Magneto-Optical Trap for Sodium Atoms from a Vapor Cell and Observation of Spatial Modes

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We have demonstrated magneto-optical trapping of Sodium atoms in a vapor cell at 80°C. The trap was used to investigate different spatial distributions of atoms arising from the misalignment of the laser beams. Exotic shapes like rings, double traps and others have been observed and theoretically justified.

I. Introduction

During the past few years there has been an enormous progress in the use of light to manipulate the translational degrees of freedom of atoms. Laser light resonant with an atomic transition has been used to slow[1], cool[2] and trap[3] neutral atoms. An intense effort is now being carried out with the purpose of using laser radiation techniques to improve methods of atomic manipulation in order to produce intense beams of slow atoms or dense traps where slow energy collisions and ultra-high precision spectroscopy will find interesting applications. If sufficiently high density and low temperature are attained, one may expect to observe collective effects, such as Bose-Einstein Condensation[4]. Until recently, the production of cold trapped atoms was achieved in a two-step process, when it was demonstrated that cesium atoms in the low velocity tail of a thermal distribution can be directly captured from a vapor[5]. In spite of technical difficulties arising from different operational conditions, sodium atoms may also be confined in a similar way[6].

Trapped cold atoms may present intriguing spatial configurations, depending on the position and transverse intensity profile of the laser beams used. One of the possible spatial distributions of cold trapped atomic samples is a ring which recently[7] has been associated with collective effects in trapped neutral atoms. However, experiments with sodium[a] revealed that, depending on the laser configuration and profile, it is possible to obtain stable rings of trapped atoms without the need of the existence of a collective behavior to explain the results. Another interesting configuration of magneto-optically trapped atoms is a double stable trap which has been observed since the first demonstration of Magneto-Optical trapping but, to our knowledge, was never explained.

In this paper we discuss the achievement of trapped sodium atoms in a vapor cell and the observation of spatial atomic distributions which are justified on the basis of the radiation pressure.

II. Magneto-Optical Trap for neutral atoms

The Magneto Optical Trap (MOT) for neutral atoms was originally proposed by Pritchard et al.[9] and demonstrated a few years later by Raab et al.[10]. The trap consists of three mutually orthogonal, retroreflected laser beams intersecting at the center of a quadrupolar magnetic field, originated from a pair of coils carrying opposite currents. Close to $B = 0$, the field grows linearly in all directions, with a maximum gradient on the coil axis and half of that on the orthogonal directions. According to the selection rules for eletronic transitions, the magnetic field allows different laser beams to exert different forces on the atoms. The Zeeman splitting of the atomic levels and the use of convenient laser beam polarizations produce an spatially dependent force which has the net effect of restoring the position of the atoms to $B = 0$. The use of red detuning for the resonant laser beam produces a viscous force in addition to the restoring one. In order to visualize the situation presented above, let us consider an atom with velocity v (Figure 1a) under the action of two counter-propagating laser beams in the presence of a linear magnetic field (Figure 1b). For simplicity, we will consider a transition $J = 0 \Rightarrow J = 1$ for this hypothetical atom (Figure 1c). The laser with frequency ν_1 carries a polarization suitable to produce the transition $(J = 0, M_J = 0) \Rightarrow (J = 1, M_J = -1)$ while the laser with frequency ν_2 has the opposite polarization, giving rise to a transition to $M_J = 1$.

In the approximation where each laser interacts only with two of the existent levels, one can write the total radiation force on the atom as[11] :

$$m\frac{d^2z}{dt^2} = 2\Gamma\hbar k\frac{S}{(1+S)^2}\frac{\Delta}{\Delta^2+\Gamma^2/4}\left(k\frac{dz}{dt}+z\frac{d\omega}{dz}\right) \quad (1)$$

