Evidence of a two-color trap-loss channel

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We have previously reported experimental results on the trap-loss rate for a mixed species magneto-optical trap involving a pair of Na and Rb atoms [Phys. Rev. A **59**, R23 (1999)]. The predicted dependence for the heteronuclear trap-loss rate as a function of laser detuning assuming a colliding pair of ground-state–excited-state atoms fails to explain the experimental results. Further investigation has shown that our observations are consistent if one assumes a loss channel involving an excited state–excited-state colliding pair of atoms. Here we present the model and discuss the physical interpretation applied to our previous experimental results. The present interpretation opens up other ways to understand the trap-loss mechanisms.

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Trap loss of atoms continues to provide important information about inelastic processes taking place within an atomic sample of confined neutral atoms. During the last decade the trap-loss rates have been measured for all the single species magneto-optical traps (MOTs) [1–3]. More recently, heteronuclear trap-loss measurements were reported, and a few two-species MOT systems have already been investigated. The production of dual cold atomic samples was first demonstrated by Santos *et al.* [4], who observed trap losses in an overlapping Na-K trap. Since then, other experiments have followed exploring different combinations: Na-Rb [5], K-Rb [6], Rb-Cs [7], Na-Cs [8], Li-Cs [9], and more recently Cs-K [10]. It was observed that, for each measured mixture, the heteronuclear trap-loss rate as a function of the light intensity presents a characteristic dependence, setting up the two-species MOTs as interesting and rich systems for investigating inelastic collisions.

For alkali-metal atoms, the main mechanisms contributing to homonuclear trap losses in a MOT involves a pair of ground and excited-state atoms. While in the ground and excited states, the attractive part of the interatomic potential accelerates the atoms toward each other, producing a quasimolecule; the pair may then decay down to the ground and ground states gaining kinetic energy as the difference between the absorbed and emitted photon energies. When this gained energy exceeds the trap depth, the pair of colliding atoms escapes from the MOT. This process is named radiative escape (RE) [1–3]. Also, there is at least one other possible mechanism causing losses when alkali-metal atoms collide: fine-structure changing collisions. However, as some reported work has pointed out [11–13], radiative escape appears as the dominant mechanism; hence, most models includes only the RE channel.

In a recently published paper [5] we reported an investigation of the heteronuclear trap loss as a function of the probe laser detuning for a Na-Rb dual sample. The experimental results could not be reproduced by the adapted Gallagher-Pritchard (GP) model [14], when assuming radiative escape from the ground-state–excited-state potential. In that paper we presented an explanation for that observation based on double excitation during the atomic scattering. In the following we shall explore this collisional mechanism in more detail by proposing a semiclassical model that is in quite good agreement with the observations.

The details about our experimental setup can be found elsewhere [5]. Briefly, our mixed species MOT operates in a closed stainless steel vapor cell. The trap laser beam for the ^{85}Rb atoms comes from a Ti:sapphire laser, whose frequency is tuned below the $5S_{1/2}(F=3)\rightarrow 5P_{3/2}(F'=4)$ transition ($\Delta_{\mathrm{Rb}}=-5$ MHz). A repumper laser beam tuned to $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F'=3)$ is provided by a frequency stabilized diode laser. The total power in the trapping beam can be as high as 300 mW while the repumper is around 50 mW. The trapping light for the sodium MOT is provided by a dye laser tuned below the $3S_{1/2}(F=2)\rightarrow 3P_{3/2}(F'=3)$ transition ($\Delta_{\mathrm{Na}}=-10$ MHz). The dye laser beam goes through an electro-optic modulator which generates the repumper beam, tuned close to $3S_{1/2}(F=1)\rightarrow 3P_{3/2}(F'=2)$, and its total power is around 30% of the carrier frequency. We normally operate at total laser intensities of about 150 mW/cm^2 for Na and about 200 mW/cm^2 for Rb (split into six trapping beams). Both laser beams have Gaussian profiles with waists of about 5 mm.

