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Time of flight technique to determine temperature of atoms in a ring-shaped trap

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Abstract

Spatial ring-shaped distribution of atoms in magneto-optical traps can be produced when the Gaussian laser beams used in the trap are misaligned as in a race-track geometry. We use a new version of the time of flight technique to determine the temperature and velocity distribution of the atoms in the ring. We found results which are consistent with the Doppler theory of laser cooling.

1. Introduction

Trapping and cooling of neutral atoms is a rapidly growing field of activity within atomic and optical physics. An especially intense effort has been developed to use light pressure techniques to obtain atomic spatial distribution for applications in atomic light pressure lithography [1,2].

Experiments carried out recently have demonstrated that different distributions of atoms, such as stable rings, are possible in magneto-optical traps (MOT) [3,4]. Investigations on the origin of such structures have revealed that for a small number of atoms ($N < 10^7$) the stabilization of the atomic orbit is achieved due to a coordinate-dependent macroscopic vortex force which arises from the misalignment of the Gaussian laser beams that constitute the trap. For larger number of atoms ($N > 10^8$) the orbit stabilization has contribution from the vortex force and from the atom–atom repulsion coming from multiple photon scattering from the atoms [3,5]. The temperature measurement of the ring-shaped trap is an important parameter to be investigated since this distribution originates from a different beam configuration when compared to conventional MOTs. In the ring, atoms behave like an atomic beam in circular motion. The standard time of flight techniques can not be applied in this case because the interruption of the trapping force causes modifications in the distribution, i.e., the atoms fly in all directions contained in the ring plane due to their circular motion. In this paper we present a variant of the time of flight measurement to obtain the temperature and velocity distribution for atoms in the ring. We start by describing the experimental setup and the beams configuration to obtain a ring-shaped trap. Next we present the devised time of flight technique, the results obtained and a discussion about them.

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2. Experimental setup and the attainment of a ring-shaped atomic distribution

The apparatus for this experiment consists of a MOT which captures sodium atoms from a vapor in a cell held at 50°C [6,7]. The cell is a stainless steel chamber with 12 entrances used as windows for trapping beams, for observation and also as ports for vacuum pumps. The background pressure is kept below 10^{-9} Torr. Three orthogonal retro-reflected Gaussian laser beams of about 1 cm in diameter and carrying opposite circular polarizations intercept in region with a magnetic field produced by a pair of anti-Helmholtz coils, which generate an axial field gradient of 15 G/cm and a transverse field gradient of 7.5 G/cm, for a current of 15 A. The laser beam, provided by a cw ring-dye laser, is tuned to about -10 MHz of the transition $3S_{1/2}$ $(F=1) \rightarrow$ $3P_{3/2}$ $(F=1)$ (Type II trap as described in Ref. [7]) and carries a 1712 MHz frequency sideband resonant with the $3S_{1/2}$ $(F=2) \rightarrow 3P_{3/2}$ $(F=2)$ transition, which works as a repumper to prevent depletion in the $F=1$ ground state population. The sideband is produced by a home-made electro-optical modulator. Before the splitting in the three directions, the trap and the repumper have almost 100 mW/cm^2 each. The determination of the number of atoms in the trap is done by imaging the fluorescence of the trapped atoms in a calibrated photo-multiplier tube. The calibration is achieved by measuring the signal produced by an attenuated laser beam with a well-known power. Once the solid angle and the photon scattering rate are known, the number of atoms can be determined through the measurement of the fluorescence intensity.

When all laser beams are well aligned with respect to the retro-reflection and crossing at the zero of the magnetic field, we observe a bright ball of atoms at the center of the trap. Under such conditions the spatial atomic distribution is close to spherical. When the laser beams are slightly misaligned as shown in Fig. 1a, different spatial distributions, mainly contained in the xy-plane, are observed [4]. The displacement ($s \sim 1$ to 2 mm) is usually much smaller than the waist of the Gaussian beams ($w \sim 6$ mm). The most common distribution is a ring, as shown in Fig. 1b. This is the result of a new manifestation of the radiative force, here referred to as a coordinate-dependent vortex force. As a brief description of this force, if Gaussian laser beams are used, the configuration in Fig. 1a produces a total

