Macro-Structures in Atomic Beams: Possible Applications in Controlling the Morphology of Film Deposition

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We discuss the origin of several different spatial distributions of laser cooled sodium atoms in a magneto-optical trap. According to this analysis, similar structures can also be impressed on the transverse profile of an effusive atomic beam. After some extra manipulation with laser lenses, the beam can be deposited on a cold substrate and the morphology of the deposit will follow the pattern of the atomic beam. This may have important applications in the field of lithography.

I. Introduction

Beams of neutral atoms can be manipulated through their interaction with light. Similarly to ordinary optics, where light can be controlled by mirrors and lenses, a beam of neutral atoms can be collimated, deflected and focused by special mirrors and lenses made of beams of light[1]. Light exerts a force on neutral atoms and the origin of this force can be of two types: (i) due to the momentum transferred from the photon to the atom during an absorption-emission cycle (spontaneous force) or (ii) due to the interaction between the spatial gradient of the light field and the electric dipole moment induced in the atom by the light (gradient force). The spontaneous force occurs whenever the photon frequency is near resonant to the atomic frequency while the gradient force is important in the case of tightly focused laser beams and standing waves (SW), where the intensity oscillates spatially every half wavelength. A possible application for this atomic- beam optics is in the field of submicron lithography[2]. Indeed, light has already been used as a lens to focus a collimated neutral atomic beam to submicron dimensions during deposition onto a substrate[3]. In this case, a regular grating of sodium atoms with a 294 nm period and covering a 0.2 cm^2 area was produced on a silicon substrate after the collimated sodium beam passed through a SW. The gradient force originated by the SW was capable of producing features on a 10-nm scale every half wavelength. Theoretically, a gradient force atomic objective lens is expected to focus a collimated atomic beam down to a width of a few angstroms. On the other hand, the spontaneous force has been used to produce (in a controlled way) different spatial distributions of cold atoms in a magneto- optical trap (MOT)[4]. Structures with a V-shape, rings, double-rings, rings with central cores, etc. were achieved through the use of a macroscopic vortex force, which is due to a combination of the radiation force and a misalignment of the laser beams[5]. Although these spatial distributions were obtained in the MOT, it is straightforward to show that these patterns can also be produced in the transverse profile of an atomic beam[6]. In this case, an effusive, collinated atomic beam of, for example, sodium will cross a magneto-optical interaction region, emerging with a specific transverse distribution. If this atomic beam is deposited on a cold substrate, the morphology of the deposit will remain as that of the beam. Thus, it would be possible to use this technique for neutral-atom lithography purposes and two schemes could be employed in order to achieve such aim. First, the specific distribution, which is tipically of the order of 1 mm, could be focused on the substrate by means of laser lenses to a μm size and second, it could be combined with the distribution generated by the SW. This may have important technological applications in the field of lithography. This work presents the main ideas related to the vortex force and some experimental results concerning to the spatial distributions produced with cold atoms in the MOT, as well as its extension to atomic beams.

II. Forces acting on magneto-optically trapped atoms

The possibility of trapping atoms magneto- optically was pointed out by Pritchard et al[7] and experimentally accomplished one year later by Raah et al[8]. The apparatus used in the MOT technique consists of a Zeeman-shift spontaneous-force trap, which traps neutral atoms (sodium in our case) in a. vapor cell. In our experimental setup, three orthogonal retro-reflected laser beams of about 15 mW at 589 nm (sodium D_2 line), 1 cm in diameter and carrying opposite circularly polarized light intercept in a region with a constant gradient magnetic field B, generated by a spheroidal quadrupole. The field is produced by a pair of anti-Helmholtz coils and has 20 G/cm in the direction of the axis of the coils and half of that in the orthogonal directions. The source of atoms for this trap comes from the low velocity tail of the atomic vapor present at the trap region, which has a density of about $5.10^8/\text{cm}^3$ when the cell is kept at about 80°C. In order to minimize collisions between sodium atoms and foreign atoms or molecules the background gas pressure is kept below 10^{-8} torr. The laser beam provided by a single mode ring dye laser is tuned about 10 MHz to the red of the 3 $S_{1/2}$ (F = 2) → 3 $P_{3/2}$ (F' = 3) transition. In order to circumvent unwanted transitions, which may pump the atom out of the 3 $S_{1/2}$ (F = 2) ground state, sidebands at 1712 MHz are added to the main frequency as a way of repumping it to that level. A more complete description of our system has been presented elsewhere[4].

