# Secondary scattering on the intensity dependence of the capture velocity in a magneto-optical trap

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(Received 30 November 2004; published 22 August 2005)

In this work, we consider a three-dimensional model to simulate the capture velocity behavior in a sample of cold-trapped sodium atoms as a function of the trapping laser intensity. We expand on previous work [V. S. Bagnato, L. G. Marcassa, S. G. Miranda, S. R. Muniz, and A. L. de Oliveira, Phys. Rev. A **62**, 013404 (2000)] by calculating the capture velocity over a broad range of light intensities considering the secondary scattering in a magneto-optical trap. Our calculations are in a good agreement with recent measured values [S. R. Muniz *et al.*, Phys. Rev. A **65**, 015402 (2001)].

DOI: 10.1103/PhysRevA.72.025403 PACS number(s): 32.80.Pj, 33.80.Ps, 34.50.Rk, 34.80.Qb

The capability of a magneto-optical trap (MOT) in dissipating kinetic energy determines the maximum velocity below from which the trap is able to capture the atom, that is defined as the capture velocity ($v_c$). Several experiments involving the measurement of the capture velocity have demonstrated that the trap laser light intensity is an important parameter to obtain this velocity [1,2]. This is an important factor in determining the trap efficiency, when it is analyzed together with the atom's velocity distribution in the loading process. It is simple to be interpreted, if one understands that the maximum number of trapped atoms occurs when there is an equilibrium between losses and the capture rate, which depends on the capture velocity.

The studies on the losses in a MOT were motivated primarily by the desire in obtaining large and dense samples of cold atoms [3], which will allow a great number of interesting and diverse applications [3]. In recent years, the importance of the knowledge of the capture velocity was pointed out in several works [2,4,5], which may be related with the escape velocity ($v_e$). The escape velocity is defined as the minimum velocity an atom has to achieve in order to escape from 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 $v_e$ [1]. One of these studies [3] emphasized the importance of the escape velocity for the calculation of trap loss rate. Recently, collision experiments have been carried out at higher intensity ranges [6,7] and the prediction for trap loss in those ranges requires a knowledge of $v_e$, as it was mentioned before. As reported by Muniz *et al.* [1] and by Bagnato *et al.* [8], many effects such as fluctuations, polarization imperfection, the multilevel nature of atoms (that is, the reason for the atom to be considered by this work as a two-level system), beam saturation effects, etc., are difficult to include in the calculation, and it is not an easy task to simulate the high intensity regime. Normally the capture velocity is obtained through numerical simulations of the trajectory of a single atom within the intersection of the trapping light forces. But these simulations, that have been useful in many cases [8,9], did not cover the ranges of the measurements performed in Ref. [1] and did not take into account the effects cited before, especially in the high intensity regime. In an experiment carried out by Muniz *et al.* [1] it was shown that the capture velocity behaves in a slightly different way from that predicted by the model used in Ref. [8]. In that reference, the authors show that the capture velocity increases by increasing the intensity of the trap laser. However, the experiment [1] showed a different behavior, the capture velocity reaches a maximum and then begins to decrease.

In this work, we have simulated the capture velocity of a sample of cold-trapped sodium atoms in a three-dimensional MOT. The method used here considers the trajectory of a single atom within the intersection of the trapping light forces, including the secondary scattering. This paper will provide a brief description of our model on the behavior of capture velocity and will show a comparison with the experimental values obtained by Ref. [1]. In our calculations we covered the same range of intensity as done in the experiment of Ref. [1] and we used a different approach considering a force applied to a cloud of atoms in the MOT. We offer an explanation for the observed behavior, not only based on the saturation of the damping force in a MOT as done in Ref. [1], but also on the re-absorption and re-radiating effects present in a MOT when one is at this intensity regime, i.e., the secondary scattering as reported by Sesko *et al.* [10]. The atoms in a MOT are subject to scattered light from the laser and this may contribute to oversaturate the light intensity felt by the atoms and to diminish the contribution from the damping term, causing the observed decrease in the velocity. The aim of this paper is to show the importance of the secondary scattering on the behavior of the capture velocity and it should be considered as a complement to the previous work [8].