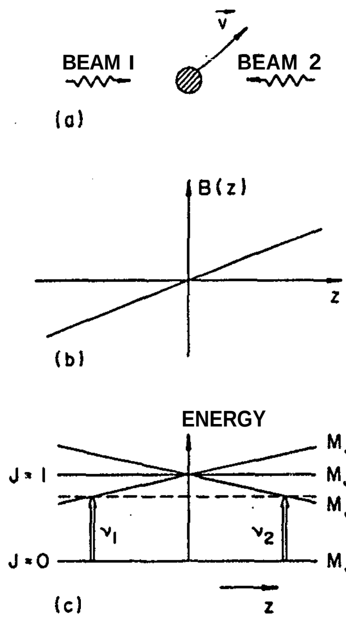

Figure 1.: Explanation of the principles involved in MOT traps: (a) atom illuminated by two counter-propagating lasers, (b) spatial magnetic field configuration and (c) electronic energy level scheme for an hypothetical atom.

where k is the magnitude of the wave vector, Γ is the natural linewidth of the transition, $S = (\Omega^2/2)/(\Delta^2 + \Gamma^2/4)$ is the saturation parameter, A is the laser detuning and $\frac{d\omega}{dz} = \frac{d\omega}{dB}\frac{dB}{dz}$ is the variation of the resonance frequency on the space. Similar equations for the two other orthogonal directions can also be written. Eq. (1) predicts an atomic motion like a damped harmonic oscillator when red detunings are used. Therefore, this configuration can capture and confine the atoms.

III. Experimental realization of MOT in a vapor cell

Let us now imagine a MOT trap filled with a vapor in a temperature not very high (about 80-100°C for Na). It is reasonable to expect that low velocities atoms present in the vapor could be slowed by the damping part of the radiation pressure of Eq. (1) and captured by the trap. In this case, the maximum velocity for an atom to be captured is that where the Doppler shift is of the order of the laser detuning.

Our experimental set-up is shown in Figure 2. A stainless steel chamber is saturated with sodium vapor at about 80°C. Laser light is introduced in the system through six coated vacuum windows and the magnetic field is produced by a pair of coils located externally to the chamber, giving rise to a field gradient of about 10 G/cm in the axial direction and 5 G/cm on the two other orthogonal directions. The laser beam is produced by a single mode ring dye laser pumped by an Ar+ laser. The trap works when the laser is

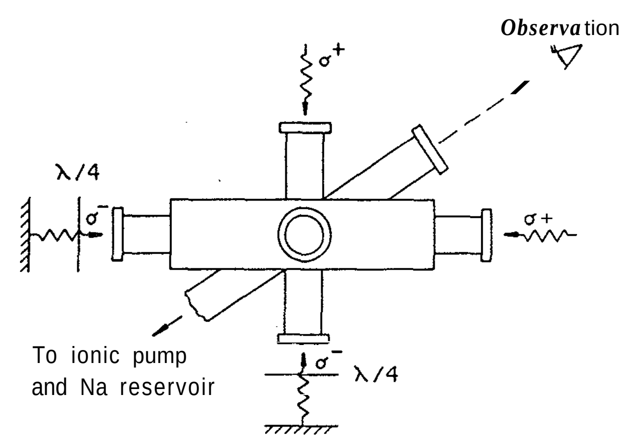

Figure 2.: Schematic representation of the sodium cell with two pairs of laser beams. The magnetic field and the third pair of beams are perpendicular to the plane of the figure.

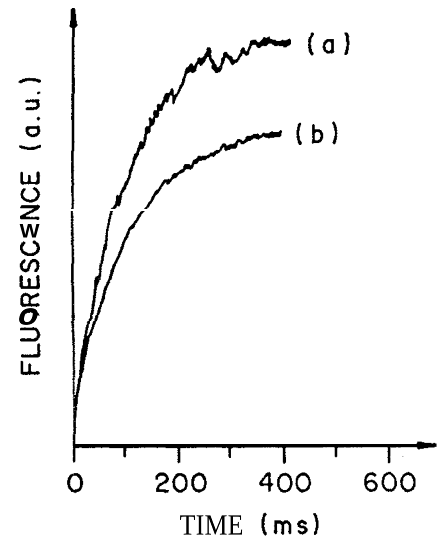

Figure 3.: Time evolution of the trapped atom fluorescence after the trapping laser is turned on, for (a) A = - 15MHz and (b) A = -20MHz.

