Eur. Phys. J. D **23**, 409–413 (2003)
DOI: 10.1140/epjd/e2003-00059-y

THE EUROPEAN PHYSICAL JOURNAL D

Comparative investigation of ^{39}K and ^{40}K trap loss rates: alternative loss channel at low light intensities

G. Modugno[1], G. Roati[1,a], M. Inguscio[1], M.S. Santos[2], G.D. Telles[2], L.G. Marcassa[2,b], and V.S. Bagnato[2]

[1] INFM and European Laboratory for Non-linear Spectroscopy, Universitá di Firenze, Largo E. Fermi 2, 50125 Firenze, Italy
[2] Instituto de Física de São Carlos, Universidade de São Paulo CP 369, 13560-970 São Carlos-SP, Brazil

Received 1st May 2002 / Received in final form 19 October 2002
Published online 4 March 2003 –

Abstract. We report a comparative investigation of trap loss rates in a magneto-optical trap for two potassium isotopes, ^{39}K and ^{40}K, as a function of trap light intensity. The isotopes present a quite similar behavior for the loss rates at high intensities, and a sudden increase of the loss rates at low intensities is present in both cases. While for ^{39}K such increase can be explained assuming that the major contribution to the losses comes from hyperfine changing collisions, a different loss mechanism must be considered for ^{40}K, which has an inverted ground state hyperfine structure. The experimental results of both isotopes are well reproduced by an alternative model based on radiative escape as the dominant loss mechanism.

PACS. 32.80.Pj Optical cooling of atoms; trapping – 33.80.Ps Optical cooling of molecules; trapping

1 Introduction

The investigation of collisional losses in magneto-optical traps (MOTs) has been extended to most of the trappable neutral atoms [1]. Although the modeling of trap losses has proved to be a nontrivial task, it may reveal useful informations about the interatomic potentials and about the nature of the inelastic processes, which constitute one of the main limits towards the achievement of high densities in cold samples of atoms.

Since the first investigations of the trap loss behavior in alkali MOTs as a function of laser intensity, the existence of two different loss regimes was clear. While all later observations indicated that at large intensities the losses are dominated by fine-structure-changing (FSC) and radiative escape (RE), the origin of the loss behavior at low intensity is still not completely understood. On one hand, the measurements on most of the alkali species showed a sharp increase of loss rate for decreasing intensity below a certain threshold value (usually, $I < 30$ mW/cm^2). Once all the studied species are trapped in their higher hyperfine ground state in a MOT, the losses were attributed to hyperfine-changing collisions (HCC), whose contribution increases as the trap depth decreases. On the other hand, recent measurements on a ^{87}Rb MOT showed that the loss rate starts to decrease again at even lower intensities, while it would be expected to raise away in presence of HCC [2]. These experimental results are indeed well reproduced by an alternative model for trap losses, assuming the RE as the dominant loss mechanism also for low light intensity [3]. In addition, the assumption for the presence of trap loss channel other than HCC has been emphasized by the loss behavior measured in a Cr MOT [4]. The overall behavior observed for the Cr MOT trap loss rate is quite similar to those for the alkalis, including the sharp rise up when the intensity decreases below some threshold value, although the Cr atoms do not present hyperfine structure.

The fermionic potassium isotope, ^{40}K, is particularly interesting in this context, due to its inverted hyperfine structure for the ground electronic state, unique among all stable alkali isotopes. This feature should result in a suppression of HCC in a MOT, allowing better investigation of trap loss mechanisms other than HCC. Actually, ^{40}K has been trapped in MOT only recently, due to its low natural abundance (0.012%) [5–7], and to our knowledge no trap loss measurement has been presented yet. On the contrary, the most abundant bosonic isotope, ^{39}K, presents a regular hyperfine structure. And it had already been the subject of loss measurements in a MOT, and in particular Santos *et al.* [8] have observed the characteristic sharp increase for the trap losses at low intensity, associated to HCC following the explanation given for other systems. In the light of new experimental results on ^{40}K and theoretical results using a new model [3], we believe that this sharp increase at low intensity can be attributed greatly to RE [3].

