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Two body loss rate in a magneto-optical trap of metastable He

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Abstract. We have measured the two body loss rate in a magneto-optical trap containing triplet metastable He atoms. We find a rate constant $\beta = 3 \times 10^{-8}$ cm^3/s at a -8 MHz detuning, with an uncertainty of a factor 2. This measurement is in disagreement with a recent experiment which measures the absolute, ion-producing collision rate, but agrees with several other published measurements.

PACS. 32.80.Pj Optical cooling of atoms; trapping – 34.50.Rk Laser-modified scattering and reactions

Metastable helium (He*) is an interesting and unusual atom for laser cooling and trapping studies. It has a very well understood structure and is thus of interest for precision measurements [1]. Its large recoil velocity poses unusual problems for producing laser cooled samples, and also provides an interesting testing ground for the theory of laser cooling when the recoil velocity is large [2]. It has also been suggested as a promising candidate for evaporative cooling [3]. Dense, cold samples would clearly be useful for furthering these studies. Already in the first magneto-optical trap (MOT) for He* however, it was reported that light assisted collisions lead to large two body loss rates and severely limit the density [4]. On the other hand, a recent experiment reported a very much lower loss rate constant [5]. It is obviously of great importance to resolve this discrepancy in order to understand the loss processes.

The loss rate measured in reference [4] was attributed to the following processes:

$$\mathrm{He}^*(2^3\mathrm{S}, 2^3\mathrm{P}) + \mathrm{He}^*(2^3\mathrm{S}) \rightarrow \begin{cases} \mathrm{He}(1^1\mathrm{S}) + \mathrm{He}^+(1^2\mathrm{S}) + e^- \\ \mathrm{He}_2^+ + e^- \end{cases} .$$

This rate was measured by monitoring all the ions produced by the trap and observing the non-exponential decay of the ion signal. By contrast, the work of reference [5] reports an absolute measurement of the He^+ and He_2^+ ion production rate and found a rate 40 times smaller than that of reference [4]. This new rate appeared to be in good agreement with a theoretical calculation made by the authors. Since the technique of reference [4] is sensitive to the total two body loss rate while that of reference [5] observes only the ion production rate, this discrepancy may point to some other light-assisted collision process that does not produce ions.

In order to help clarify this issue, we have undertaken a new experiment to measure the two body loss rate paying close attention to several possible sources of systematic errors including the measurement of the density. We use the trapped atom fluorescence to observe the non-exponential decay of the trap. Our experiments confirm the measurements of reference [4] and seem to indicate that the two body loss rate is much higher than the rate measured by [5]. In addition, even more recent experiments, one measuring the trap loss [6] and one measuring the absolute ion production rate [7], appear to agree with our results. Thus, the preponderance of experimental data indicate that the two body loss rate from the trap is higher than measured in [5] and is largely due to ionizing collisions.

Our starting point is the phenomenological equation for the evolution of the number $N(t)$ of trapped atoms during the loading of the MOT

$$\frac{\mathrm{d}}{\mathrm{d}t}N(t) = R - \frac{N(t)}{\tau} - \beta \int n^2(\mathbf{r}, t)\mathrm{d}^3 r \, . \qquad (1)$$

In this equation R is the flux of atoms captured by the trap during the loading. It depends on various parameters of the MOT, particularly on the detuning and intensity of the trapping laser. The lifetime τ of the trap is due to collisions of He* with background gas molecules. Our measurements indicate that τ is independent of the MOT parameters to within 20%. The last term of the equation describes the two body losses resulting from collisions between trapped atoms. Our definition of β is the same

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as that of references [4–6], and we have assumed that the quantity β is independent of position.

If one assumes that the spatial distribution is independent of the number of atoms in the trap, one can write $n(\mathbf{r},t)$ as a product $n_0(\mathbf{r})f(t)$ where $n_0(\mathbf{r})$ describes the shape of the trapped atom distribution. In this case the last term in equation (1) can be expressed as $-\beta N^2(t)/V_{\rm eff}$, where $V_{\rm eff}$ is an effective volume of the trap. Our measurements indicate that $V_{\rm eff}$ is indeed independent of the number of trapped atoms and, during the trap decay, independent of time. As the trap has a Gaussian profile in 3 dimensions $V_{\rm eff} = \pi^{\frac{3}{2}}(2\sigma_x)(2\sigma_y)(2\sigma_z)$, where σ is the rms size.