In the model used in Ref. [8], the authors considered the atom as a two-level system, under the influence of the damping and the restoring forces only. The model used by Ref. [8] for the forces acting in a MOT was written as

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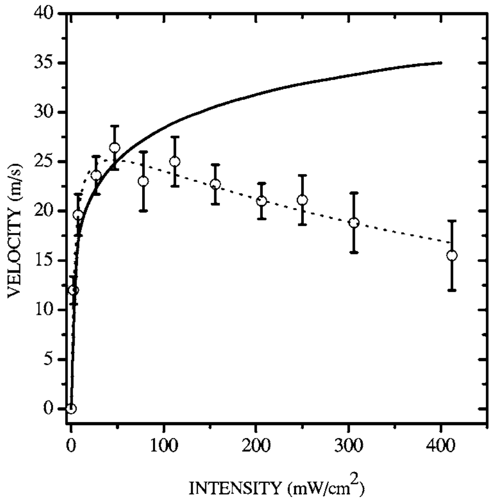


FIG. 1. Behavior of capture velocity as a function of the trap laser total intensity. The solid line is a simulation using the model described by Eq. (1) and shows that the capture velocity was supposed to increase with the laser intensity. The dashed line is only a guide to follow the experimental data of Ref. [1]. [The experimental plot (dots and dashed line) is a courtesy of Muniz *et al.*]

$$\vec{F} = -k\vec{r} - \delta\vec{v}, \tag{1}$$

where

$$k = \frac{16\,\hbar\,\kappa\,\Gamma|\Delta|\Omega^2\gamma\,b}{[4\,\Delta^2+\Gamma^2+2\,\Omega^2]^2}, \tag{2}$$

$\hbar$ is the Planck's constant divided by $2\pi$, $\Gamma$ is the natural width of the atomic transition, $\Delta$ is the detuning of the optical field from the atomic transition frequency, $\Omega$ is the Rabi's frequency, and

$$\delta = \frac{k\kappa}{\gamma b}, \tag{3}$$

where $\gamma$ is the Zeeman constant, $b=dB/dz$, and $\kappa=2\pi/\lambda$.

If we, in order to be as close as possible to the experimental values for the capture velocity, consider in our simulations the same values as considered for parameters such as detuning and magnetic-field gradient used in Ref. [1], we can simulate the behavior of the capture velocity using Eq. (1) and show it together with the experimental results in Fig. 1. From this plot we can observe that such a model fails when the laser intensity is increased to values greater than 100 $\text{mW/cm}^2$. Thus in order to improve the model we have included the secondary scattering in our calculations. As pointed out by Sesko *et al.* and by Steane *et al.* [10,11], the atoms in a cloud are subjected to the light scattered from each other.

When one is working in the high-density regime and specially in the high intensity of laser light regime, it is worthwhile to consider that there is a force (photon-pressure force [11]) between the atoms which comes from the interaction between them, since the increase in density is limited by repulsive forces and the spring constant of the trap [11]. The repulsive force has, in this case, its origin in the re-radiated photons and it is related to the cross section of the atoms. This scattered light is reabsorbed by the atoms and then re-radiated, and this process will be limited by the saturation intensity of each atom. Thus the saturation parameter $s$ (that will be defined later on) is a very important parameter when the secondary scattering is considered, because it connects the intensity of light and the cross sections of the atoms, and by using this parameter it is possible to obtain the rate at which one atom scatters photons from the laser, $\Gamma s/2(s+1)$ [11]. In the same way, it is helpful to think that the cross section of the re-radiated light will be linked to the light coming from the laser field [10,11]. In all our calculations we have assumed the atom as a two-level system for the sake of simplicity. As shown by Steane *et al.* [11] this force satisfies the inverse-square law, and based on the fact that the repulsive force is larger then the attractive force for typical parameter values in a MOT [11,12] we may think of it as a repulsive force between the radiation and the atoms. We are assuming for simplicity a spherical symmetry for the cloud.

So based on the equation of motion of an atom in a MOT considering the secondary scattering in the force, Eq. (1) can be rewritten as

$$\vec{F} = -k\vec{r} - \delta\frac{d\vec{r}}{dt} + \alpha\frac{N'}{r^2}\hat{r} \tag{4}$$

where $N'$ is the number of atoms in the MOT, $\hat{r}$ is a dimensionless unit vector, and

$$\alpha = \frac{I\sigma_L{}^2}{4\pi c}\left(\frac{\sigma_R}{\sigma_L} - 1\right), \tag{5}$$

where $\sigma_R$ is the cross section for absorption of the scattering light and $\sigma_L$ is the cross section for absorption of photons from the laser field. $\sigma_R$ and $\sigma_L$ are related by the saturation parameter $s$, defined as [11]

$$s = \frac{\Omega^2/2}{\Delta^2 + \Gamma^2/4}. \tag{6}$$

The saturation parameter and the cross sections are related by [11]

$$\sigma_R \simeq \frac{1}{s+1}\sigma_L + \left(1 - \frac{1}{s+1}\right)\frac{s+1}{s+\Gamma^2/(4\Delta^2+\Gamma^2)}\sigma_L, \tag{7}$$

and one can calculate $\sigma_L$ using Ref. [10]

$$\langle\sigma_L\rangle = \sigma_0\left\{\left[1 + 4\left(\frac{\Delta}{\Gamma}\right)^2\right]\left[1 + \frac{6I}{I_S} + 4\left(\frac{\Delta}{\Gamma}\right)^2\right]\right\}^{-1/2}, \tag{8}$$

where $\sigma_0$ is the resonant scattering cross section. We use this spatially averaged cross section, in Eq. (8), as used by the authors in Ref. [10,13].

