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Inelastic cold collisions of a Na/Rb mixture in a magneto-optical trap

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We report results on inelastic cold collisions for a mixed species magneto-optical trap containing Na and Rb. The rate of collisional trap loss of Na is due to different contributions: Na-Na and Na-Rb collisions. Both parts are investigated with respect to trap laser intensity and frequency. The observations are explained based on a Gallagher-Pritchard model. Possibilities for studies and applications involving mixed species traps are discussed. [S1050-2947(99)51301-2]

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Studies of loss mechanisms for trapped neutral atoms continue to provide important information about inelastic processes occurring in the regime of ultralow energy. Many aspects of the mechanisms of trap loss collisions involving only one species of atom have been extensively investigated [1–4]. A particularly interesting class of inelastic processes is the one involving a pair of identical atoms where one is in the ground state and the other is in the excited state. In this excited-ground quasimolecule state, the $-C_3/R^3$ attractive interaction accelerates the cold atoms against each other. If the pair decays to the ground state during this process, the energy difference between the absorbed and emitted photons caused by change in potential energy on the excited potential will go to kinetic motion. If this gain in kinetic energy exceeds the trap depth (typically 1 K) the pair will escape from the MOT. This mechanism is referred to as radiative escape (RE).

For alkali-metal atoms there is another possible loss mechanism: fine-structure change (FSC). For this case, the collision starts in the $S+P_{3/2}$ attractive molecular asymptotic state. During the course of the atomic encounter the pair may change molecular state, going to the $S+P_{1/2}$ state. The energy difference goes again to kinetic motion; and for most alkali metals it is enough for the pair to escape from the MOT. Most experiments use a single atomic species in the trap and obtain only the combined effects of both mechanisms. In this Rapid Communication we present [5] a systematic study of the total trap loss rate for heteronuclear cold collisions occurring in a mixed species MOT (MSMOT). This is an important step taken with the major aim of understanding the fundamental issues of intraspecies interactions in the cold atomic regime. We also believe that such a study may be of fundamental importance for the development of techniques that will allow the achievement of recently proposed two-species quantum systems [6–8] opening up new and exciting possibilities.

In the following, we shall present some considerations about our MSMOT, the binary alkali-metal mixture, and the experimental procedure to determine the trap loss rate for the heteronuclear inelastic collision process. Furthermore, we compare the experimental results with a model, based on the existing the Gallagher-Pritchard theory (GP model), originally proposed for Na atoms [9] and adapted for the heteronuclear binary case. A reasonable understanding of the experiments is obtained with this simple model.

The production of cold atomic mixtures consisting of different alkali-metal atoms was first demonstrated by Santos *et al.* [10], using a Na/K combination. Other experiments have also started to investigate systems such as Na/Cs and Na/Rb [5]. However, no systematic studies involving the determination of the trap loss rate for binary heteronuclear cold collision has been reported.

The MOT operates in a closed stainless-steel vapor cell, and is loaded with the slowest atoms of a Maxwellian velocity distribution from the gas. Details about the vapor cell MOT operation have already been described elsewhere [10]. A peculiarity of our cell is that it contains separate reservoirs for sodium, potassium, rubidium, and cesium that were assembled in a six-way cross on one arm of the main chamber. Each reservoir has an independent control for temperature and a valve that provide the desired flux of atoms from the species picked to be trapped. The background pressure inside the cell is kept to about 10^{-9} torr, which is obtained using a combination of turbomolecular and ion pumps. The control of partial pressures (via the reservoir temperature) is important because of the considerably different vapor pressures of the various alkali-metal atoms when at the same temperature. If the partial pressures are too different the excessive background vapor of one species compromises the performance of the other species trap [10]. In this work we use only Na and Rb atoms, and their partial pressures are on the order of 10^{-9} torr.

Light from a monomode-ring dye laser (Coherent 699) passes through an acousto-optic modulator (AOM), introducing an extra beam whose frequency is separated from the carrier by 1712 MHz, before dividing into three beams of equal intensity along the orthogonal trapping axes. We tune the carrier laser frequency close to the sodium $3S_{1/2}(F=1) \rightarrow 3P_{3/2}(F'=2)$ transition, which works as the repumper, and the extra generated frequency provides the trapping laser beams working close to the $3S_{1/2}(F=2) \rightarrow 3P_{3/2}(F'=3)$ transition. Both frequencies (trap and repumper) carry practically the same total power.

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For trapping ^{85}Rb we used light coming from a Ti:sapphire (Coherent 899) laser whose frequency was tuned close to $5S_{1/2}(F=3)\rightarrow 5P_{3/2}(F'=4)$ transition. In this case, the repumping transition, $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F'=3)$, was provided by a frequency stabilized diode laser. Here the trap frequency had about six times more power than the repumper. It is important to emphasize that both Na and Rb traps were spatially overlapped, although independent optical components for each trap laser were used.