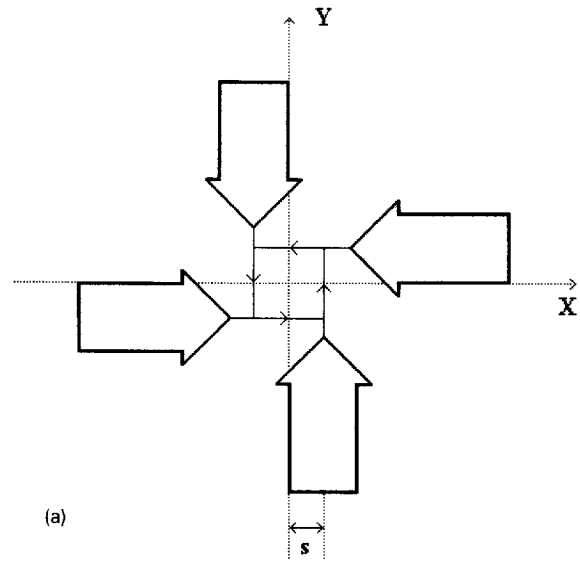



Fig. 1. (a) Geometrical distribution of the trap laser beams to produce a ring-shaped distribution. The misalignment is usually the same for all beams and forms a race-track configuration in the plane. (b) A typical picture of the ring-shaped distribution of atoms in the trap. The radius is on the order of 1 mm for conditions as described in the text.

force acting on the atom located in the xy-plane given by

$$F = -Kr - \alpha r + \zeta(x, y)\ (yx - xy)\ , \qquad (1)$$

where K is the trap spring constant, α is the damping constant and $\zeta(x,y)$ $(yx-xy)$ is the vortex force arising from the misalignment of the Gaussian laser beams, in

a way to form a race-track around $B = 0$. A full deduction of Eq. (1) is provided in Ref. [4]. An atom under the action of this force is accelerated until its velocity becomes large enough so that the vortex force is balanced by the damping. This situation may produce a stable circular trajectory for the atoms. The stability of such orbit has already been analyzed in Ref. [4].

Investigations about the dependence of the ring-shaped distribution on the parameters involved in the experiment (misalignment of the beams, magnetic field gradient, laser detuning and intensity) show good agreement with the model based on the vortex force described here [5].

3. Time of flight technique to measure the atomic temperature of the ring-shaped trap

Once we have the ring distribution, one of the important properties to be measured is the temperature. The most used techniques for this purpose, in the case of conventional traps are: time of flight and trap-size measurements. The time of flight technique can be applied in at least two ways. In the first way [8] atoms confined are released by suddenly turning off the laser beams and magnetic field. The atoms then fly ballistically to a laser probe located a few centimeters below the confinement center. The atoms are detected by the fluorescence as they travel through the probe beam. The observed fluorescence as a function of time permits to obtain the initial velocity distribution and hence the temperature of the atoms. Variations of the height and width of the probe beam allow good confirmation of the measurements. In a second variant of this technique, after turning off the confinement, the atomic cloud is observed as its expansion takes place, by using instantaneous pulses of light [9]. Instead of pulses of light, one can also turn on the confinement again after a delay to observe the amount of atoms recaptured [10]. The recaptured fraction as a function of the waiting time interval provides information about the atomic temperature.

On the other hand, several groups have measured temperature through the use of the equipartition energy principle, i.e., $\frac{1}{2}Kr_0^2 = \frac{3}{2}K_BT$, where K_B is the Boltzmann constant and r_0 the trap radius. Once K and r_0 are known, the temperature T can be determined.

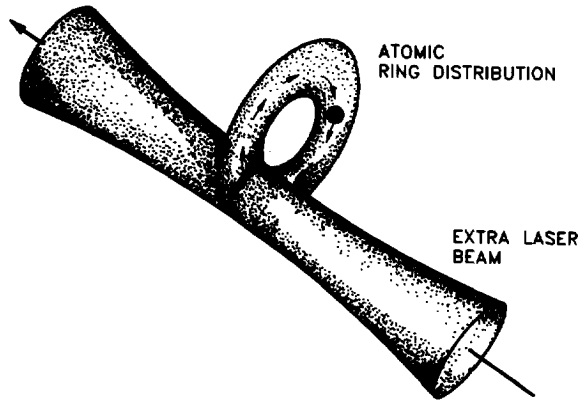

Fig. 2. Schematic representation on the intersection of the extra laser with the ring distribution. The beam diameter is close to the width of the ring.

