A technique to observe "negligible" collision trap losses

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Abstract

A short time after the first successful experiments on magneto-optical trapping of neutral atoms, it was recognized that the number, density and storage time are ultimately limited by collision processes between the cold atoms in the trap light fields. During the last decade, these collision mechanisms were extensively studied in magneto-optical traps of alkali-metal elements. The theoretical analysis for small laser detuning, that is, excitation at large interatomic distance, is difficult because of the hyperfine structure. In addition to this, there is still some controversy about the collision mechanisms involved at low trapping laser intensities. On the other hand, interest on laser cooling and trapping of alkaline-earth elements has grown over the past few years. The simplicity in the level structure of alkaline-earths provides a possibility for effective calculations and comparison with experiments. Nevertheless, there are still little experimental data related to cold collisions in these elements. One reason for this is that cold collisions represent only a small fraction of the total trap losses, in contrast to the case of alkali-metals. To address this limitation we present here a new method for detecting cold collisions even when they contribute nearly negligibly to the trap loss rate. This technique is based on a subtle asymmetry in the loading and decay processes in a magneto-optical trap. We demonstrate the capability of this technique with a determination of a collisional rate coefficient for ^{40}Ca despite the fact that collisions contribute only 3% of the total measured loss rate. Our method has general applicability and should considerably reduce the experimental challenges associated with these important measurements.

The interest in laser cooling and trapping of alkaline-earth elements is growing in the last years. For example, they are attractive for precision frequency standards and optical clocks, atomic interferometry and new Doppler cooling strategies, which allows temperatures near the recoil limit and might open the path to the achievement of Bose-Einstein condensation by all optical means. The most abundant, even isotopes of alkaline-earths have a non-degenerate ground state, no nuclear spin and therefore no hyperfine structure. One advantage of this is the enormous simplification in the analysis of trap loss collisions for large interatomic distance [1]. The simplicity in the level structure of alkaline-earths provides a possibility for effective calculations and comparison with experiments. Nevertheless, there are still little experimental data related to cold collisions in these elements [2,3]. In spite of the small number of groups working with them, one reason for this is that cold collisions represent only a small fraction of the total trap losses, in contrast to the case of alkali-metals. This is because the resonant $^1S_0$-$^1P_1$ cooling transition is not optically closed, with the exception of magnesium. From the upper level the atom has a small probability to decay into the low-lying metastable $^1D_2$ state, instead of back to the ground state. Atoms in the $^1D_2$ level decay to the $^3P_2$, $^3P_1$ or directly to the ground state. The lifetime of the $^3P_2$ state is very long and all atoms on it are lost from the trap. Either through the $^3P_1$ state or directly, the time it takes an atom to return to the ground state can be sufficient for it to escape from the trap volume, depending on the initial velocity and MOT capture volume. Therefore this optical pumping process results in a high, dominant trap loss mechanism, which limits the MOT storage time to some tens of milliseconds. In order to reduce it, "repump" lasers have been employed [2-5], but the typical storage times are still much shorter than for alkali-metal elements and cold collision effects are still difficult to observe.

In a MOT, the total number of trapped atoms, N, evolves with time as [3]:

$$\frac{dN}{dt} = R - \alpha N - \beta \int n^2(r)\, d^3r \qquad (1)$$

where R is the atom capture rate, α is the linear loss rate coefficient, β is the rate coefficient for two-body collisions, r is a space variable and $n(r)$ is the local number density. In traps of alkali-metals, α is due to elastic collisions with hot background atoms. This linear loss is proportional to the background pressure, and the non-linear loss rate can be more than a hundred times larger [6]. If the term on β is null, the load and decay curves are obviously pure exponentials, with the same time constant. If cold collisions become significant, we have to take into account the density distribution of the trapped atoms. There are two limits for density in a MOT. Below a critical value n_C, the spatial distribution of trapped atoms resembles the velocity distribution in the quasi-harmonic potential of the MOT [7]. The density distribution can be written as a Gaussian function

