STUDY OF LASER DECELERATION OF AN ATOMIC BEAM BY MONITORING THE FLUORESCENCE ALONG THE DECELERATION PATH

V.S. BAGNATO, A. ASPECT [1] and S.C. ZILIO

Departamento de Fisica e Ciencia dos Materiais, Istituto de Fisica e Quimica de Sao Carlos, Universidade de Sao Paulo, Caixa Postal 369, 13560 Sao Carlos, SP Brazil

Received 16 February 1989

We present a technique to study the laser deceleration of an atomic beam by monitoring the fluorescence along the deceleration path. Since the same laser is used to decelerate and observe the resulting slow atoms, the fluorescence signal is simply related to the number of atoms captured in the deceleration process, allowing a direct study of this process. The experimental data are in good agreement with the theoretical analysis, supporting the validity of the method.

1. Introduction

In the past few years, the problem of controlling the motion of atoms with laser light has attracted a great deal of attention. A series of successful experiments concerning the deceleration [1–3], cooling [4,5], trapping [6–8] and diffraction [9] of neutral atoms has been of fundamental importance in demonstrating the feasibility of light manipulation of atoms. These techniques have proven to be quite powerful for the production of samples of stopped atoms at low temperature where new effects can be studied [10,11].

Another possible very important application of these techniques is the production of intense beams of slow atoms, that might be useful in fields such as atomic clocks, collisions and surface studies, atomic micro probes. In that perspective, the Zeeman tuning laser slowing technique [2] is specially appealing, since it is able to yield a constant intensity slow beam (contrarily to the chirping method [3] that produces pulses of slow atoms). However, in spite of its successful use for loading traps or molasses [6,8,10,11], the Zeeman tuning technique has not yet allowed to produce very intense slow beams out of the slowing magnet. The major difficulty seems to be that transverse magnetic field gradients affect the motion of slow atoms and entail an "explosion" of the beam. Another crucial point is the focussing of the slowing laser beam in order to minimize transverse escape of the atoms during the deceleration process.

The optimization of these various parameters would be facilitated by experimental studies of the decelerating process itself along the deceleration path. In this paper, we show that monitoring the fluorescence light of the atoms along the decelerating path [#1] is a simple and direct method for studying the slowing of atoms in a tapered magnetic field. Since only one laser beam (the decelerating laser) is used, the fluorescence is due to the decelerating process itself, and the observed signal at a given point is proportional to the number of atoms participating to the decelerating process at this point. We show in section 2 that the coefficient of proportionality does not depend on the laser intensity, which is an important feature of this method. We have applied this method to the study of the deceleration of a sodium beam inside a tapered magnet (sections 3 and 4).

[1] Permanent address: Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris.

[#1] A similar procedure to observe the deceleration of an atomic beam has also been used at MIT. See ref. [12].

2. Description of the method

Laser deceleration of an atomic beam relies on the so-called radiation pressure force exerted on the atoms by a counterpropagating laser beam

$$\mathcal{F}_1 = \mathcal{N}\hbar\boldsymbol{k}, \tag{1}$$

where $\mathcal{N}$ is the rate of absorbed photons, and $\boldsymbol{k}$ the wave-vector of laser photons (spontaneous emissions give a zero force, on the average). The process may be very efficient, provided that each atom keeps interacting resonantly with the laser during the deceleration process. In order to maintain the resonance condition, one must compensate for the change in the Doppler shift.

Zeeman tuning [2] allows to deal with the Doppler shift problem. In this method, a tapered magnetic field

$$B(z) = B_0\,(1 - z/z_0)^{1/2} \tag{2}$$

is used to maintain the atomic transition (ω_{At}) on resonance during the deceleration by a laser (ω_L) propagating along Oz, towards $z<0$. The dynamics of the deceleration process can easily be analyzed in a decelerated frame of reference $\mathcal{R}$ [#2] moving at a velocity (in the laboratory)

$$v = (B_0\mu/k)(1 - z/z_0)^{1/2}. \tag{3}$$

In this formula, $k = |\boldsymbol{k}|$ (wave-vector of the laser photons), and μ is the Zeeman constant of the atomic transition ($\mu = 2\pi \times 1.4$ MHz G^{-1} for a Landé factor equal to 1). Note that this frame of reference is uniformly decelerated, at an acceleration

$$a = -\frac{B_0^2\mu^2}{2k^2 z_0} = -\gamma\frac{\hbar k}{m}\frac{\Gamma}{2} \tag{4}$$

(γ is a convenient dimensionless expression of a).