In our model, to find the capture velocity, we solve numerically the equation of motion [Eq. (4)]. We assume the trapping region to be spherical and with the diameter equal to two times the beam diameter. We have included in our model the Gaussian profile of the beam and the magnetic field present in the MOT, when we write the equation for the trajectory of the atom, in the same way as done by Lindquist *et al.* [9].

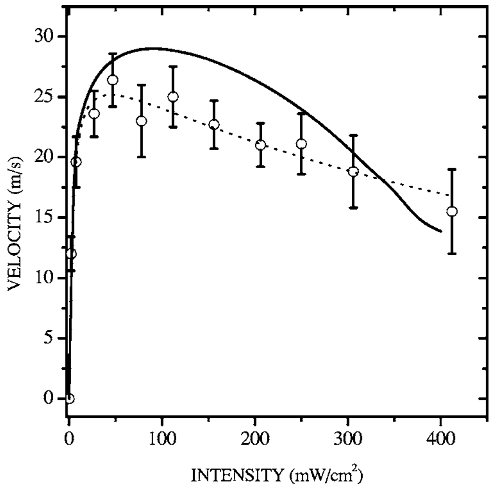


FIG. 2. Behavior of capture velocity as a function of the trap laser total intensity. As the intensity increases, the capture velocity reaches a maximum and then decreases, as shown by the experimental points (dots) measured by the authors of Ref. [1]. The dashed line is, once again, only a guide to follow the experimental points of Ref. [1]. The solid line is the simulation performed in the present work, using the model described by Eq. (4). By comparing the experimental data to our simulation, one can see a good agreement. [The experimental plot (dots and dashed line) is a courtesy of Muniz *et al.*]

The behavior of $v_c$ in the low intensity regime is as previously reported [8,9], $v_c$ goes to zero at zero intensity and increases at a decreasing rate as the intensity increases (see Fig. 1 for more details). The existence of a maximum is in contrast to the previous idea that capture velocity would either always increase or saturate [8,9]. In our case (considering the secondary scattering), the maximum occurs around 60 $\mathrm{mW/cm^2}$, as shown in Fig. 2, which is qualitatively in a good agreement with the experiments of Ref. [1]. In Fig. 2 the dots are the experimental data [1], the dashed line is only a guide to follow the experimental points, and the solid line refers to our simulation. In our simulations we have considered the total intensity as the sum of the six beams considered as they do in the experiment [1], and also the same values for the parameters like detuning, number of atoms, etc.

This result seems also to confirm the discussions in Ref. [5], namely that the capture process might depend more on the damping part of the radiation pressure than on the restoring force of the trap. And any further increase in the 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 [1].

The behavior of capture velocity qualitatively agrees with experiments [1] and presents a correction on the model presented in Ref. [8], which also considers the atom as a two-level system. However, according to those simulations (Ref. [8]), the peak velocities occur at much higher intensities. Such an assumption does not present a quantitative agreement with the experiments as one can see in Fig. 1. We believe this discrepancy is due to the limitations of the model that does not consider the second scattering term at high intensities. Previous works [9], that consider to some extent the multilevel aspects, have limited their discussion to intensity ranges up to $\sim 100\ \mathrm{mW/cm^2}$, where the resulting calculated velocities always tend to increase with intensity. With our simulations, presented in this work, we show that reradiation and re-absorption effects play an important role in the context of the determination of the capture velocity. It clearly shows that a quantitative and qualitatively good agreement is possible only when the secondary scattering is taken into account.

The behavior for the capture 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 in 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 [5] of the behavior of the loss rate coefficient at low intensities regime.

We have reported results on a theoretical study of the influence of the second scattering on the dependence of the capture velocity. We have used a three-dimensional model based on the forces acting over the atom in a cloud, expanding on previous work [8] to a high intensity regime of laser trapping light. We have also shown that our results are in a qualitative and quantitative good agreement with experimental results. These results intend to be a contribution to the trap loss and load process studies.

The authors wish to thank Dr. Luis Marcassa for his critical reading of the original manuscript, and Dr. Kilvia Magalhães for the experimental curves. The authors also thank CNPq for financial support.

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