[a] *Alternative address*: Dipartimento di Fisica, Universitá di Trento, 38050 Povo (Tn), Italy.
[b] e-mail: marcassa@if.sc.usp.br

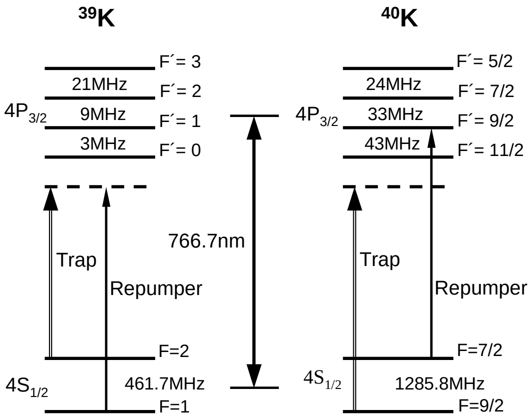

Fig. 1. Energy level scheme for the two isotopes ^{39}K and ^{40}K, showing the hyperfine structure. The trapping and repumping frequencies for the MOT operation are indicated by arrows.

In this paper we present a comparative study of trap loss rates measured for two potassium isotopes held in a MOT, ^{39}K and ^{40}K, as a function of trap laser light intensity. The experiments were carried out in similar experimental conditions, but in separate laboratories in Brazil and in Italy. On the next section we present a brief description of the experimental setup used during the trap loss measurements. Then we present the experimental results, and we show that they are quite well reproduced by a model based on RE [3] as the main loss channel also at low light intensity.

2 Experimental setup

The electronic structure of both isotopes investigated in this work are shown in Figure 1. For the bosonic isotope ^{39}K, the ground state ($4S_{1/2}$) presents two hyperfine levels with total angular momenta $F = 2$ and $F = 1$, frequency shifted by 462 MHz. On the other hand, ^{40}K presents a inverted hyperfine structure of the ground state, with $F = 7/2$ higher than $F = 9/2$ by 1286 MHz. Also in the excited ($4P_{3/2}$) the hyperfine structure of ^{40}K is inverted with respect to that of ^{39}K.

This work results from the cooperation of two independent laboratories, one in Italy at LENS, and the other in Brazil at IFSC-USP, which have investigated the trap loss rate for the two isotopes independently. The experimental conditions for trapping both isotopes were kept as close as possible to allow comparison, although there were some differences, especially in the detuning of the trapping light, needed to optimize the MOT operation. The Brazilian experiment has performed measurements in ^{39}K, using an experimental setup fully described elsewhere [8]. In brief, the MOT operates in a room temperature vapor cell, and the trapping beams comes from an external stabilized Ti:sapphire laser tuned 40 MHz to the red from the $4S_{1/2}(F = 2) \rightarrow 4P_{3/2}(F' = 3)$ atomic transition. The repumper is provided when the carrier beam passes through an electro optical modulator that introduces 462 MHz frequency shifted sidebands. Using high

Table 1. Typical conditions used for magneto optical trapping of the two potassium isotopes.

Isotope	^{40}K	^{39}K
Detuning (MHz)	−19	−40
HWHM of Gaussian beams (mm)	7.5	6.5
Saturation intensity (mW/cm^2)	1.8	1.66
Total number of loaded atoms	10^7	10^8
Density (cm^{-3})	10^{10}	10^{10}

laser intensity (150 mW/cm^{-2}) up to 5×10^8 atoms are loaded in the MOT at a density of 10^{10} cm^{-3}. The sudden change of intensity technique, developed by Santos [8], was used to measure the trap loss rate at low light intensities. The MOT is loaded at full intensity and then, after the steady state has been reached, the intensity is suddenly reduced by introducing a calibrated neutral density filter across the trap laser beam path. After the intensity reduction, the number of trapped atoms decreases to reach a new steady-state value, with a temporal evolution determined by the trap loss rates in the low intensity regime. The transient variation of atom number and density are therefore monitored by measuring the fluorescence coming from the atoms with a calibrated photodiode and charge-coupled device (CCD) cameras. This technique, based on the detection of the unloading of the weak MOT, allows to determine the loss rate also in a very low intensity regime ($I \approx I_S$), differently from the standard method based on the MOT loading analysis. Indeed, the latter method would not work at very low intensities once the atomic density and, therefore, the collisional rates are too small.