The decay of N is given by integrating equation (1) with respect to time in the absence of loading ($R = 0$) and assuming that the initial number of atoms is equal to the steady state value $N(0) = N_{\rm S}$. This leads to

$$N(t) = \frac{N_{\rm S}}{\left(1 + \dfrac{\beta N_{\rm S}\tau}{V_{\rm eff}}\right)\mathrm{e}^{\frac{t}{\tau}} - \dfrac{\beta N_{\rm S}\tau}{V_{\rm eff}}}\cdot \tag{2}$$

In the presence of a loading rate ($R \neq 0$) the solution for equation (1) with $N(0) = 0$ is

$$N(t) = N_{\rm S}\frac{1 - \mathrm{e}^{-\frac{t}{\tau_0}}}{1 + \dfrac{N_{\rm S}^2\beta}{V_{\rm eff}R}\mathrm{e}^{-\frac{t}{\tau_0}}} \tag{3}$$

where

$$\tau_0 = \frac{\tau}{\sqrt{1 + \dfrac{4\beta R\tau^2}{V_{\rm eff}}}}\cdot \tag{4}$$

Equation (3) describes the number of trapped atoms during the loading phase. The steady state solution for equation (1) gives a simple relation between β and $N_{\rm S}$

$$\beta = \frac{R - \dfrac{N_{\rm S}}{\tau}}{N_{\rm S}^2}V_{\rm eff}\cdot \tag{5}$$

The above equations all offer different, though related routes to get β. Taking for example equation (5), one can measure $V_{\rm eff}$ using camera observations, τ using the exponential decay of the trap when the density is low, and $N_{\rm S}$ from the number of trapped atoms observed in steady state. The quantity R can also be measured by observing the initial slope of the loading curve $R = \mathrm{d}N/\mathrm{d}t(t = 0)$. Note that the uncertainty with which one measures R is highly correlated with that of $N_{\rm S}$. If τ is very large, $N_{\rm S}/\tau$ can be neglected compared to R and thus τ is unimportant in determining β. Equations (2, 3) permit the determination of β by fitting the decay and loading curves. However, the fitting parameters contain combinations of the quantities β, $N_{\rm S}$ and $V_{\rm eff}$, so that it is still necessary to make independent measurements of $N_{\rm S}$ and $V_{\rm eff}$ to extract β. Our strategy is to use all three methods to check the consistency of our approach while making the best measurements we can of $N_{\rm S}$ and $V_{\rm eff}$.

Our LN_2 cooled helium source is similar to the one described in references [8,9]: a high voltage DC discharge produces metastable atoms. The flux of metastable atoms is 10^{12} s^{-1} (luminosity of 4×10^{14} sr^{-1}s^{-1}). The mean longitudinal velocity is 1300 m/s and the FWHM of the velocity distribution is 300 m/s. We optically manipulate the atomic beam with laser light using the closed transition 2^3S_1–2^3P_2 at a wavelength of 1083 nm. The natural linewidth is $\Gamma/2\pi = 1.6$ MHz. The light is emitted by 50 mW DBR laser diodes. Their frequency width $\Gamma_{\rm diode}$ is estimated from the measured beat note between two identical diodes. The measured width was 4 ± 0.5 MHz, FWHM from which we deduce $\Gamma_{\rm diode}/2\pi = 2 \pm 0.3$ MHz, assuming Lorentzian line shapes. They are locked on the transition $^3S_1$–$^3P_2$ using saturated absorption in a He RF discharge cell. The detuning of the laser trapping beams is controlled with an adjustable Zeeman shift produced by Helmholtz magnetic coils around the He cell.