$$n(r) = n\exp\left(-\frac{r^2}{a^2}\right) \tag{2}$$

where n is the peak density and the atomic cloud waist a is related to temperature and the MOT parameters. The total number of trapped atoms is found simply by an infinite volume integration of Eq. (2), giving $N = n\left(\sqrt{\pi}a\right)^3$. By increasing the number of atoms in the trap, the density increases until n_C, but the atomic cloud size remains constant (the so-called constant volume regime). After this limit, because of radiation trapping the volume increases, but the density stays constant. As in the case of strontium [3], we observed no limitation of density in our trap, for numbers below 10^7 and typical cloud waist a of 0.5 mm [8]. We will consider from now only the constant volume case, Eq. (2), which applied into Eq. (1) gives the following trap load-decay equation

$$\frac{dN}{dt} = R - \alpha N - \frac{\beta}{\left(\sqrt{2\pi}a\right)^3} N^2 \quad . \tag{3}$$

According to this, at the initial time of the decay process the total loss rate is $\alpha + \beta n_0/2^{3/2}$, where n_0 is the steady state peak density. Therefore cold collisions account for a loss rate $\beta n_0/2^{3/2}$, or a fraction:

$$\xi = \frac{1}{1+\sqrt{8}\dfrac{\alpha}{\beta n_0}} \tag{4}$$

of the total losses. For a trap decay curve, the filling of the trap stops suddenly at $t = 0$ and the solution of Eq. (3) is given by

$$N(t) = N_0 \frac{(1-\xi)\exp(-t/\tau_D)}{1-\xi\exp(-t/\tau_D)}, \tag{5}$$

where the time constant $\tau_D = 1/\alpha$ is the inverse of the linear loss rate. When the collision loss fraction ξ is much smaller than unity, the time evolution of the number is basically exponential. For a trap load curve, when the flux of slow atoms at the trap volume is turned on at $t = 0$ for a MOT loaded by a decelerated atomic beam, or when the trap beams are switched on for a background gas cell MOT, the solution of Eq.(3) reads

$$N(t) = N_0\left[1 - \frac{(1+\xi)\exp(-t/\tau_L)}{1+\xi\exp(-t/\tau_L)}\right], \tag{6}$$

where the load time constant is given by

$$\tau_L = \frac{1-\xi}{1+\xi}\frac{1}{\alpha}. \tag{7}$$

From the deviation of a pure exponential behavior of the decay, Eq. (5), or the load curve, Eq. (6), the collisional rate coefficient β is normally extracted [3,6]. We note, however, that in the limit of small ξ, to first order both Eqs.(5) and (6) reduce to exponentials, but still with slightly different time constants.

In the few reported observations of collisional effects in MOTs of alkaline-earth elements [2,3,5] the high linear loss channel due to optical pumping of metastable states was reduced by the addition of extra lasers that transfer the population of the $^1D_2$ level back to the ground state. In this way, it was possible to observe a small departure from an exponential behavior in the load or decay curves [3,5] or small variations in the trap number in a photoassociation experiment [2]. The JILA group [3] reported measurements of losses from a ^{88}Sr MOT where ξ values up to 50 % were observed. Even at this level of collisional loss fraction, small power fluctuations of the trapping lasers can degrade or completely obscure collision effects, since the determination of ξ relies on the deviation of the exponential law. It has then been usual to implement somewhat sophisticated power servo control systems [2,3]. The Hamburg [5] group reported observation of a loss fraction ξ of 0.32 in a ^{40}Ca MOT, for specific atom number, density and laser intensity and detuning. Also working in a ^{40}Ca MOT with a repump scheme, the PTB group [2] performed a photoassociative spectroscopy experiment with an extra, far detuned, laser to induce transitions to bound molecular states. This additional laser increases the light-induced collision fraction from $\xi = \xi_0$, due only to the trap light field, to $\xi = \xi_0 + \xi'$. The effect of collisions also manifests as a reduction of the number of trapped atoms. By measuring the number of trapped atoms with and without the photoassociation laser, the PTB group measured the molecular spectra of the ^{40}Ca dimmer. Due to the difficulties imposed by the small value of ξ' on that experiment (around 1%) it required a high precision laser power control, since the number was measured by detecting fluorescence of the trapped atoms. It is important to

stress that it is not possible to measure collisions induced only by the trap light fields with the method used by PTB [2]. Again, in the few experiments performed [2,3,5], the repumping schemes reduce the linear losses, but the situation is still very different from alkali-metal traps, where the quadratic losses exceed by far the linear term.