The Italian experiment performed the measurements with ^{40}K, loaded from a 5% enriched vapor sample. The laser cooling and trapping is carried using the $4S_{1/2}(F = 9/2) \rightarrow 4P_{3/2}(F' = 11/2)$ atomic transition, while repumper beams are tuned to the $4S_{1/2}(F = 7/2) \rightarrow 4P_{3/2}(F' = 9/2)$ hyperfine transition as indicated in Figure 1. Both trapping and repumping frequencies come from a single-mode Ti:sapphire by means of two independent acousto-optic modulators (AOMs). A more detailed description of the MOT setup can be found in [7], and the main MOT parameters are compared to the ^{39}K ones, in Table 1. In the Italian experiment the sudden laser intensity reduction is obtained by a quick power lowering of the AOM radio frequency, providing the trapping beams, after a typical 4 s loading phase at full intensity.

As described above, to obtain the trap loss rates we measure the time evolution of the total number of trapped atoms after the sudden decrease of the laser intensity. The first step is to load the potassium MOT at full intensity during a few seconds. The rate equation describing the behavior is:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = L_0 - \gamma N - \beta n_0 N, \qquad (1)$$

where L_0 is the loading rate, γ is the loss rate due to collisions between the trapped K atoms and the hot background vapor, and β is the loss rate resulting from collisions among the trapped potassium atoms due to inelastic mechanisms. As first observed for Cs [9] and verified for ^{39}K [8], the MOT is loaded at constant atomic density (n_0), so that the solution of equation (1) is

$$N(t) = N_0 \left[1 - \mathrm{e}^{-(\gamma+\beta n_0)t}\right]. \quad (2)$$

In equation (2) above, N_0 stands as the total number of trapped atoms achieved at the steady state, after the loading at high intensity. The second step is to suddenly decrease the trap laser beam intensity down to some fraction of the initial total intensity. During this process, the atomic density changes quickly from n_0 to n_1, but the total number of trapped atoms remains N_0. Therefore, the rate equation (1) will have to change to support the new experimental conditions. The new equation has to link two steady-states: the initial condition after the intensity change, containing N_0 atoms trapped at n_1 density, and the final ($t \to \infty$), containing N_1 trapped at n_1 density. Also, at the new intensity, the MOT still continues to load atoms, but with a smaller loading rate, L_1, that has to be a fraction of the initial one (L_0), at full intensity. Thus, the time evolution for the trapped potassium atoms, after the intensity decrease, becomes:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = L_1 - \gamma N - \beta n_1 N. \quad (3)$$

The solution for the above rate equation (3) can be easily found, by ordinary means, simply imposing the correct boundary conditions. That is,

$$N(t) = N_1 + (N_0 - N_1)\,\mathrm{e}^{-(\gamma+\beta n_1)t}, \quad (4)$$

and it presents an exponential decay solution linking the two steady state regimes. Note that in equation (4), N_1 has to be smaller than N_0 and that is obviously the situation achieved during the experiment, once the trap laser intensity was suddenly decreased down to a small fraction of the total initial one. In Figure 2 we show a typical decay curve fitted using equation (4). We should point out that the results for ^{39}K were analyzed in reference [8] according the methodology presented here. However, in reference [8] the text is not clear enough to transmit the idea that the trap loads at constant n_0 and decays after the light intensity change at n_1 [10] in accordance to the new trap parameters imposed by this change.

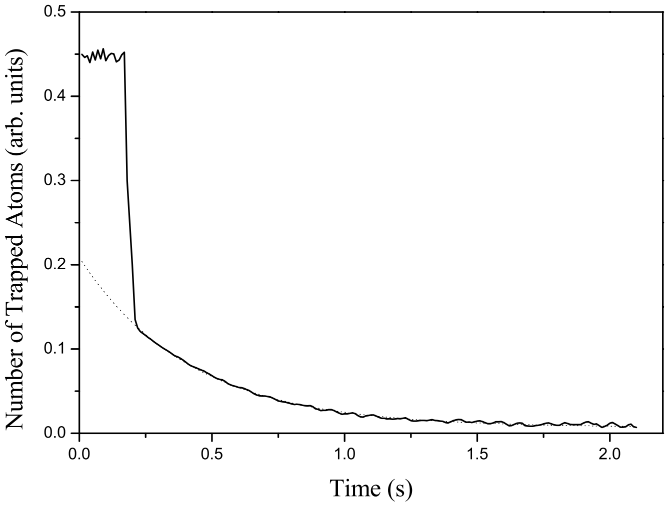

Fig. 2. Typical decay curve for ^{40}K at $I/I_\mathrm{S} = 8.3$.

