltage (\( \sim -100 \text{ V} \)), for which we have performed a detailed numerical simulation of the ion trajectories.
using a commercial modelling package. The extraction efficiency determined using the known unpolarized rate is 0.5%, which is consistent with the predictions of our model.

To produce an upper limit for the polarized Penning rate coefficient we use the uncertainty in our background He* ion rate. This rate constant is $5 \times 10^{-12} \text{ cm}^3 \text{s}^{-1}$, demonstrating a spin-polarized suppression of at least a factor of $\sim 100$. Note that our experiments produce a limit on the total inelastic losses since the measured ion signal is directly proportional to the number of atoms. Thus any non-ionizing loss process, which has been observed in inelastic two-body collisions between He* atoms [16], would only increase the observed suppression.

4. Conclusions

The observed suppression is larger than that measured in any previous experiments, except for the case of He*–He* collisions. Measurements on ultra-cold metastable neon, for example, have demonstrated a factor of $\sim 40$ suppression [17], whereas for metastable xenon no suppression is seen at all [18]. Thus, it was not a priori apparent that a large suppression of Penning ions would be the case for a He*–$^{87}$Rb mixture.

This surprising result can be explained by the fact that in our mixture both species are in symmetric S states, whereas all other trappable noble gas atoms are in asymmetric metastable P states. In the case of a collision involving two metastable atoms both in a P state, the atoms experience a mutual electrostatic interaction. In the case of metastable neon, the asymmetric P-core generates an electric quadrupole–quadrupole potential that depolarizes the atoms during their approach and thus Penning ionization is no longer forbidden by spin conservation. For a He*–$^{87}$Rb mixture the interaction of ground-state atoms is purely van der Waals and thus spin polarization can lead to a large suppression of Penning ions.

In summary, we have demonstrated that spin suppression of Penning ionization occurs in a spin-polarized mixture of ultra-cold He*–$^{87}$Rb and have placed an upper limit on the Penning rate constant. This limit is not low enough to guarantee that the mixture will enable the creation of a dual BEC of both He* and $^{87}$Rb; however, it is encouraging to say the least. In the future, we intend to load the mixture into a magnetic potential created on the surface of an atom chip. This set-up will enable the production of a strongly confining magnetic trap that will allow us to directly measure the polarized Penning rate, and to attempt to create a He*–$^{87}$Rb BEC. Hopefully, our initial measurements will stimulate interest among scattering theorists, as at present little is known about the molecular interactions of ultra-cold He* and $^{87}$Rb.

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