We collimate the atomic beam using a transverse molasses with curved wave fronts [9–11]. Under normal trapping conditions, we observe an increase in the number of trapped atoms of a factor 6. This molasses also allows us to bend the atomic beam by an angle of 1° so as to reduce the flux of ground state atoms as well as ions and UV photons produced in the discharge. The atoms are then slowed down in a Zeeman slower to a velocity less than 50 m/s. The Zeeman field passes through zero partway along the slowing path so as to allow us to detune the slowing laser by −400 MHz from the $^3S_1$–$^3P_2$ resonance. The total slowing length is 2.4 m.

The resulting slow atomic beam then loads a MOT consisting of three retroreflected laser beams. The center intensity per beam is 4 mW/cm^2, and the waist diameter of the order of 2 cm. The magnetic field gradients were 10, 6 and 4 G/cm in the different directions. The lack of symmetry is due to the presence of the Zeeman slower and a compensation coil which remained on during the experiment. A typical background pressure of 4×10^{-8} mbar results in a lifetime τ of the trap of 150 ms. This lifetime is unchanged when either the atomic beam or the cooling laser is blocked by a mechanical shutter. The temperature of the trap was roughly measured by an absorption technique to be 1.5 mK at a detuning of the trapping laser of −20 MHz.

The measurement of β proceeds in two steps. First one fits the data to one of the equations (2, 3) or (5). For example typical decay curves of the trap fluorescence at 1.083 μm when cutting off the slowing laser beam at time $t = 0$ are shown in Figure 1 for two detunings of the trapping laser. For a –16 MHz detuning the decay is purely exponential whereas at –6.4 MHz the decay is exponential only for times bigger than 150 ms. Before that the influence of the non linear terms of equation (1) is clearly visible. Fitting this nonlinearity leads generally to a measurement of $\beta N_{\rm S}/V_{\rm eff}$. The next step is to measure $N_{\rm S}$ and $V_{\rm eff}$ to extract the rate constant β. We discuss these steps below.

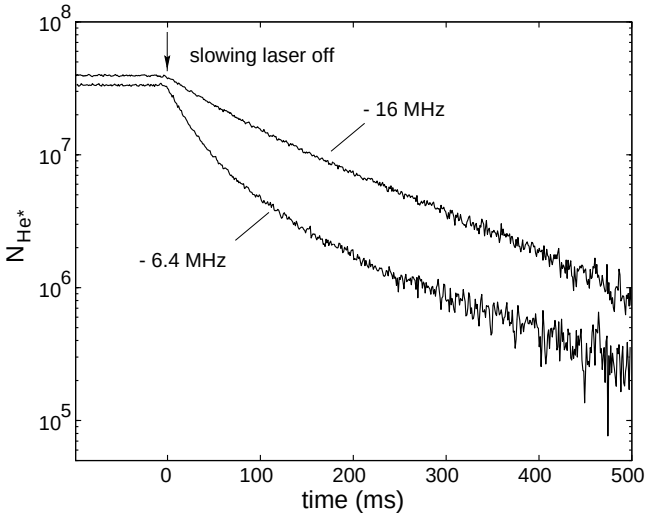

Fig. 1. Time dependence of the trap fluorescence for two different detunings. The vertical axis is logarithmic, and the curvature is due to two body loss processes

To analyse curves such as in Figure 1 we use the analytical solution (2) with $\beta N_{\rm S}/V_{\rm eff}$ and the lifetime τ as fitting parameters. We checked that the value of τ is the one deduced from a fit of the exponential part of the decay, reached when the number of trapped atoms is low enough for the two body collisions between He* atoms to be negligible. We measured $V_{\rm eff}$ as a function of the number of atoms in the trap. We did this both by changing the loading rate and observing the size in steady state as well as by taking pictures during the decay of the trap. In both cases we see a 30% increase in the size as the number of atoms increases from 3×10^6 to 3×10^7. This change in size only has a small effect on the resulting value of β ($\sim 10\%$). We estimate the uncertainty in the fitted parameters to be approximately 10% by examining dispersion in the results when we fit the same data over different time intervals. Fits to data taken under nominally the same conditions within several hours show a statistical dispersion of 15%.