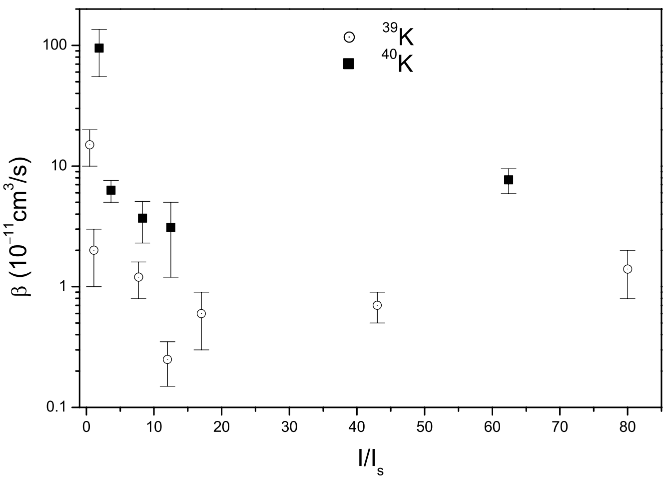

Fig. 3. Experimental trap loss coefficients for the two potassium isotopes: ^{39}K (hollow squares), and ^{40}K (full squares).

3 Results and discussions

In Figure 3 the experimental results for the trap loss rate β of the two isotopes are presented as a function of the light intensity, normalized to the saturation intensity of each isotope. The light intensity considered here is the sum of all six trapping beams. Each β value results from the average of five independent measurements, and the error bars represent the resulting variance. The general behavior of trap losses for the two isotopes is similar: from high intensity down to about $I = 15 I_\mathrm{S}$, seems to decrease with intensity; and at lower intensities we observe an increase of trap loss for both isotopes. This increase in trap loss rate at low intensity has been attributed to HCC [11]. Also in this case, HCC could explain the observed increase of β for ^{39}K [8], because the atoms are trapped in the higher hyperfine ground state $F = 2$ may change to the ground $F = 1$ state through inelastic collisions with subsequent release of the hyperfine energy.

However, for ^{40}K this explanation for the raise of β is not correct, since the atoms are trapped mostly in the lowest energy ground state ($F = 9/2$), and therefore HCC are expected to be reduced. In fact, a quantitative estimation of the HCC contribution to the MOT losses can be performed using the HCC rate measured in an optical trap [12]. Those measurements were performed at approximately the same temperature of the MOT, and very likely with the same distribution of population on the magnetic substates, allowing for a fair comparison. Since in the ^{40}K MOT the intensity of the repumper beams remains large when the trapping intensity is reduced, we estimate the ratio of densities in $F = 7/2$ and $F = 9/2$ states to be

$$r = \frac{n_{7/2}}{n_{9/2}} \leq \frac{1}{50}, \qquad (5)$$

in the whole range of intensities explored. Thus the main contribution to the losses due to HCC is expected to come from the $(F = 9/2, F = 7/2) \rightarrow (F = 9/2, F = 9/2)$ channel, for which we measured a rate $G_{7/2,9/2} = 4(2) \times 10^{-12}$ cm^{3}s^{-1} [12]. Assuming HCC to be the dominant loss channel, the time evolution of the MOT atom number is thus described by

$$\frac{\mathrm{d}N}{\mathrm{d}t} = L - \gamma N - G_{7/2,9/2} \int n_{7/2}(r) n_{9/2}(r) \mathrm{d}^3 r, \qquad (6)$$

which in the case of a constant density n becomes

$$\frac{\mathrm{d}N}{\mathrm{d}t} = L - \gamma N - G_{7/2,9/2}\, r(1-r) nN. \qquad (7)$$

Comparing equation (6) with equation (3), we get $\beta \leq 10^{-13}$ cm^{3}s^{-1}, which is in fact between two and three orders of magnitude smaller than the experimental observation. The possible contribution of HCC to the losses for ^{40}K is therefore ruled out, unless an enhancement of collisional rate in presence of near resonant light is assumed, as proposed for Rb in references [2,13].