red-tuned between 0.5Γ and 1.0Γ from the transition $3S_{1/2}$ (F=2) $\Rightarrow$ $3P_{3/2}$ (F=3), considered here as the trapping transition. In order to circumvent unwanted transitions which may pump the atom out of the $3S_{1/2}$ (F=2) ground state, sidebands at 1712 Mhz are added to the main frequency as a way of repumping it to that level. After setting the laser with the correct polarizations and frequency, a bright ball of atoms of about 1mm in diameter appears at the center of the trap, close to the position where the magnetic field is zero. The characteristic charging time of the trap can be measured by following the evolution of the fluorescence with time just after openning the trapping laser. The results of the fluorescence build-up for two different laser frequencies are shown in Figure 3. Typical charging time are of the order of 200 msec.. We are presently investigating the dependence of the charging time on the laser frequency and magnetic field.

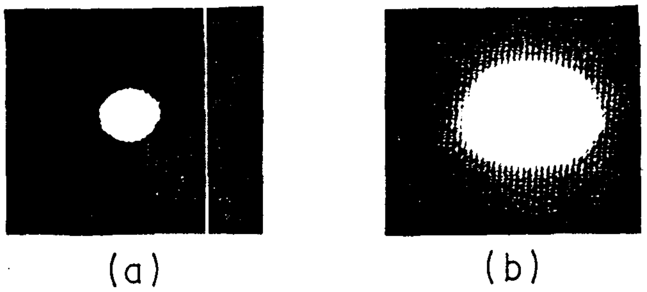

Figure 4.: Visual aspect of the trapped atoms for (a) trapping in the transitions $S_{1/2}$ (F=2) $\Rightarrow$ $P_{3/2}$ (F=1) and (b) trapping close to the transition $S_{1/2}$ (F=2) $\Rightarrow$ $P_{3/2}$ (F=2).

Sweeping the laser frequency we observe the existence of two traps. One of them is resonant to the $S_{1/2}$ (F=2) $\Rightarrow$ $P_{3/2}$ (F=3) transition and the other one seems to be resonant with $S_{1/2}$ (F=2) $\Rightarrow$ $P_{3/2}$ (F=2). These two traps present very different behaviors concerning to their sizes and intensities. Indeed, even a visual observation shows very distinct pictures, as presented in Figure 4. From a preliminary analysis of the fluorescence dependence on the frequency for both traps, we have indications that the trapping may be ocurring in the transition $S_{1/2}$ (F=2) $\Rightarrow$ $P_{3/2}$ (F=1), which demands blue detuning because it is a transition of the type $(J+1) \Rightarrow (J)$. If this fact is confirmed it will be a new regime of trapping that uses blue detuning instead of red detuning. However, the damping occuring in this case is not explained yet.

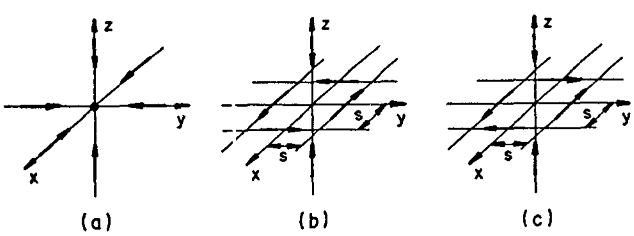

Figure 5.: Laser beams configurations for the observation of (a) spherical shape, (b) rings and (c) double trap.

IV. Observation of spatial modes in MOT

In a normal MOT, each pair of laser beams is well aligned to be counter-propagating, as indicated in Figure 5a. In this case, the most common stable spatial distribution for the atoms is close to a spherical shape, with minor deformations, as shown in Figure 4. However, when the laser beams are slightly misaligned, exotic shapes such as rings, double clouds, pancakes, etc, can be produced in a stable way.