The number of trapped atoms for both species is determined using the MOT fluorescence measured by calibrated photomultipliers. The dimensions of the MOT are determined by imaging the sample onto a charge-coupled device camera. These two measurements allow us to obtain the atomic density profiles. The number of trapped atoms is on the order of 10^6 for Na and 10^8 for Rb, and both densities are about 10^{10} atoms/cm^3. During the experiment, one could directly observe the spatial overlap such that the Na atoms were completely embedded in the cold Rb cloud, assuring that all the Na atoms could interact with the cold Rb sample.

The time evolution for the trapped Na atoms in the presence of the cold Rb cloud is given by the following rate equation:

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

where L is the loading rate, γ is the loss rate due to collisions with background gas (composed mainly of hot Na and Rb vapor), β is the exoergic loss rate due to collisions among

Na atoms only, and β' is the loss rate due to cold collisions between trapped sodium and rubidium atoms.

We evaluate L, γ, β, and β' individually for different trapping conditions. We point out that β' stands for the loss rate of Na atoms in the presence of Rb, which is not the same as the loss rate of Rb in the presence of Na. If one measured the Rb loss due to the Na atoms a different result would be obtained. Here we are interested in evaluating the variation of β' with the laser detuning. In order to do that we use the ''optical catalysis'' technique, originally developed for a single species MOT [15], and adapted for our two-species MOT.

We added an extra (catalysis) laser to the system, whose frequency was scanned around the Na trapping frequency. Therefore, we introduced an additional and tunable collisional loss rate β_c, from here on called the catalysis loss rate contribution. In this situation, the steady state number of trapped atoms for a single catalysis laser frequency is given by

$$N \simeq \frac{L}{\gamma + (\beta + \beta_c) n_c}, \tag{2}$$

where β is the loss rate due to the trapping laser beams, β_c is the catalysis loss rate arising from the extra laser, and n_c stands for the uniform atomic density in the steady state regime. In order to obtain information about $\beta_c(\Delta)$ one has to keep the number of trapped atoms constant, for each laser detuning (Δ_c), for a given intensity of the catalysis laser, I_c. Also, it can be shown that $\beta_c = \beta_c(\Delta_c) I_c(\Delta_c)/I_0$, where I_0 is the intensity at some arbitrarily chosen reference frequency, and therefore one gets $\beta_c(\Delta_c) \propto 1/I_c(\Delta_c)$. The details of the technique can be found in Ref. [15]. It is worth mentioning that in a two-species MOT the extra laser will increase both the homonuclear and the heteronuclear collisions. Thus, we did not measure any specific catalysis loss rate β_c or β_c', but a total loss β_{Tc}, which is a combination of both. However, from our previous results [5] we strongly believe that the contribution of β' to the total trap loss is higher than that due to β, at least for this specific two-species system (Na-Rb).

The catalysis laser beam was provided by a second dye laser (Coherent 699), near resonance with the Na $3S_{1/2}(F=2) \rightarrow 3P_{3/2}(F'=3)$ transition, and it was applied simultaneously with the trapping beams. It was superimposed onto the three orthogonal MOT arms. The Gaussian beam waist and total intensity at the trapping region were about 8 mm and 80 mW/cm^2, respectively.

There are special conditions to be fulfilled to assure that the catalysis laser is not affecting the MOT performance. We observed that the MOT was not affected for detunings greater than -100 MHz and that the signal to noise ratio was good enough to go to detunings up to about -1000 MHz. Hence we have restricted ourselves to this detuning range.

The measured dependence of the total catalysis loss rate β_{Tc} as a function of detuning is presented in Fig. 1. The error bars result from the standard deviation taken from each independent data point and each point is an average of five runs. The logarithmic plot shows that the measured frequency dependence for the total catalysis trap loss rate is $\beta_{Tc} \propto \Delta^{-2 \pm 0.2}$, whose uncertainty is obtained from three different trapping intensities. This dependence is different from that obtained for Na alone ($\beta_c \propto \Delta^{-7/6}$), correctly predicted by the Gallagher-Pritchard model [14] when a C_3/R^3 attractive potential is considered. In a first attempt to explain the experimental result we modified the homonuclear GP model by simply changing the internuclear asymptotic dependence to a C_6/R^6 attractive potential, which is the dominant coefficient for the heteronuclear long range interacting potential, when one atom is excited and the other remains in the ground state. The result for the loss rate is $\beta_c' \propto \Delta^{-5/6}$, which is far from the experimentally observed dependence.