The MOT operates with unfocused Gaussian beams such that the Force acting on the atoms is purely spontaneous. It is well stablished[8] that in the case where the laser beams are perfectly aligned with respect to their retro-reflections, an atom in a MOT undergoes a damped harmonic motion described by:

$$m\frac{d\vec{v}}{dt} = -K\vec{r} - \alpha\vec{v}\ , \qquad (1)$$

where m is the atomic mass, $\vec{r}$ is the displacement from the origin, which is defined to be the position where the light beams intersect (at $B = 0$) and $\vec{v}$ is the atomic velocity. The spring constant K is related to the position-dependent atomic frequency due to the Zeeman effect, while the damping constant is the same which occurs in optical molasses. They are given, in units of $\hbar k\Gamma$ *(h* is the Planck's constant, R is the inverse of the radiation wavelength and $\Gamma/2\pi = 10$ MHz is the transition linewidth), as:

$$\frac{K}{2\pi} = \frac{16\Omega_0^2|\Delta|}{(1+2\Omega_0^2)^2\left(1+\frac{4\Delta^2}{1+\Omega_0^2}\right)^2}\frac{d\omega}{dx} \qquad (2)$$

and

$$\frac{\alpha}{2\pi} = \frac{16\Omega_0^2|\Delta|(k/\Gamma)}{(1+2\Omega_0^2)^2\left(1+\frac{4\Delta^2}{1+2\Omega_0^2}\right)^2}\ , \qquad (3)$$

where Ω_0 is the Rabi frequency at the center of the Gaussian beam, A(< 0) is the laser detuning and $d\omega/dx$ is the variation of the transition frequency with position due to the inhomogeneous magnetic field. For simplicity we have considered all frequencies in units of Γ and distances in units of the Gaussian beam waist w. Due to the spontaneous emission, the atom undergoes a ramdon walk in momentum space and as a consequence it acquires a finite temperature. The steady-state solution of the Fokker-Planck equation for an isotopic damped harmonic oscillator predicts a spatial distribution of atoms with a Gaussian shape. This has actually been found experimentally for low densities of trapped atoms; at high densities, a collective effect known as radiation trapping may change the Gaussian distribution.

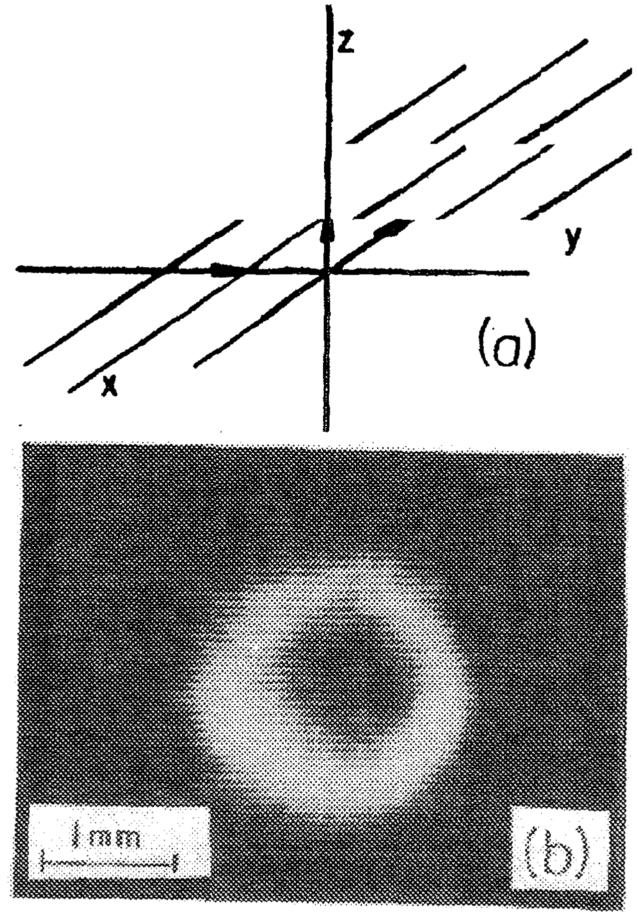

Figure 1: (a) Geometry of the laser beams forming a race track in the xy plane and aligned in the z-direction. The displacement of each beam is labelled s. (b) Stable ring distribution of atoms formed in the configuration shown at (a).