An alternative explanation for our experimental observations is based on the model proposed in [3], which can fully explain the behavior of the trap loss rate as in Figure 3 without relying on the existence of HCC. In brief, it is possible to model the trap losses in a MOT based exclusively on the radiative escape for any light intensity, by applying the well-known Gallagher-Pritchard theory [14] associated with an intensity dependent escape velocity model. According to recent observations [15], the escape velocity seems to follow quite well a simple model based on the damping portion of the radiative force, that predicts a sudden reduction of the escape velocity at low laser intensity. As already mentioned, an interesting result of GP theory was its capability of reproducing the experimental observations for the β variation with light intensity in a ^{87}Rb MOT [2,3] that could not be easily explained within the theory based on HCC.

We have therefore applied such model to our potassium MOTs, calculating the dependence of the escape velocity on the light intensity as discussed in [15]. The result of the simulation for the β variation with light intensity is presented in Figure 4, together with the experimental results. It reproduces quite well the behavior observed in the experiments, presenting the rise up at low intensity, a minimum and an slow increase at high intensity for both isotopes. Therefore, the model assuming RE as the main trap loss mechanism can reproduce all the observed features not only for the ^{40}K losses, but also for those in ^{39}K, which were expected to be dominated by HCC at low intensity. This result indicates that RE might be in general the main loss channel in an alkali MOT.

The discrepancies between the theory and the experiment shown in Figure 4 can be qualitatively explained

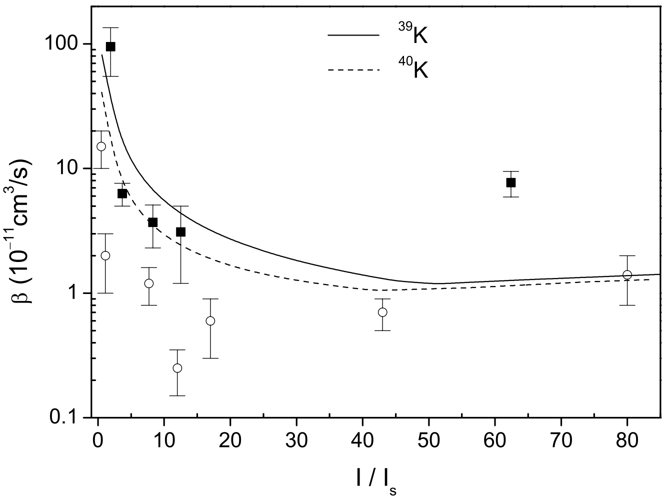

Fig. 4. Comparison of the theoretical and the experimental loss rates due to the RE for the two isotopes.

considering the approximations present in the model we use. In particular, for the conditions actually used in the two MOTs, the simulation predicts a larger trap loss for ^{39}K, contrarily to the experimental observation. We note that our theory [3] assumes a two level atom, and the main parameters which determine the loss rate are the intensity and detuning of the MOT light, together with the C_3 coefficient of the molecular potential. For the latter quantity we have used the value suggested in [16], while for the first two we have used just the experimental values. The simulation predicts a higher value of β for ^{39}K, since larger detunings result in a smaller trap depth potential while compared to ^{40}K. This is due to the fact that for larger detunings the escape velocity, or the trap depth, is smaller than for small detunings. When considering the multilevel character of the atoms, one should note that the ^{39}K trapping laser is tuned to the red of the whole excited hyperfine manifold, due to the small separations between the states, and therefore one would expect that the trapping effectiveness is reduced. On the other hand, an opposite behavior for the trap losses might be expected from very general features of the molecular potential along with RE can take place. Indeed, in the case of ^{39}K the trapping laser promotes coupling of the atoms to the molecular potentials having as asymptotes the lower atomic hyperfine components. The presence of a large number of state-mixings and avoided crossings in this region is possibly resulting in a reduced atomic flux towards the attractive states connecting asymptotically to the higher hyperfine state, which mostly contributes to the losses at low light intensities. The situation is quite different for ^{40}K, since the trapping laser couples the atoms directly with the attractive molecular potentials, because of the inverted hyperfine structure of the excited level. In this sense, the fermionic isotope is closer to the approximations made in the model, and this seems to be the reason for the better agreement with the theory, at least in the low intensity regime. A better agreement between the magnitude of β given by the theory and those observed in the experiment would be only reach using an improved modeling, including the multilevel atomic character. Nevertheless, we also note that the present simulation predicts the correct intensity values in which β suddenly starts to increase.