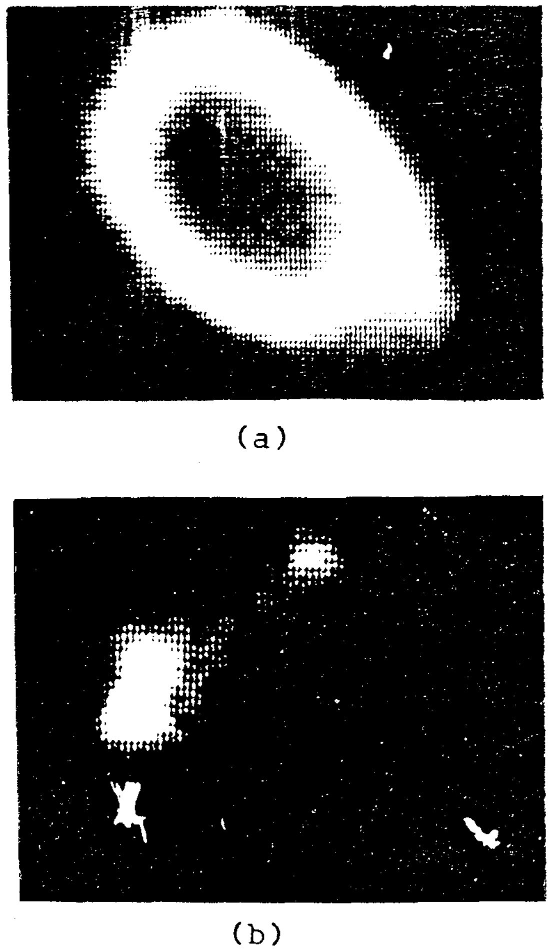

Figure 6.: Observed spatial atomic distributions corresponding to the configurations of Figures 5b and 5c, respectively.

Let us start by considering ring shaped traps. If instead of the configuration of Figure 5a we produce a misalignment as shown in Figure 5b, we have the production of stable rings as presented in Figure 6a. They are dependent on the magnetic field and laser frequency as well as to the shift s between beams.

To understand the stability of these rings we consider the radiation pressure on the atom in the case of a real Gaussian profile. For atomic displacements not larger than half waist(w) of the laser beam, one can show that the equation of motion for the atom in such a configuration has the form:

$$m\frac{d^2\vec{r}}{dt^2} = -\alpha\vec{r} - \beta\frac{d\vec{r}}{dt} + \xi(r)(y\hat{x} - x\hat{y}) \qquad (2)$$

where $\vec{r}$ is a vector in the horizontal (x,y) plane of Figure 5b. The equation of motion in the z-direction is the same as in Eq. (1). $\xi(r) = \xi_0(1 - r^2/w^2)$ and α, β and ξ_0 are constants dependent on Δ dB/dz and s.

The consequence of a beam displacement as indicated in Figure 5b is the introduction of a vortex force in the equation of motion, which may produce circular motion of the atoms. The condition for stable trajectories is found to be $\alpha/m = \xi^2/\beta^2$ which physically represent a balance among all the forces involved in the process. From this condition we obtain the radius of the trajectory as $R = w(1-(\alpha/m)^{1/2}(\beta/\xi_0))^{1/2}$. Evaluation of R for normal experimental conditions shows good agreement with observation.

A second interesting spatial distribution was obtained for a laser configuration shown in Figure 5c. In this case we observe the existence of a double stable trap as presented in Figure 6b. The explanation for this spatial distribution also relies only on the radiation pressure and the stable points arise from the balance between the trapping force and a expelling force caused by spatial shifts of the laser beams.

We have also observed other shapes besides rings and double clouds. For special conditions, it is possible to observe multiple stable configurations which we are presently investigating.

V. Conclusions

In conclusion, we have demonstrated the realization of MOT traps for sodium atoms from a vapor cell. Using Gaussian shifted laser beams it is possible to obtain different spatial distributions of atoms, which may have applications in the production of stable spin polarized samples of cold atoms and eventually in collisions experiments.

Acknowledgements

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