The number of trapped atoms of both species was determined by imaging their fluorescences onto calibrated photomultiplier tubes (PMTs) (an individual PMT was used for each species of atom), while their dimensions were measured with a charge-coupled-device (CCD) camera. The atomic densities were obtained using these parameters. To perform separate trap measurements for each, we used passband optical filters and dichroic mirrors. For trap laser intensities of about 150 mW/cm^2 for Na and 230 mW/cm^2 for Rb, we measured the spatial atomic distributions (i.e., density profiles), which are close to Gaussians. We found $w_{Na}\sim 5\times 10^{-2}$ cm, and total number $N_{Na}\sim 10^6$ atoms for sodium; and $w_{Rb}\sim 10^{-1}$ cm, $N_{Rb}\sim 10^8$ for rubidium (^{85}Rb), where w is the Gaussian waist. The small sodium atomic cloud stayed inside the large rubidium cloud during the experiments. We observed densities as high as 2×10^{10} atoms/cm^3 for sodium and 4×10^{10} atoms/cm^3 for rubidium. The sample parameters (density, volume, number of atoms) for each species presented here are applied individually (in the absence of the other species).

The experiments were carried out as follows: looking at the PMT signal (which is proportional to the total number of trapped atoms), we observed the loading process for sodium atoms in either the presence or absence of the rubidium cloud. In the steady-state operation we could observe a decrease as high as 40% of the total number of trapped Na atoms when the ^{85}Rb cold cloud was introduced. This decrease is due to the additional loss channels, for sodium atoms, introduced by the presence of cold rubidium.

The time evolution for the number of Na trapped atoms when the cold cloud of Rb is present is given by the rate equation as follows:

$$\frac{dN_{Na}}{dt}=L-\gamma N_{Na}-\beta\int_v n_{Na}^2 d^3r-\beta'\int_v n_{Na}n_{Rb}d^3r, \quad (1)$$

where L is the loading rate, γ is the loss rate due to collisions between the trapped Na atoms and the hot background gas composed mostly of thermal Na and Rb, β is the loss rate due to cold collisions among the trapped Na only, and β' is the loss rate due to cold collisions between trapped sodium and rubidium. Here our main interest is the measurement of β' as a function of Na trap laser intensity and detuning. In Eq. (1), n_{Na} and n_{Rb} are the density profiles of sodium and rubidium atoms. The integration is performed over the whole volume (v) of the Na cloud of trapped atoms. Since for the conditions that we are presently using the spatial trapped atoms distribution is close to Gaussian, i.e., $n(r,t)=n_0(t)e^{-2(r/w)^2}$, Eq. (1) can be rewritten as

$$\frac{dN_{Na}}{dt}=L-\gamma N_{Na}-\frac{2\beta N_{Na}^2}{w^3\pi^{3/2}}-\beta' n_{Rb}N_{Na}, \quad (2)$$

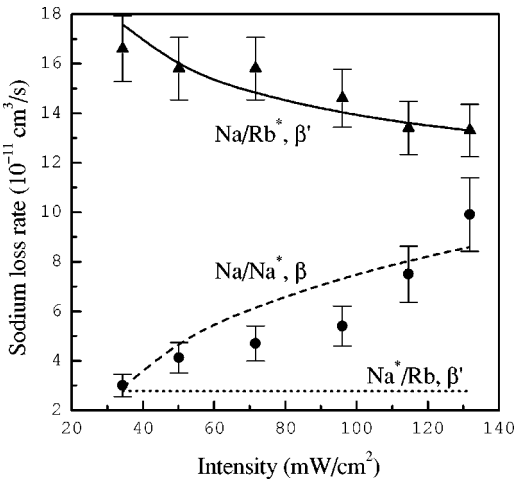

FIG. 1. Experimental results for the trap loss rates β and β' as a function of sodium trapping laser intensity. The dashed line is the normalized result obtained from the GP model [9] for Na alone. The solid line is the normalized result obtained from our adapted GP model for the Na/Rb mixture considering Na/Rb*, and the dotted line is the result considering Rb/Na*. Note that the predicted β' for the mechanism involving Rb/Na* collisions gives much lower values than that for Na/Rb* and a much weaker intensity dependence.

where we have considered the rubidium density as spatially constant across the sodium cloud. This is in fact a good approximation because the size of the Rb cloud is considerably larger than the Na cloud.