In our ^{40}Ca MOT loaded from a decelerated atomic beam and without repumping [8], we estimated by the semi-classical Gallagher-Pritchard model [3] that the small detuning trap loss would be on the order of few percent of the total losses. In fact, cold collisions in alkaline-earth atoms have not been observed in "standard" MOTs, e.g., without any kind of repump scheme. Grünert and Hemmerich [5] argued that, without repump, the parameter ξ turn out to be negligible. According to the solutions of Eq.(3), the decay occurs with a linear time constant $1/\alpha$ while the load occurs with a time constant given by Eq.(7). This means that the load time is connected to the decay time by

$$\tau_L = \frac{1-\xi}{1+\xi}\tau_D . \tag{9}$$

As the ξ parameter assumes values between 0 and 1, the load time is always smaller than the decay time. In the small non-linear loss regime, the difference between the load and the decay is approximately $2\xi\ \tau_D$. By measuring this time difference it is possible to get information about the collisional rate β. Let consider an example. In our ^{40}Ca MOT the decay time is limited to 16 ms by optical pumping into the $^1D_2$ level [9]. A very small collisional fraction ξ = 0.01 would cause a difference between the load and decay times of 0.32 ms, which can be measured with reasonable precision.

We have done some loss measurements in a ^{40}Ca MOT loaded from an atomic beam. For an oven temperature up to 580^{0}C it can trap around 10^7 atoms with a storage time which depends on the optical pumping of the $^1D_2$ metastable level, determined by the trapping laser total intensity and detuning [9]. Figure 1 shows two curves for the normalized number of trapped atoms, after switching on and off the decelerating laser beam (N_0 is the steady state number of the trapped atoms). This measurement was done for a laser detuning of –70 MHz (about two natural linewidths to the red), an effective trapping intensity of 200 mW/cm^2, magnetic field gradient of 66 Gauss/cm and an oven temperature of 477 ^{O}C. The number of trapped atoms determined by fluorescence, detected on a calibrated photodiode, in this situation is 6.5 (1.0) $\times$ 10^5 and the atomic cloud waist a, obtained with a CCD camera, is 500 (50) μm, which corresponds to a steady state peak density n_0 of 9.3 (2.3) $\times$ 10^8 cm^{-3}. We note that there is no significant deviation of the load and decay curves from an exponential behavior and, as predicted, the load occurs with a time constant a little smaller than the decay process. The two straight lines are exponential fittings to the data, from which we determine a decay time constant of 8.35 (5) ms and a load time constant of 7.84 (5) ms. Using this value and Eq. (9), we obtain a collisional loss fraction ξ =0.031 (6). From this, we estimate that for this specific laser intensity and detuning, the collisional rate coefficient β is 1.1 (5) $\times$ 10^{-8} cm^3 s^{-1}.

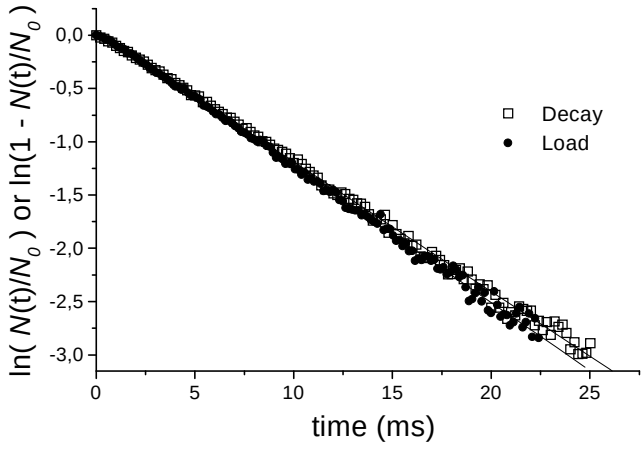


Figure 1: MOT load (•) and decay (□) curves for a MOT laser detuning of –70 MHz and an effective intensity of 200 mW/cm^2. Also shown are the exponential fittings of these curves (straight lines).