Let us now consider the extra force that appears when the trapping laser beams are misaligned by s in the xy plane as shown in Fig. 1a, with the z-direction beam perfectly aligned. This force is referred to as the vortex force. We will consider all beams as ideal Gaussians, such that the Rabi frequency for each one can be written as $R = \Omega_0 \exp(-r^2/2\,w^2)$ and we will analyze the force acting on an atom placed along the x-axis. The results obtained in this case can be extended to anywhere in the plane through a convenient rotation if the atom is close to the trap center such that the trap anisotropy can be neglected. The presence of the vortex force produces a rotation around the trap center. For the geometry considered here, the velocity is mainly in y-direction and the total force acting on the atom is

$$\vec{f} = -Kx\hat{x} - \alpha v\hat{y} + F(x)\hat{y} \; , \qquad (4)$$

where

$$F(x) = \frac{b e^{-x^2+2xs}}{1 + 2b e^{-x^2+2xs}} - \frac{b e^{-x^2-2xs}}{1 + 2b e^{-x^2-2xs}} \; , \qquad (5)$$

with $b = \Omega_0^2 \exp(-s^2)/(1+4\Delta^2)$, is the vortex force arising from the misalignment of the Gaussian laser beams. An atom in this configuration is accelerated by the vortex force until its velocity becomes large enough such that the vortex force is balanced by the damping force. The energy removed by the damping is replaced by the work of the vortex force and in this situation we may have an stable circular trajectory. The stability condition requires that $\alpha v = F(x)$ and $mv^2/x = Kx$, and by combining these two equations one finds

$$\alpha\sqrt{\frac{K}{m}}x = F(x) \; . \qquad (6)$$

The term in the left-hand side, called "the effective trapping force"! has the effect of pulling the atom towards the trap center while the vortex force pushes the atom far from the origin. The solution of Eq. (6), with $F(x)$ given in Eq. (5) gives rise to three possible structures: ball of atoms, ring and ring with core [5].

III. Observation of different spatial distributions of atoms in a MOT

When the laser beams are well aligned and crossing at the point $B = 0$, we always observe a spherical cloud of atoms with a diameter of less than to 1 mm at the trap center, for all detunings where the trap works. When the small misalignment shown in Fig. 1a is introduced to the beams contained in the xy plane, different spatial structures are observed. At a high field gradient and/or small misalignment (s $\approx$ 0.2w) we obtain a slightly distorted cloud of atoms close to the origin. However, as the misalignment increases, different structures are obtained depending on the detuning, laser intensity and field gradient. For large detunings ($|\Delta| \sim 2\Gamma$), moderate field gradients and laser intensities, we found that for beam displacements between 0.5 w and 2 w, the atoms are distributed in a ring-shaped structure, as the one shown in Fig. 1b. Decreasing the detuning and increasing the laser power produces

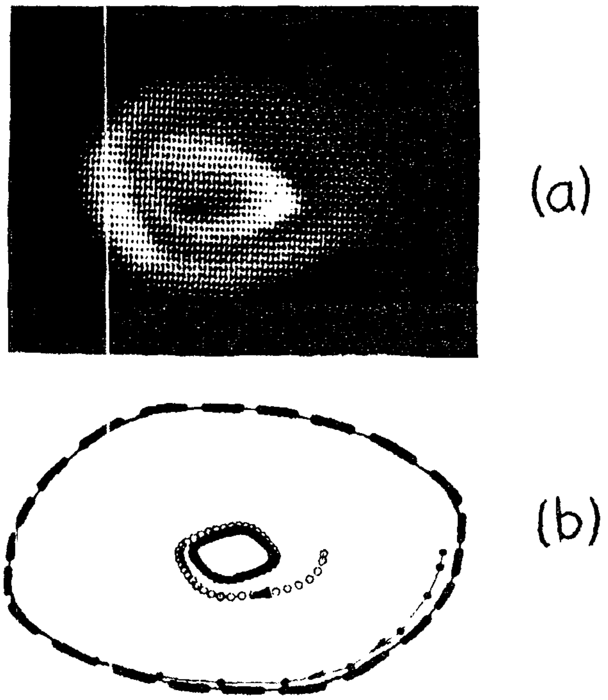

Figure 2: (a) Double ring distribution occuring due to the spatial dependence of K and α. (b) Computer simulated trajectory for this configuration.

a ring with a central core of atom. All these structures are predicted by Eq. (6), where K and α were assumed to be independent of r. However, when the ring radius increases, the trap anisotropy and the spatial dependence of K and α becomes important. In this case. we observe the double ring pattern shown in Fig. 2a. A computer simulated trajectory with the following parameters: $\Omega_0 = 13\Gamma$, $\Delta = -25\Gamma$, $s = 2.6$w and $d\omega/dx = 1\Gamma$/cm (Fig.2b) using the exact expressions for K and α from Eqs. (2) and (3) and including the spatial dependence of the Rabi frequency supports well this experimental result.