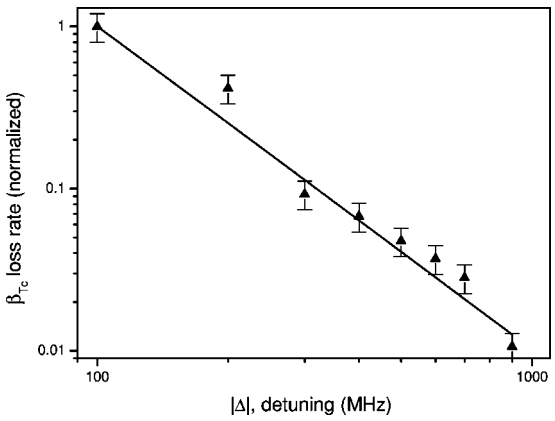

FIG. 1. Experimental total catalysis loss rate (β_{Tc}) as a function of the catalysis laser detuning.

As previously discussed for this experiment, there are other possible loss channels occurring when the extra laser is on. Indeed, the sodium MOT is located in a cloud of Rb atoms, and by introducing an extra excitation channel for sodium atoms one may turn on an additional collisional process involving the presence of double excited states Na*-Rb*, increasing the trap losses. In fact, in our previous investigation with the Na-Rb system [5] as a function of trap laser intensity, it was observed that the main mechanism contributing to β' was the Na-Rb* collision channel. The trap laser intensity dependence was correctly obtained when only this channel was supposed to cause the heteronuclear loss rates. On the contrary, when a contribution of Na*-Rb was assumed, the result was completely different from the experimental observation in Ref. [5].

Hence, it seems natural now to assume that the catalysis laser exciting sodium atoms is introducing an extra loss channel: Na*-Rb*. To verify this possibility we implemented a model whose main steps are illustrated in Fig. 2. First, we suppose that the collision starts at some internuclear distance R_0. The Na-Rb colliding pair absorbs a photon from the Na catalysis laser, ω_c. This takes the atoms to an attractive potential asymptotically connected to the Na*-Rb dissociation limit, which depends on the internuclear distance as C_6/R^6. After some time moving in this potential, the pair is expected to decay back down to the ground state, or it also may absorb an extra (infrared) photon from the Rb trapping laser (ω_{Rb}). The extra photon takes the pair to a

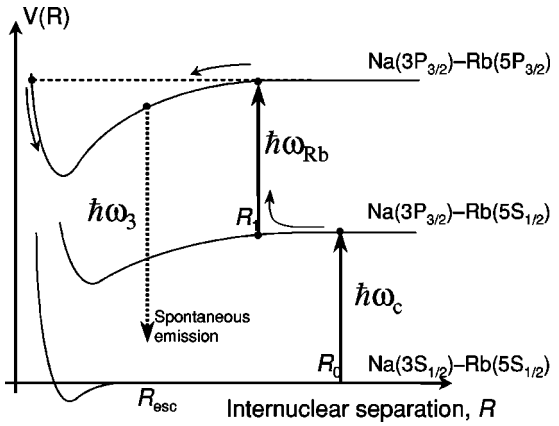

FIG. 2. The doubly excited trap-loss channel, level scheme, and steps assumed in the model to explain the experimental results.

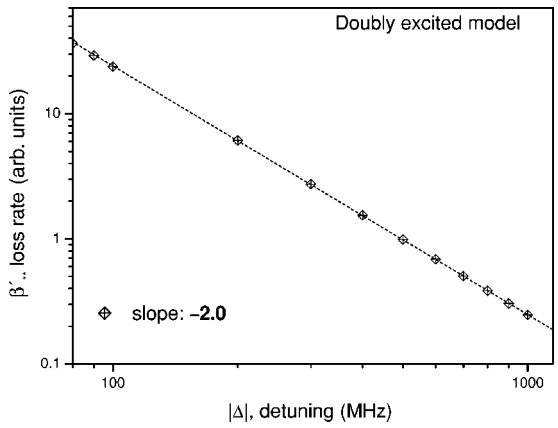

FIG. 3. Theoretical heteronuclear doubly excited trap-loss rate (β'_{**}) evolution obtained from the model. The linear dependence, with slope -2, is in quite good agreement with the experimental results presented in Fig. 1.