For the case of the ring-shaped trap, none of the variants described above is convenient because of the tangential velocity of the atoms in the ring. Interruption of the laser beams and/or magnetic field destroys the distribution in the ring. We have devised a new way of applying the time of flight technique in this case.

Consider the ring with the addition of an extra laser beam resonant with the atoms and crossing it as shown in Fig. 2. If this extra laser beam is strong enough, it can remove atoms from the ring as they pass through it. The extra laser is chosen to have the same size as the ring width. With the extra laser switched off, the ring-shaped trap reaches a steady state regime. At $t = 0$ the extra laser is turned on by using an acoust-optical modulator or an electro-mechanical shutter. In both cases, the raising time is below 1 ms. As soon as the extra laser is turned on, atoms from the ring start to escape out of the trap. In order to estimate the acquired velocity during the interaction atom–extra laser, consider the average longitudinal atomic velocity in the ring as 5 cm/s and the spot size of the extra laser as 0.5 mm. The interaction time is about 10 ms. Since the extra laser is well above saturation, the number of scattered photons during the interaction can be as high as 10^5. Since each photon is able to transfer about 3 cm/s to the atom, the velocity acquired by it will be well above 50 m/s, i.e., high enough to remove the atom out of the trap in a single passage. In this case, the interaction of the extra laser with the ring creates a leak such that each atom passing through it leaves the ring. Fast atoms will escape before slow ones and by following the decrease

of the number with time ($t>0$) one can obtain the velocity distribution as shown below.

Let us consider $f(v)$ as the tangential velocity distribution in the ring. For a specific velocity class $[v, v+\mathrm{d}v]$, the variation in the number of atoms during a time interval $\mathrm{d}t$ is:

$$N(t)-N(t+\mathrm{d}t)=v\ \mathrm{d}t\ (N_0/L)f(v)\ \mathrm{d}v\,, \tag{2}$$

where N_0 is the total number of atoms at $t=0$ ($\int_0^\infty f(v)\ \mathrm{d}v=1$) and $L=2\pi r$ is the length of the ring (r=average radius). Therefore the decay rate in the number of atoms for this specific velocity class is:

$$\left(\frac{\mathrm{d}N}{\mathrm{d}t}\right)=-v\left(\frac{N_0}{L}\right)f(v)\ \mathrm{d}v\,. \tag{3}$$

The rate given in Eq. (3) holds up to $t=L/v$, after which all the atoms in this velocity class have already left and their contributions goes to zero. Therefore, the decay rate for atoms with velocities within the interval $[v, v+\mathrm{d}v]$ must be written as:

$$\left(\frac{\mathrm{d}N}{\mathrm{d}t}\right)_v=-v\,\frac{N_0}{L}f(v)\ \mathrm{d}v\left[1-\Theta\left(t-\frac{L}{v}\right)\right], \tag{4}$$

where $\Theta(t)$ is the well known step function [11].

The total decay rate of the number of atoms in the ring (contribution from all velocity classes) is obtained after integration of Eq. (4),

$$\left(\frac{\mathrm{d}N}{\mathrm{d}t}\right)_{\text{total}}=-\frac{N_0}{L}\int_0^\infty v f(v)\left[1-\Theta\left(t-\frac{L}{v}\right)\right]\mathrm{d}v \tag{5}$$

and the time integration of Eq. (5) allows us to obtain $N(t)$ as the ring is emptied. The results contain information about the velocity distribution of atoms and hence about their kinetic temperature. Fig. 3 shows the experimental data for the decrease in the number of atoms and the best fitting obtained through the time integration of Eq. (5). The results show that the data is consistent with a unidirectional (as if the atoms were in an atomic beam) Maxwell–Boltzmann distribution with temperature 230 ± 20 μK.