Introducing the relative velocity v_r of an atom in $\mathcal{R}$, one finds a simple form for the detuning between the laser and the atomic transition (taking into account the Zeeman and the Doppler effects)

$$\delta = \omega_L - \omega_{At} + kv_r = \delta_0 + kv_r. \tag{5}$$

The equation of motion of the atom in $\mathcal{R}$ is then

$$m\frac{dv_r}{dt} = -\frac{\Gamma}{2}\left(\frac{s}{1+s} - \gamma\right), \tag{6}$$

with

$$s = \frac{\omega_1^2(z)/2}{\Gamma^2/4 + \delta^2}$$

($\omega_1(z)$ is the Rabi frequency related to the laser intensity at position z, and Γ is the natural linewidth of the atomic transition).

If $\omega_1(z)$ is constant, s only depends on v_r, and eq. (6) has two steady state solutions, obtained by solving

$$s = \gamma/(1-\gamma). \tag{7}$$

Solutions of eq. (7) exist provided that

$$\gamma < s_0/(1+s_0) \quad \text{with } s_0 = 2\omega_1^2/\Gamma^2. \tag{8}$$

Note that the condition (8) puts a limit on the magnetic field gradient (see eq. (4)). This limit depends on the laser power, but it is always smaller than the maximum value (corresponding to) $\gamma = 1$ [2,14]. By methods analogous to the ones used in the study of bistability [13], it is easy to show that only one solution is stable (the one corresponding to the smallest value of v_r) namely

$$kv_r^{(0)} = -\delta_0 - \frac{\Gamma}{2}\left(\frac{1-\gamma}{\gamma}s_0 - 1\right)^{1/2}. \tag{9}$$

Indeed the development of eq. (6) around $v_r^{(0)}$ yields

$$dv_r/dt = -(1/\tau_D)(v_r - v_r^{(0)}), \tag{10}$$

with

$$\frac{1}{\tau_D} = \frac{\hbar k^2}{m}\frac{s_0}{2}\gamma^2\left(s_0\frac{1-\gamma}{\gamma} - 1\right)^{1/2}. \tag{10'}$$

We thus find that atoms with a velocity v_r close to $v_r^{(0)}$ get rapidly locked at $v_r^{(0)}$ (the capture range is about Γ'/k where Γ' is the width of the power broadened lorentzian). The damping time τ_D assumes the value 12 μs in the case of sodium, for typical values $s_0 = 2$ and $\gamma = 0.5$. The corresponding distance of flight is 10 mm (for thermal atoms) or less (cooled atoms).

In the case where ω_1 depends on z, the previous results are still valid if the variation of ω_1 due to the

[#2] An analogous analysis is developed for the chirping deceleration method in ref. [13].

displacement of the atoms during τ_D is small – i.e. if the corresponding modification of $v_r^{(0)}$ is small compared to Γ'/k. This is usually the case in cooling experiments where the laser beams are only slightly focused (see section 3) [#3]

The important conclusion of this paragraph is that all the atoms which have been "captured" in the cooling process adjust their velocity to a value such that eq. (7) is verified at any point along the decelerating path. As a consequence, the rate of fluorescence of a captured atom

$$\mathcal{N}=\frac{\Gamma}{2}\frac{s}{1+s}=\gamma\frac{\Gamma}{2} \qquad (11)$$

is constant along the decelerating path, and the intensity of the fluorescence light at a given point is directly proportional to the density of captured atoms. Note in particular that the fluorescence rate per decelerated atom (11) does not depend on the laser intensity (provided that condition (8) is fulfilled). The quantity γ is completely determined by the field profile (eq. (4)) and it can be known from auxiliary measurements. The observation of the fluorescence light thus allows to analyze precisely the process of capture and losses along the decelerating magnet.