C_5/R^5 attractive potential asymptotically corresponding to Na*-Rb*. The whole process occurs just like ''two-color'' trap loss [1] with a special detuning dependence of the catalysis laser in the first step. Due to the C_5/R^5 internuclear separation dependence, the final potential is stronger when compared to the intermediate C_6/R^6, and the atoms' kinetic energy can increase faster in the Na*-Rb* potential. Therefore, this channel appears to be a reasonably important contribution to the loss mechanisms, at least in the case of this experiment.

During the motion in this doubly excited state, eventually either Na on Rb or both may decay, releasing kinetic energy. If the gained kinetic energy overcomes the trap, depth both atoms escape from the trap increasing the losses. The theoretical loss rate due to the doubly excited potential, β'_{**}, is, according to Ref. [6], given by

$$\beta'_{**}=\frac{1}{2}\int_0^\infty\int_0^{R_0}4\pi R_0^2\epsilon_{\mathrm{Na}}(R_0,\omega_c,I_c)P_{\mathrm{S}}(R_0,R_1)\times\epsilon_{\mathrm{Rb}}(R_1,\omega_{\mathrm{Rb}},I_{\mathrm{Rb}})P_{\mathrm{RE}}(R_0,R_1,R_{\mathrm{esc}})\frac{dR_1}{v(R_0,R_1)}dR_0, \tag{3}$$

where $\epsilon_{\mathrm{Na}}(R_0,\omega_c,I_c)$ is the excitation rate for the first photon absorption; $P_{\mathrm{S}}(R_0,R_1)$ is the probability that the atomic pair will not decay or undergo a RE process while in the Na*-Rb potential; $\epsilon_{\mathrm{Rb}}(R_1,\omega\mathrm{Rb},I_{\mathrm{Rb}})$ is the excitation rate for the second photon absorption (the $1/R^5$ potential of the excited-state–excited-state combination and the $1/R^6$ potential of the excited-state–ground-state combination are taken into account); $v(R_0,R_1)$ is the velocity of the pair at R_1; $dR_1/v(R_0,R_1)$ is the transit time in the region of the second absorption; and $P_{\mathrm{RE}}(R_0,R_1,R_{\mathrm{esc}})$ is the probability that a RE will take place while in the excited-state–excited-state potential. In the model, the possibility of oscillation within the potentials is taken into account in the expressions for P_{S} and P_{RE}. The value of R_{esc} is the internuclear separation where the released kinetic energy is high enough to free the Na atoms from the trap. We used the C_5 and C_6 coefficients provided by Marinescu and Sadeghpour [16], while we considered the ground-state–ground-state interacting potential Na($3S_{1/2}$)-Rb($5S_{1/2}$) flat compared to the singly and doubly excited ones. Details about the model and Eq. (3) are available in Ref. [6].

In Fig. 3 we show the theoretical β'_{**} result as a function of the catalysis laser detuning. By plotting it on a logarithmic scale we obtain the value -2.0 for the slope, that is, $\beta'_{**}\propto\Delta^{-2.0}$, in quite good agreement with the experimental observation. That is obtained assuming the following collisional loss channel:

$$\mathrm{Na}(3S_{1/2},F=1)+\mathrm{Rb}(5S_{1/2},F=2)+\hbar\omega_c$$

$$\Rightarrow\mathrm{Na}(3P_{3/2})+\mathrm{Rb}(5S_{1/2},F=2),$$

$$\mathrm{Na}(3P_{3/2})+\mathrm{Rb}(5S_{1/2},F=2)+\hbar\omega_{\mathrm{Rb}}$$

$$\Rightarrow\mathrm{Na}(3P_{3/2})+\mathrm{Rb}(5P_{3/2}).$$

We note that the above channel is very likely to be present within our dual species MOT, especially because we regularly run the experiments with the trapping lasers at full power (intensity), far above the saturation intensity limit ($\leqslant 6$ mW/cm^2). Thus, we believe that the many excited cold atoms colliding with each other will enhance the trap losses. On the other hand, if we assume another collisional channel where the Rb atoms are first excited, and then the Na atoms are later excited, we obtain a different dependence, $\beta'_{**}\propto\Delta^{-1.35}$. The reason that the former channel overcomes the latter is not clear to us and therefore demands further investigation.

