Measurements of capture velocity in a magneto-optical trap for a broad range of light intensities

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We use a dark-spot Zeeman-tuned slowing technique to measure the capture velocity in a sodium magneto-optical trap as a function of the trapping laser intensity. We expand on previous work by measuring the capture velocity over a broad range of light intensities. We observe that the capture velocity reaches a maximum value and then decreases with increasing light intensities, which might imply a minimum in the trap-loss rate. This observation supports a recently published explanation of the dependence of the trap-loss rates, at low intensities, based mainly on the escape velocity.

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Experiments involving exoergic cold collisions are important to understand the role of these processes in the final number and density of atoms in a magneto-optical trap (MOT). The study of these collisions has been quite intensive in the last decade [1], motivated primarily by the desire for large samples of cold and dense atoms [2]. Such a sample allows a great number of interesting and diverse applications, such as high-resolution spectroscopy, metrology, and studies of quantum-degenerate gases. An important parameter used in the analysis of the trap-loss rate is the escape velocity v_e, which is usually defined as the minimum velocity that an atom has to achieve in order to escape from the trap. This velocity is normally obtained through numerical simulations of the trajectory of a single atom within the intersection of the trapping light forces. These simulations have been useful in many cases [3], but real measurements are important to reveal effects not included in those models, especially in the high-intensity regime. The direct measurement of v_e would be ideal, but so far nobody has devised a direct scheme to perform such an experiment. So what has actually been measured is either the trap depth, using a method of repulsive states excitation [4], or the so-called capture velocity v_c [5]. The capture velocity is defined as the maximum velocity of an atom traversing the trap volume that can still be captured into the trap. The value of v_c is related to the value of v_e and v_c can be considered as an upper limit for v_e.

In a previous publication [5] we reported using a magneto-optical trap loaded from a dark-spot Zeeman-tuned slower [6] to measure the capture velocity for trap laser intensities ranging from 0 to 27 $\mathrm{mW/cm^2}$. At that point, due to technical limitations, we were restricted to this relatively small range that covers only one part of the interesting region when one is dealing with trap-loss measurements. Recently, collision experiments have been carried out at higher-intensity ranges and the prediction for trap loss in those ranges requires a knowledge of v_e. The high-intensity regime, however, is a difficult one to simulate, because effects such as fluctuations, polarization imperfection, the multilevel nature of atoms, beam-saturation effects, etc., are difficult to include in the calculation. Therefore, measurements of v_c in this range are important because they are related to v_e, allowing for a better understanding of the results of the most current collision experiments. The technique presented in [5] and extended here allows one to measure the capture velocity of a MOT basically in any operating condition.

In this paper we provide a brief description of our experimental technique followed by our most recent measurement of v_c, which covers a much broader range of intensities. We observe that the capture velocity of our MOT, as a function of increasing trap laser intensity, increases to a maximum value and then decreases. We offer an explanation for the observed behavior, based on the saturation of the damping force in a MOT. This paper should be considered as a complement to our previous work [5].

To load our sodium MOT we use a cold atomic beam produced by a Zeeman slower where a dark spot is placed in the center of the slowing laser beam, producing a shadow on the position of the trap. This technique, described in detail in Ref. [6], allows a large accumulation of atoms in the MOT, due to the minimum disturbing effect of the slowing laser on the atoms in the MOT region. Scanning the slowing laser frequency, different velocity distributions appear in the outgoing cold beam of atoms [5]. These distributions are narrow, with a width δv, and the peak velocity v_{out} depends on the slowing laser frequency, basically obeying the relation $k v_{out} = -\Delta$ [7], where Δ is the slowing laser detuning and k is the wave vector of light. The output velocity distribution from the slowing process is close to a Gaussian distribution $g(v) = A \exp[-(v+\Delta/k)^2/2\sigma^2]$, where A is a normalizing constant and $\sigma = \delta v$ is obtained from previous investigations [5,8].

To obtain the capture velocity we measure the number of trapped atoms in the MOT as the slowing laser frequency is scanned within a range of ∓ 150 MHz around the slowing transition. The frequency ramping speed is ~ 5 MHz/s. This rate was observed to be slow enough to allow a sufficient equilibration in the number of trapped atoms in the MOT for each frequency of the slowing laser. If the laser frequency is far to the red, the atoms cross the trap volume too quickly and will not be captured. When the frequency is such that sufficiently small velocities are present in the outgoing velocity distribution, atoms start to accumulate in the trap. Assuming that all the atoms below the capture velocity are trapped into the MOT, the number of captured atoms at each laser detuning is well represented by the expression below [5],

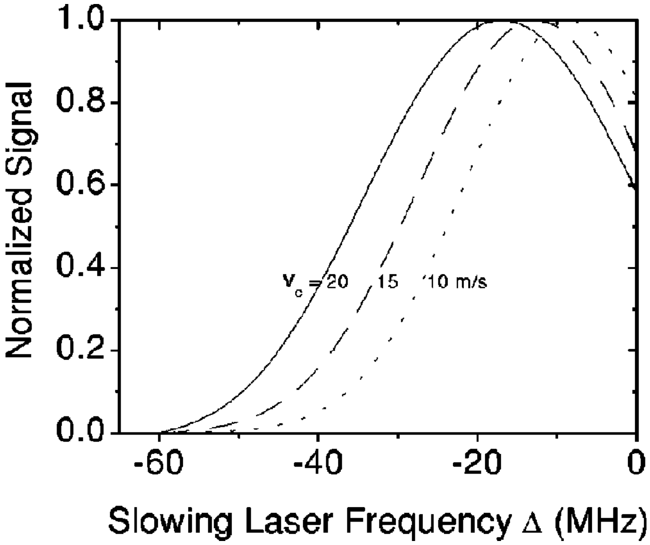

FIG. 1. Theoretical curves showing the number of trapped atoms as a function of the slowing laser frequency. As the capture velocity is increased, the curves shift to higher values of negative detuning.