4 Conclusions

In conclusion, we have measured and compared the trap loss rate as a function of the MOT light intensity for two potassium isotopes, ^{39}K and ^{40}K. The measured behavior of β shows in both cases the general features already observed for other trapped alkali species, including the sharp increase of the losses at low light intensities. In the case of ^{39}K such increase had been previously explained with the assumption that losses at low light intensity were dominated by hyperfine changing collisions. To explain the data obtained for ^{40}K we have instead to rely in a theory where radiative escape is the dominant process for all ranges of intensities. The dependence of trap loss rate on the laser intensity calculated according to this model seems to fit quite well the experimental observations for both potassium isotopes, therefore supporting the theory of alternative trap loss channels in a MOT [3].

This work was carried out at Centro de Pesquisas em Óptica e Fotônica (CePOF) and supported by FAPESP, CNPq through the PRONEX program and by European Community Council through Contract HPRICT1999-00111.

References

1. J. Weiner, V.S. Bagnato, S. Zilio, P. Julienne, Rev. Mod. Phys. **71**, 1 (1999)
2. R.C. Nesnidal, T.G. Walker, Phys. Rev. A **62**, 030701R (2000)
3. G.D. Telles, V.S. Bagnato, L.G. Marcassa, Phys. Rev. Lett. **86**, 4496 (2001)
4. C.C. Bradley, J.J. McClelland, W.R. Anderson, R.J. Celotta, Phys. Rev. A **61**, 053407 (2000)
5. F.S. Cataliotti, E.A. Cornell, C. Fort, M. Inguscio, F. Marin, M. Prevedelli, L. Ricci, G.M. Tino, Phys. Rev. A **57**, 1136 (1998)
6. B. de Marco, D.S. Jin, Rev. Sci. Instrum. **82**, 4208 (1999)
7. G. Modugno, C. Benko, P. Hannaford, G. Roati, M. Inguscio, Phys. Rev. A **60**, R3373 (1999)
8. M.S. Santos, A. Antunes, P. Nussenzveig, J. Flemming, S. Zilio, V.S. Bagnato, Laser Phys. **8**, 880 (1998)
9. T. Walker, D. Sesko, C. Wieman, Phys. Rev. Lett. **64**, 408 (1990)
10. In order to clarify reference [8] on the light of the discussion presented here, the equation (2) [8] should be written as $N(t) = N_0\left[1 - \mathrm{e}^{-(\gamma+\beta n_0)t}\right]$, and equation (3) [8] as $N(t) = N_1 + (N_0 - N_1)\,\mathrm{e}^{-(\gamma+\beta n_1)t}$
11. D. Sesko, T. Walker, C. Monroe, A. Gallagher, C. Wieman, Phys. Rev. Lett. **63**, 961 (1989); C. Wallace, T. Dinneen, K. Tau, T. Grove, P. Gould, Phys. Rev. Lett. **69**, 897 (1992)
12. G. Roati, W. Jabstreski, A. Simoni, G. Modugno, M. Inguscio, Phys. Rev. A **63**, 050709 (2001); `arXiv physics/000`
13. S.D. Gensemer, P.L. Gould, P.J. Leo, E. Tiesinga, C.J. Williams, Phys. Rev. A **62**, 030702R (2000)
14. A. Gallagher, D. Pritchard, Phys. Rev. Lett. **63**, 957 (1989)
15. V.S. Bagnato, L.G. Marcassa, S.G. Miranda, S.R. Muniz, A.L. Oliveira, Phys. Rev. A **62**, 013404 (2000)
16. M. Marinescu, H.R. Sadeghpour, A. Dalgarno, Phys. Rev. A **49**, 982 (1994)