The value of the collision rate coefficient β obtained here is impressively large when compared to that obtained from photoassociation spectroscopy (2.9×10^{-11} cm^3 s^{-1} [2]). This discrepancy can be understood by a semiclassical Gallagher-Pritchard model calculation [3]. The Ca dimmer has two attractive potentials, $-C_3^{\Sigma}R^{-3}$ and $-C_3^{\Pi}R^{-3}$, with the constants C_3^{Σ}=16.5 (1) a.u. [2] and C_3^{Π} half of this value [6]. Figure 2 shows the result of the semiclassical Gallagher-Pritchard calculation of the collision rate coefficient considering the excitation of both molecular states [3]. For small red detuning, up to 200 MHz, the excitation of the $^1\Pi_g$ state clearly is the

dominant process involved in the collision trap loss. This happens because this molecular state can absorb efficiently at large *R* but weakly radiates at small *R*, given a high survival probability of the pair to very small internuclear separation, where state changing collisions can occur. Therefore, this difference between small and large detuning collisional rates explains the discrepancy between the β value determined here, for detuning in the range from 20 to 90 MHz, and that reported from photoassociation spectroscopy [2], where it was analyzed the effect of an additional laser detuned from 2 to 30 GHz.

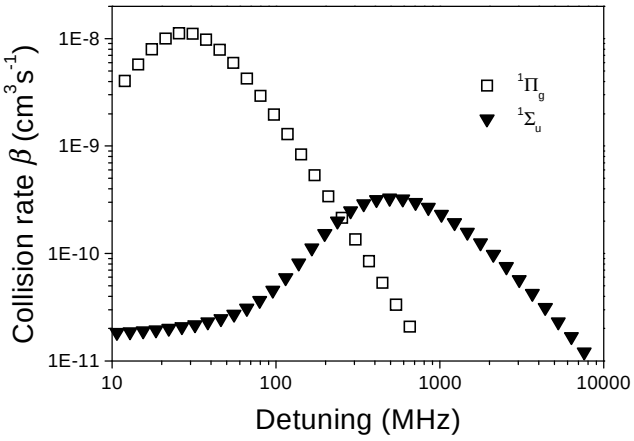


Figure 2: Variation of the collisional rate β with laser detuning, according to a semiclassical Gallagher-Pritchard calculation, for laser intensity of 200 mW/cm^2. It is considered the probability for excitation of the two attractive molecular potentials $^1\Pi_g$ ( ) and $^1\Sigma_u$ (θ) and further survival probability against radiative decay at small interatomic distance.

In conclusion, we demonstrated another method to detect cold collisions in MOTs when they account for just a small fraction of the total losses and, therefore, a departure from pure exponential behavior on the load and decay curves can not be easily observed. Since this is the typical case of alkaline-earth elements, we exemplify the method by measuring the collision loss rate β in a standard $^1S_0$-$^1P_1$ ^{40}Ca MOT. As in the case of ^{88}Sr [3], the importance of the long-lived $^1\Pi_g$ molecular state for detunings of a few atomic linewidths is confirmed. Further investigations of trap loss for alkaline-earth MOTs for small laser intensities can finally clarify the role of hyperfine changing collisions [10]. We hope the method described here can make possible systematic measurements of β as function of trap laser detuning and intensity, with a significant simplification of the experimental requirements. This will be particularly important for the theory of trap loss collisions [1].

Acknowledgements

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