$$N_c = \int_0^{v_c} g(v)\,dv, \tag{1}$$

$$N_c(\Delta) = A\int_0^{v_c} \exp[-(v+\Delta/k)^2/2\sigma^2]\,dv, \tag{2}$$

where this integral can be expressed as a combination of error functions, which provides an analytical expression for $N_c(\Delta)$. This function is, however, very dependent on v_c. In Fig. 1 we show $N_c(\Delta)$ normalized for several considered capture velocities. As the capture velocity increases, the curves for $N_c(\Delta)$ are shifted towards higher values of negative detunings. To determine v_c, we have fitted the rising part of the measured spectrum with the best value of v_c. The process was repeated for several intensities and v_c was obtained as a function of trap laser intensity. We used a trap laser detuning of -10 MHz and a MOT field gradient of $dB/dz \sim 10$ G/cm. In Fig. 2 we show the obtained results for the capture velocity. The dot line is only for eye guidance. The uncertainties shown in the experimental points come from the statistical deviation of the best fittings values, due to the scatter of the data for subsequent measurements.

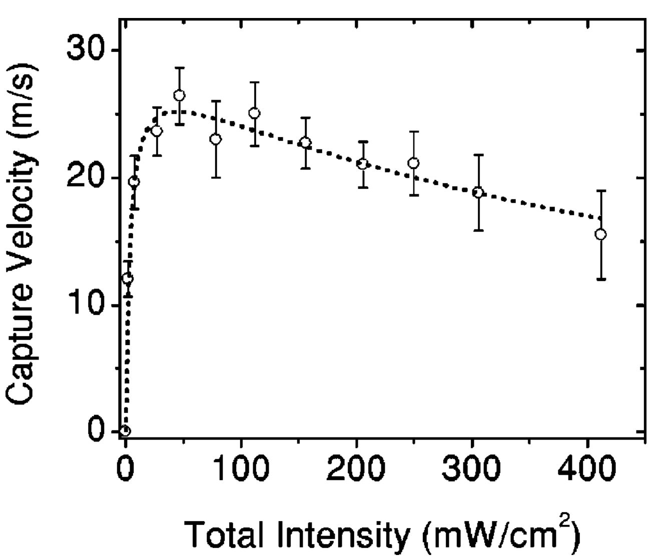

FIG. 2. Measured capture velocity as a function of trapping laser intensity for a detuning $\Delta \sim -10$ MHz, half waist of the Gaussian beam of 4.5 mm, and $dB/dz = 10$ G/cm. The dotted line is just for guiding the eye.

The behavior of v_c in the low-intensity regime is as previously reported [3,5], v_c goes to zero at zero intensity and increases at a decreasing rate as the intensity increases. The characteristic feature presented here is that v_c reaches a maximum value for a given intensity and starts to decrease slowly after that point. The existence of a maximum is in contrast with the previous idea that the capture velocity would either always increase or saturate [3,5]. In our case, the maximum seems to occur around 50 mW/cm^2. Since this is the total laser intensity, when the six beams are considered, the maximum in v_c is taking place at about 8 mW/cm^2 per beam (close to the saturation intensity for sodium). This result seems to confirm the discussions in Ref. [9], that the capture process might depend more on the damping part of the radiation pressure than on the restoring force of the trap. In this case, the maximum capture would correspond to the situation of optimum balance between the beams. And any further increase in intensity oversaturates the transitions and the power broadening thereafter compromises the atom's ability to distinguish between the two counterpropagating laser beams. In such a situation the damping coefficient starts to decrease and the same happens to the capture velocity.

This behavior agrees qualitatively with simulations based on the model presented in Ref. [5], that considers only a two-level atom. However, according to the simulations, the peak velocities occur at much higher intensities. We believe this discrepancy is due to the limitations of the model at high intensities. Previous works [3], that consider to some extend the multilevel aspects, have limited their discussion to intensity ranges up to ~ 100 mW/cm^2, where the resulting calculated velocities always tend to increase with intensity. Therefore, the measurements shown here call to attention an important feature of the capture velocity, and maybe of the escape velocity as well, that has not really been considered. A natural question is: How important is the restoring force for determining v_c? To answer this question, we measured the capture velocity for some different values of the magnetic-field gradient. Since the restoring force is proportional to dB/dz, the dependence of v_c on this gradient reveals the importance of this force on v_c. What we observed is that v_c is weakly dependent on dB/dz for gradients in the range 5–10 G/cm, where we typically operate. This seems to indicate that the main contribution comes from the damping part of the optical force. Perhaps the main conclusion of the observations presented here is that the escape velocity v_e might follow a similar pattern. Such a behavior for the escape velocity, with respect to the trapping laser intensity, would mean that the effective trap depth of a MOT has also a maximum. This maximum in the trap depth would imply the existence of a minimum in the trap-loss rate, not necessarily at the same laser intensity. This is consistent with the recent alternative interpretation [9] of the behavior of the loss rate coefficient at low intensities. We should emphasize, however, that such a dependence is very much related to the overall operation of the trap and, therefore, a more comprehensive study is still necessary.

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