A possible explanation is the following. Assuming R^{-6} and R^{-5} distance dependence for the singly and doubly excited potentials, respectively, the transition frequency between those states does not present a strong dependence on R. That is, in the frequency range of the experiment, the R dependencies of those potentials are so similar that the frequency for the singly to doubly excited state transition dependence on R is not large. Hence, this transition (singly to doubly excited) is still close to resonance for small R even

for the relatively small detunings of the Rb MOT beams, and so it is likely to occur following the excitation by the catalysis laser. The reverse process would entail excitation first by the Rb MOT beams, which would likely occur at relatively large R, followed by survival to small R and excitation by the catalysis laser. These processes seem less likely to occur, especially for the larger catalysis laser detunings, which would require survival to smaller R; this is apparently confirmed by the success of the model.

During the experiment [5], we also investigated the total catalysis loss rate β_{Tc} for a few different sodium trap laser intensities. The results are shown in Fig. 4(a); in Fig. 4(b) we plot the theoretical evolution obtained from the model. We observed that the slope of β_{Tc} vs Δ does not present significant changes for the three different trapping intensities used in the experiment. This was verified and is true within the experimental uncertainties (10%). The theoretical and the experimental loss rate constants both exhibit the same monotonically decreasing behavior as a function of the catalysis laser detuning, as one can see from the two plots in Fig. 4.

In conclusion, the investigation of the detuning dependence for the heteronuclear trap-loss rate in the Na-Rb system indicates that the doubly excited channel is allowed to occur and contribute to the observed losses. In fact, in a recently published work with a mixed trap involving K-Rb [6] the explanation for the observed intensity dependence of the trap-loss rate was also based on the doubly excited channel. Trap losses certainly still demand a lot of study to be well understood and other mechanisms that could be present may contribute to building more realistic models. In a single species trap the intermediate potential with a C_3/R^3 dependence is strong enough to suppress losses due to a doubly excited channel. Nevertheless, there is no theoretical reason forbidding it to take place in regular experimental conditions and thus it remains to be investigated. For two-species MOTs, the doubly excited channel seems to be a fundamental mechanism to be taken into account when heteronuclear trap losses are experimentally observed.

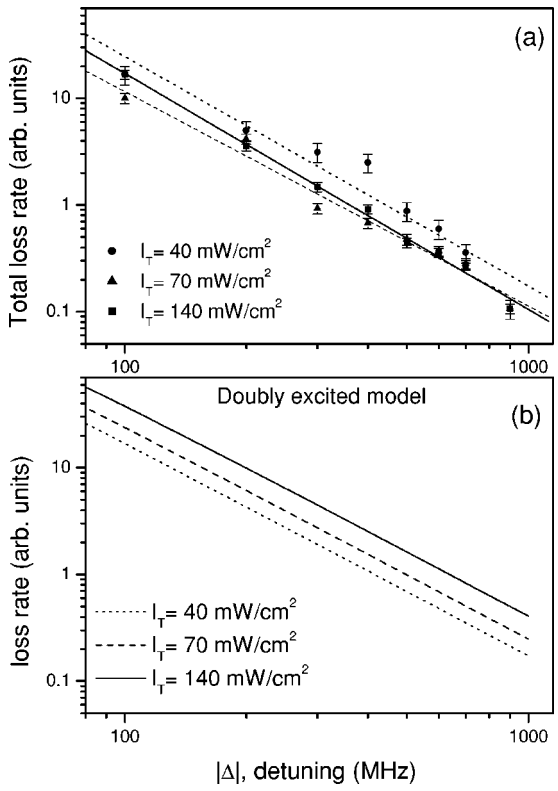

FIG. 4. (a) Experimental total loss rate plotted as a function of the catalysis laser detuning for three different trap laser intensities. (b) Theoretical heteronuclear loss rate as a function of detuning, predicted by the doubly excited model for the same trap laser intensities as in (a).

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