A few other interesting spatial distributions, not described by Eq. (6), can also be obtained. In the anti-vortex configuration the two laser beams parallel to the x-axis are exchanged such that the previous race-track configuration is destroyed. We then have a double-well potential which gives rise to the distribution shown in Fig.3a, made of two almost spherical clouds. This structure is fully described in ref. [9]. Another way of achieving different spatial distributions of atoms is through the change of the transverse profile of the trapping laser beams. The V-like structure shown in Fig. 3b

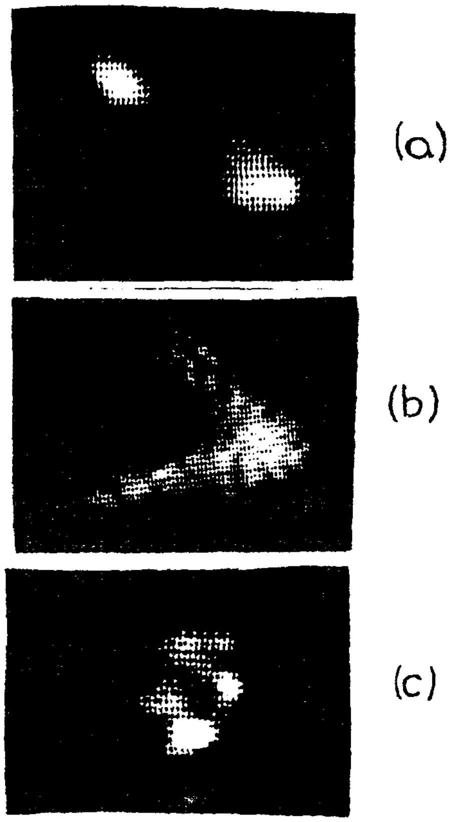

Figure 3: Distributions obtained with special experimental conditions. See text for details.

is obtained whenever a thin wire blocks the central part of one of the laser beams. One could also use one or two of the trapping laser beams with a TEM_{10} transverse mode to achieve other types of spatial configurations. Finally, just by playing with the misalignment, one can obtain a great variety of structures such as the one shown in Fig. 3c.

IV. Spatial distributions in atomic beams

The spatial distributions presented in the previous section could also be obtained in atomic beams. For this purpose the spheroidal magnetic quadrupole has to be replaced by a two-dimensional quadrupole whose $B = 0$ axis coincides with the atomic beam. Besides, instead of using six TEM_{00} Gaussian laser beams, one has to use four elliptic beams impinging perpendicularly to the atomic beam, which runs inside a pyrex tube. This two-dimensional configuration of laser beams and magnetic field will produce a transverse cooling, which gives rise to an atomic collimation and the desired transverse spatial distribution[10]. This distribution could be deposited on a cold substrate, either by reducing its size with a laser lens or combining it with the distribution generated by a S.W. The pattern obtained in this way may be of technological importance in the field of neutral-atom lithography. Experiments on this subject are being prepared in our laboratory.

Finally, we would like to address the problem of a possible chromatic aberration associated with the finite atomic energy spread. Since the longitudinal velocity of the atomic beam follows a Maxwell-Boltzmann distribution, each velocity class will take a different time to transverse the interaction region. As soon as the atom gets into the interaction region, there is a transient motion, with a time characterized by the inverse of the damping constant a, until it finally follows a helix-like path (in the case of a ring-shaped transverse distribution). In order to avoid chromatic aberration, the interaction region has to be long enough such that the fastest atoms have enough time to go to the steady state motion. In sodium, this condition can be easily fulfilled for an interaction length of a few centimeter.

V. Conclusions

In conclusion, we have observed a great number of spatial distributions of cold atoms in a MOT. We discussed the possible extension of this technique to an effusive atomic beam, which would acquire a specific transverse distribution after crossing a magneto-optical interaction region. After some extra manipulation with laser lenses, the beam could be deposited on a cold substrate and the morphology of the thin film would be the same of that impressed in the beam. This may have important technological applications in lithography.

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