An important fact to be underlined is that if the extra laser beam does not cross the ring as in Fig. 2, rather, if it is not completely overlapping with the ring, the decay time (1/e) for the number is longer because in this case atoms can undergo a few round trips before extraction by the extra laser. This could result in a longer decay time and hence in a temperature lower than the actual value. To avoid this problem, we scan the position of the extra laser with respect to the ring by measuring the decay (1/e) time of the spectrum.

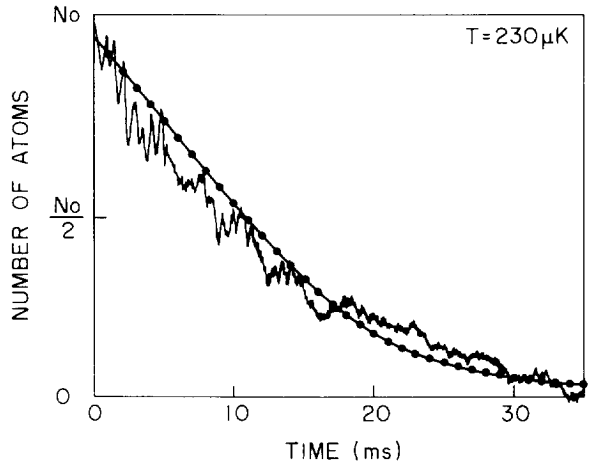

Fig. 3. Decay of the number of trapped atoms as a function of time after the extra laser is turned on. The smooth dotted line is the best fitting using a unidirectional Maxwell–Boltzmann distribution (as if the atoms were in an atomic beam) with $T=230$ μK. Uncertainty of about 20 μK arises from the measurement of the ring dimensions and fluctuations in the data.

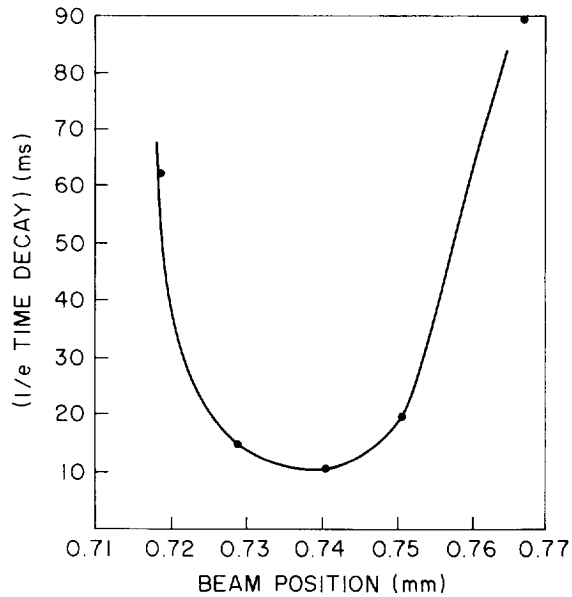

Fig. 4. Decay (1/e) time of the number of atoms for different positions of the extra laser. The minimum time corresponds to a complete overlap ring-beam. The time increases as the extra laser beam is closer or farther to the ring center.

The result is presented in Fig. 4. Here, x is the distance from the center of the ring to the center of the extra laser beam. The position where the decay time is minimum corresponds to the desired situation where the ring and the laser beam completely overlaps as in Fig. 2. This must be the position where the measurement is made.

4. Final remarks and conclusions

The temperature measured in remarkably close to the well known Doppler cooling limit [12] and this may be a consequence of the fact that in the ring-shaped trap the laser beams are well misaligned and this prevents the formation of standing waves, polarization gradient configurations and keeps the atoms in a finite magnetic field such that sub-Doppler cooling mechanisms [13] cannot take place. This result is also considered a strong support to the model employing Doppler theory which we have used to explain rings [4,5] and double traps [14] distributions in MOTs. We are now preparing an experiment to investigate variations of the atomic temperature in the ring-shaped trap for situations where heating will be deliberately introduced by intensity imbalance of the trap beams. We are also considering the possibility of applying the ring shaped trap to study atomic cold collisions, where the collision temperature could be varied.

Acknowledgements

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