To confirm the results we get from the decay curves, we also performed a fit of the loading of the trap to the function in equation (3). Our fits give a value of $\beta N_{\rm S}/V_{\rm eff}$ that is a factor of 2 smaller than the one we get using the decay data from the same run. We also used equation (5) to get β by measuring $R/N_{\rm S}$ from the initial slope of the loading curve (and using the value of τ from the fit of the decay curve). This method also gives a β that is 2 times smaller than the decay curve. This disagreement is surprising because although the absolute uncertainties with which we measure $N_{\rm S}$, $V_{\rm eff}$, and β are of order a factor of two, most of the uncertainties should be common to the three methods.

To explain this discrepancy we first checked that it is not due to the presence of the slowing laser or the atomic beam. We found that decay data give the same value of β and τ regardless of the presence of the slowing laser and the atomic beam. We also checked that the value of β derived from the loading curve did not change when we blocked that part of the slowing laser beam which intersected the MOT by an absorber, thus making a dark spot slower [12].

We also made measurements of the trap size and shape during loading. In the first 10 ms of loading the trap is not Gaussian but rather appears to have a slight halo in the direction from which the atomic beam arrives. It appears that in the early phases of loading the atoms are not immediately captured in the steady state volume of the trap. Thus the effective volume of the trap is slightly bigger than is assumed in equation (3). This may account for the discrepancy. It is difficult to quantitatively estimate the influence of this effect on the value of β deduced from the loading curve because the temporal resolution with which we were able to observe the loading trap was only of order 5 ms. At the start of the loading the number of atoms in the trap varies rapidly on this time scale. We conclude that the loading curves are probably not as reliable for extracting β as the decay data. On the other hand, in view of our overall uncertainty, this discrepancy is not large and thus the loading curves do confirm our results at the factor of two level. In what follows we will only show data derived from the decay curves.

In order to determine the number of trapped atoms $N_{\rm S}$ we monitor the total power P scattered by the trapped atoms into a solid angle Ω with a photodiode. This power is given by $P = \hbar\omega\Gamma(\Omega/4\pi)\pi_P N_{\rm S}$, where ω and Γ are the frequency and natural linewidth of the MOT transition and π_P is the fraction of atoms in the excited state. We use the following formula to calculate π_P [13]

$$\pi_P = \frac{1}{2}\frac{C\dfrac{I}{I_0}}{1 + C\dfrac{I}{I_0} + \left(\dfrac{2\Delta}{\Gamma_{\rm diode}+\Gamma}\right)^2} \qquad (6)$$

where Δ is the laser detuning from resonance and I is the total laser intensity of all 6 beams taken at the center of the Gaussian profile. I_0 is the saturation intensity of the transition taking into account the width of the lasers, that is $I_0 = (\Gamma_{\rm diode}+\Gamma)I_{\rm sat}/\Gamma = 0.37$ mW/cm^2, where $I_{\rm sat} = 0.16$ mW/cm^2 for the transition $m_J = 1 \longleftrightarrow m_J = 2$. The phenomenological parameter C would be equal to unity if a single, circularly polarized beam were present and all atoms were in $m_J = 1$ ground state. However, since 6 differently polarized beams are present at the center of the trap, C should be smaller. In reference [13] it was found empirically for a Cs MOT that C is somewhat larger than the average of the squares of the Clebsch-Gordan coefficients over all possible transitions. For the $J = 1 \longleftrightarrow J = 2$ transition this average is 0.56. We will assume here $C = 0.8\pm0.2$. Because of the high saturation of our MOT, the uncertainty we have assumed for C amounts to only a 5% uncertainty in π_P for small detunings and 10% for large detunings. The high saturation also means that we are not very sensitive to the effect of the linewidth of the lasers.