A two-step procedure was used in the determination of β'. We first blocked one arm of the Rb trap laser, avoiding the formation of the cold Rb cloud while leaving most of the laser light on. In this situation $n_{Rb}=0$ and the term containing β' in Eq. (2) drops out. We observed the loading process of Na atoms with a PMT. From that, and with the images of the CCD camera, we obtained the rates γ and β by fitting the loading curves using $n_{Rb}=0$ [Eq. (2)]. Second, the Rb trap arm was unblocked, allowing the complete formation of the Rb cloud, and we again observed the loading process for Na. Both clouds were then observed and measured. Finally we fitted the loading curve with the solution of Eq. (2) and obtained the rate β', using γ and β values previously measured. Values of β and β' over a range of laser intensities are shown in Fig. 1. The error bars represent the variances obtained from several independent measurements.

The first clear observation is that β' decreases with the increase in the trapping laser intensity, while β increases in the same intensity range. For β, the values and the behavior were as expected following previous experiments [11] and it is qualitatively well explained by the model proposed by Gallagher and Pritchard (GP-model) [9]. In brief, the model consists in a semiclassical treatment, which accounts for the frequency dependence in the absorption due to a $-C_3/R^3$ potential and spontaneous emission during the collision between sodium atoms. The application of the GP model to the Na trap alone is presented in Fig. 1 as the dashed line after introducing a scale factor.

To interpret the behavior of β' we have adapted the GP model for the heteronuclear case with the following assumptions: (i) Only the RE loss mechanism was considered. This can be justified on the basis of recent experiments where RE

seems to be the dominant mechanism for trap loss [15,16]. (ii) There are two main exoergic collision possibilities: Na/Rb* and Na*/Rb, which involve either rubidium or sodium excited states. These attractive potentials at long range are represented by $-C_6/R^6$ (we have used interatomic potential information contained in the paper by Bussery *et al.* [12] and Aubert-Frécon [13]). (iii) The escape velocity of the Na trap is considered as being intensity dependent. To obtain such dependence we have carried out numerical simulations about the capability of trapping different velocities (similar to [11]). We should point out that due to their mass ratio ($m_{Na}/m_{Rb} \simeq 0.27$) Na atoms will acquire velocities greater than Rb. The main limitation for the application of the GP model in the heteronuclear case is the fact that the range of the potential cannot be considered much greater than the de Broglie wavelength of the atoms.

To understand the behavior of the experimental points for β' as shown in Fig. 1, we have separately considered the contribution of Na*/Rb and Na/Rb* collisions. The results are shown in Fig. 1 as full and dotted lines. For the mechanisms involving Na*/Rb the model predicts a very weak intensity dependence; a stronger dependence is predicted for the Na/Rb* case. Because of the difference in the intensity dependence, we believe that the main contribution to β' comes from collisions involving the Na-ground state with an excited Rb. In fact, introducing an overall scale factor in the results of the adapted GP model, a very good agreement is obtained between theory and experiment, as shown in Fig. 1 (full line). As the intensity goes down, the Na trap depth decreases but the population of excited Rb is kept constant, producing an increase in β'. The consistency of our data with the model shows that this interpretation is plausible. The reason that the Na/Rb* interaction dominates the Na*/Rb in the GP model is the fact that $C_6(\text{Na/Rb*}) \sim 10 C_6(\text{Na*/Rb})$. This difference causes Na to acquire greater velocities during the radiative decay of the pair, causing higher loss rate.

As for the relative experimental values between β and β', that difference is due to the mass ratio. Since Na is much lighter than the Rb atom, the former will move faster than the latter after the energy division following spontaneous emission. One must remember that both the energy and the momentum have to be conserved during the process. So this results in higher loss rates than the homonuclear case when the Na atoms keep only half of the acquired kinetic energy.

In the study of excited–ground-state collisions within cold atoms, the rate variation of the loss rate with the laser frequency is important and provides additional information about excitation occurring at different internuclear separations. Also these kinds of data allow one to observe the important role of spontaneous emission in the process. Normally, the investigation of the loss rate dependence on detuning is done using the technique named ''*optical catalysis*'' [14]. It consists in adding an extra laser to the system, whose frequency is scanned, introducing extra collisional losses (reducing the total number of trapped atoms). To obtain information about the dependence of β, or β', on the detuning, one has to keep the number of atoms constant, for each laser frequency, while the intensity of the extra laser (''catalysis laser'') is adjusted. If $Ic(\Delta)$ is the intensity required to keep N, then $\beta(\Delta) \propto 1/Ic(\Delta)$, as demonstrated in Ref. [14]. To ensure the reliability of this procedure special care must be taken to verify that the ''catalysis laser'' is not affecting the optical pumping rate or the loading rate, and that it is not causing extra force on the atomic cloud.