We have roughly confirmed the value of π_P by measuring the absorption of a weak resonant probe beam through

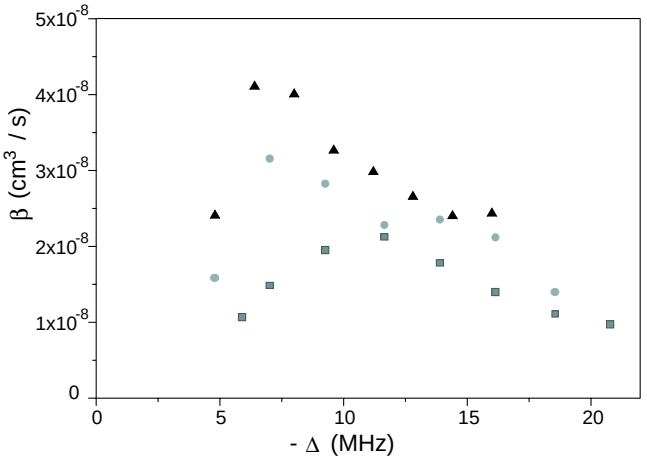

Fig. 2. Fitted two body loss rate coefficient β as a function of detuning at total intensity $I/I_{\rm sat} = 160$. Different symbols refer to different runs taken on different days.

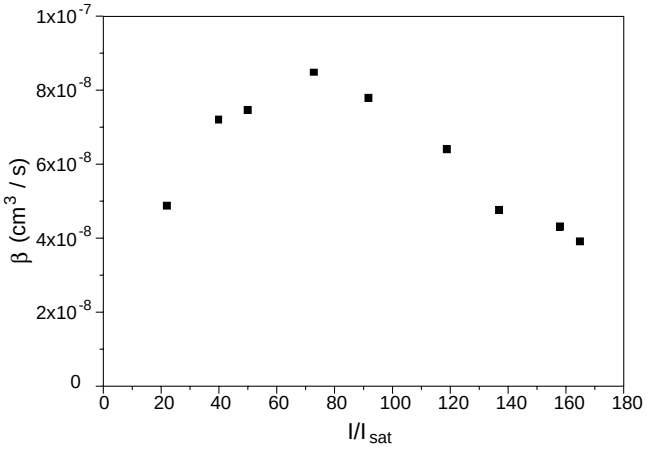

Fig. 3. Fitted two body loss rate coefficient β as a function of total intensity at detuning $\Delta = -6$ MHz.

the atomic cloud after the MOT laser beams had been turned off. Our observation of 30% absorption on resonance confirms the measurement of the number of trapped atoms to within a factor of two. Note also that the observed absorption indicates that, at typical MOT detunings, the optical thickness of the cloud is negligible. The calibration of our photodiode is known to the order of 10%. The major source of uncertainty in $N_{\rm S}$ is the solid angle which we can only estimate to within a factor of 1.5. We estimate the uncertainty in our detected power measurement (P) to be about 20%.

The volume $V_{\rm eff}$ is measured by observing the size of the trap along three orthogonal axes in the steady state regime using a calibrated CCD camera. The Zeeman shift due to the magnetic field gradient is negligible compared to our detuning and therefore does not affect our estimate of the volume. Similarly the Doppler shift at 1.5 mK, about 2 MHz, is negligible as well. We estimate the uncertainty in $V_{\rm eff}$ to be about 20%.

Our final uncertainty in the absolute value of β is the quadrature sum of the contributions described above and is dominated by the statistical fluctuations in $\beta N_{\rm S}/V_{\rm eff}$ and by the uncertainty in the solid angle, both of order 50%. The total uncertainty is a little less than a factor of two. Therefore our conclusion that $\beta = 3\times10^{-8}$ cm^3/s at a –8 MHz detuning of the trapping laser is to be understood as 1.5×10^{-8} cm^3/s $< \beta < 6 \times 10^{-8}$ cm^3/s.

We performed the measurement of β for various detunings of the trapping beams, from -5 MHz to -16 MHz, and various intensities corresponding to $I/I_{\rm sat}$ varying from 10 to 160. We found that in steady state, the shape of the trap is always Gaussian. The volume $V_{\rm eff}$ varies between 30 mm^3 and 200 mm^3. The number of trapped atoms slightly increases with the detuning of the trapping beams from 3×10^7 up to 4×10^7 while the density at the center decreases from 3×10^9 cm^{-3} to 6×10^8 cm^{-3}. The dependence of β with the detuning and the intensity is shown in Figures 2 and 3. Figure 2 presents the measured values for β *versus* the detuning of the trapping laser for experiments carried out on 3 different days at nominally the same conditions. There are clearly some conditions in the MOT that are not very reproducible. The uncertainty in the solid angle is common to all measurements, therefore the trends shown in Figures 2 and 3 are weak but statistically significant. The detuning dependence shows the same general behavior as the data of reference [5] although it was taken over a much smaller range of detunings. This behavior can be understood in terms of a model similar to reference [14] in which one assumes that a competition between incident flux and survival give a maximum collision rate at some value of the detuning.

In order to compare our results to other measurements, we note that our results are consistent with those of reference [4], which found 2×10^{-8} cm^3/s $< \beta < 3 \times 10^{-7}$ cm^3/s for a detuning of -5 MHz and approximately the same intensity. Our results also agree with two recent experiments done with MOT parameters similar to ours: reference [6] used the decaying trap signal to find $\beta = 1 \times 10^{-8}$ cm^3/s and reference [7] reports a measurement $\beta = 4 \times 10^{-8}$ cm^3/s using the absolute ion signal. All these results disagree with that of [5], who measured $\beta = 2 \times 10^{-9}$ cm^3/s at -5 MHz detuning and about the same intensity. The experiment of reference [7] is very important in ruling out the possibility that a decay mechanism producing no ions can account for the result of reference [5]. Note also that the work of reference [6] also includes measurements of trap loss processes resulting in metastables escaping from the trap (radiative escape). This also lends credence to the view that ionizing collisions are indeed the primary trap loss mechanism.

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References

1. F. Minardi, G. Bianchini, P. Cancio Pastor, G. Giusfredi, F.S. Pavone, M. Inguscio, Phys. Rev. Lett. **82**, 1112 (1999).
2. B. Saubaméa, T.W. Hijmans, S. Kulin, E. Rasel, E. Peik, M. Leduc, C. Cohen-Tannoudji, Phys. Rev. Lett. **79**, 3146 (1997).
3. P. Fedichev, M. Reynolds, U. Rahmanov, G. Shlyapnikov, Phys. Rev. A **53**, 1447 (1996).
4. F. Bardou, O. Emile, J.-M. Courty, C.I. Westbrook, A. Aspect, Europhys. Lett. **20**, 681 (1992).
5. H.C. Mastwijk, J.W. Thomsen, P. van der Straten, A. Niehaus, Phys. Rev. Lett. **80**, 5516 (1998).
6. P.J.J. Tol, N. Herschbach, E.A. Hessels, W. Hogervorst, W. Vassen, Phys. Rev A. **60**, 761 (1999).
7. M. Kumakura, N. Morita, Phys. Rev. Lett. **82**, 2849 (1999).
8. W. Rooijakkers, W. Hogervorst, W. Vassen, Opt. Commun. **123**, 321 (1996).
9. G. Labeyrie, Ph.D. thesis, University Paris-Sud, 1998.
10. J. Nellessen, J. Müller, K. Sengstock, W. Ertmer, J. Opt. Soc. Am. B **6**, 2149 (1989).
11. N. Vansteenkiste *et al.,* J. Phys. II France **1**, 1407 (1991).
12. S. Miranda, S.R. Muniz, G.D. Telles, L.G. Marcassa, K. Helmerson, V.S. Bagnato, Phys. Rev. A **59**, 882 (1999).
13. C.G. Townsend, N. Edwards, C. Cooper, K. Zetie, C. Foot, A. Steane, P. Szriftgiser, H. Perrin, J. Dalibard, Phys. Rev. A **52**, 1423 (1995).
14. A. Gallagher, D.E. Pritchard, Phys. Rev. Lett. **63**, 957 (1989).