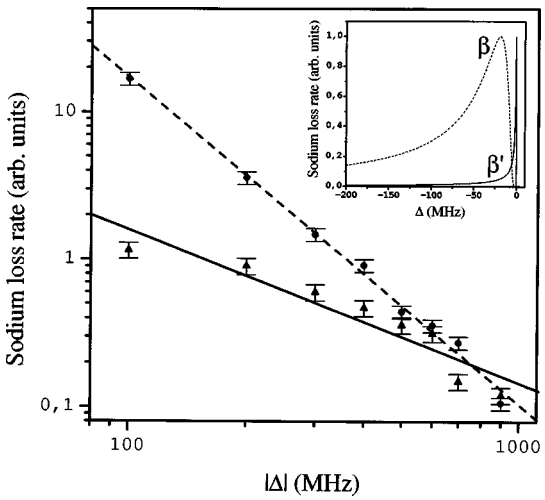

FIG. 2. Variation of total trap loss with laser detuning in the case of the pure Na trap (▲) and the combined Na/Rb trap (●) obtained using the ''*catalysis technique*'' [14]. The total intensity of the sodium trap in both cases is 140 mW/cm^2. The inset shows the expected variation of β and β' as a function of laser frequency. Note the lack of variation in β' in the frequency range of these experiments.

For our experimental conditions, we verified that, for the catalysis laser frequency closer than -70 MHz from the atomic resonance, the trapping performance was affected. Therefore we restricted ourselves to a detuning range from -100 to -1000 MHz. In the case of homonuclear trap loss, the interatomic potential dependence $-C_3/R^3$ causes a variation in the trap loss rate, with the detuning well described (in this range) by $\beta \propto \Delta^{-7/6}$ [14]. Near the resonance, the survival factor due to the occurrence of spontaneous emission becomes more important modifying this dependence, and the trap loss rate suffers a sudden decrease as the detuning gets closer to the resonance.

For the case of heteronuclear trap loss collisions, where the internuclear long-range part of the potential varies as $-C_6/R^6$, the β' dependence on detuning is expected to be $\beta' \propto \Delta^{-5/6}$. To observe the Δ dependence on the loss rate of Na in the combination Na/Rb there are two possibilities for applying the catalysis technique. We can either introduce a laser near resonant with Rb or near resonant with Na. We chose to start with a catalysis laser near resonant with Rb, but still looking for losses in Na. For these conditions, we basically did not observe significant variation of the Na number (at least, not above the noise level). To understand this result we performed calculations using the adapted GP model to obtain the expected loss rate dependence on the detuning. The result is presented in the inset of Fig. 2. No significant variation on $\beta'(\Delta)$ is expected, except in a very narrow region for $\Delta \gtrsim -20$ MHz, which was not reached in the experiment. This flat behavior is a consequence of the small value of the C_6 coefficient for the case Na/Rb*. The small C_6 makes the potential flat at long range, resulting in a very small dependence with Δ. Only close to resonance is this variation important. Just for comparison we had also

plotted the $\beta(\Delta)$, which presents a much broader variation than the $\beta'(\Delta)$, due to the strong C_3/R^3 dependence.

The second catalysis possibility was carried out using a laser near resonant with sodium, either in the presence or absence of the rubidium cloud. The results for both cases are shown in Fig. 2. The detuning dependence observed for β in the absence of Rb atoms was $\Delta^{-1.0\pm0.1}$, which is consistent with the expected $\Delta^{-7/6}$. However, we observe a much stronger Δ dependence than predicted by our simple theory, when we only considered the contribution of crossed species ($\Delta^{-5/6}$). The experimental results show a dependence of $\Delta^{-2.0\pm0.2}$, very different from the homonuclear case. We have performed the experiment for trapping intensities ranging from 40 to 140 mW/cm^2, and no observable intensity dependence was obtained.

A possible explanation for this result is the existence of other collisional channels. One example would be Na*/Rb*. In this case the ''catalysis photon'' would transfer the colliding pair from the Na/Rb* potential ($-C_6/R^6$) to the Na*/Rb*($-C_5/R^5$). And the whole process would behave like a ''two-color'' trap loss. This may introduce a stronger detuning dependence, and enhance the losses. At the present stage this possibility cannot be implemented within the simple GP model. We should point out that such a channel does not need to be included in the intensity-dependence trap loss experiment. The detunings are small and the colliding pair does not survive in the doubly excited potential to get kinetic energy enough to escape from the trap. From our intensity-dependence results, where β' agrees well with the adapted GP theory, we strongly believe that this explanation is plausible. However, it is necessary to do a more detailed study to support this hypothesis. In any case, this should be a motivation for further theoretical/experimental studies in exoergic heteronuclear ultracold collisions. Further experiments involving K/Rb, Na/K, and Na/Cs are in progress and will help our understanding about the inelastic processes.

For the realization of two-species Bose-Einstein condensation, the MSMOT is a necessary first step. The correct understanding of trap loss processes in such a system seems very important for the achievement of a higher number and density of atoms, which appears as an important constraint on those experiments.

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