3. Experimental set-up

The apparatus is schematically shown in fig. 1. An effusive source, operating at about 500°C, produces a beam of sodium atoms. After leaving the oven, the beam passes through a skimmer and is collimated to approximately 10 mrad. About 40 cm downstream, the beam enters in a 130 cm long solenoid which has an axial magnetic field described by the equation

$$B(z)=B_b+B_0(1-z/z_0)^{1/2} \qquad (12)$$

in the interval [40 cm, 105 cm], with $z=0$ taken at the input of the solenoid, $z_0=120$ cm, and B_b and B_0 depending on the current ($B_b=277$ G and $B_0=1070$ G for the experiment described below). B_b is a bias magnetic field to avoid unwanted transitions by Zeeman shifting them out of resonance and making their matrix elements small [14]. This field is produced by a suitable configuration of layers of current carried by water cooled copper tubes ($I=36$ A for the values of the field reported here). Note that the field deviates from eq. (12) at the end of the solenoid.

The laser beam is provided by a ring dye laser (Coherent 699.21) pumped by an argon ion laser. The light is circularity polarized and tuned to a σ^+ transition from the $F=2$, $M_F=2$ sublevel of the $3S_{1/2}$ ground state to the $F=3$, $M_F=3$ sublevel of the $3P_{3/2}$ excited state. The selection rules for this transition are such that the atoms keep cycling only between these two states [14]. The cooling laser is enlarged, passed through a diaphragm to select the quasi constant intensity central region, and focused onto the nozzle of the atomic beam. At the entrance window (80 mW on a 2 cm diameter disk) the resonant saturation parameter s_0 (formula (8)) is about 4, and it is larger inside the chamber. With a parameter γ (eq. (4)) about 0.35 the condition (8) is easily fulfilled, which guarantees a good stability of the decelerating process against perturbations. The absolute value of the laser frequency is obtained by monitoring at the fluorescence produced by the reference beam crossing at right angle the atomic beam in a zero magnetic field region, which yields a marker at resonance.

A set of Si-photodiodes is located around the atomic beam which runs inside a glass tube concentric with the solenoid. The detector assembly can be moved along the whole extension of the magnetic field and collects the fluorescence light of the atoms during the deceleration process. Due to the symmetry of this detector, the collection efficiency is almost constant (as a function of the transverse coordinates) for atoms located close to the axis of the beam, i.e. in the interaction region.

4. Results and discussion

The fluorescence of the atoms is monitored along the deceleration path as a function of the detector position and of the laser frequency. Fig. 2 shows the fluorescence versus laser frequency at various positions. The laser sweep is slow enough (50 MHz s^{-1}) so that its frequency can be considered constant dur-

[#3] Note that if the laser intensity is not uniform in a z plane, $v_r^{(0)}$ depends on the transverse position of the atom. This point is crucial to evaluate the temperature of the atoms [15] but it does not change the conclusions of this paragraph.

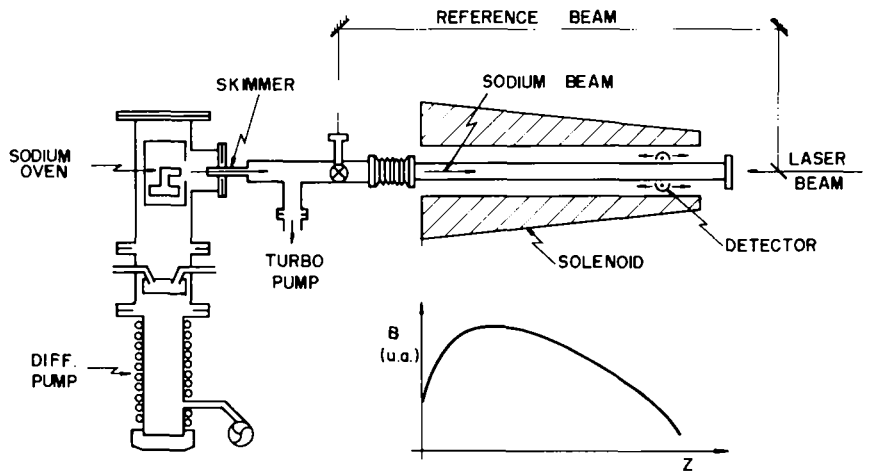

Fig. 1. Schematic diagram of the apparatus, with a plot of the measured magnetic field profile in the solenoid.

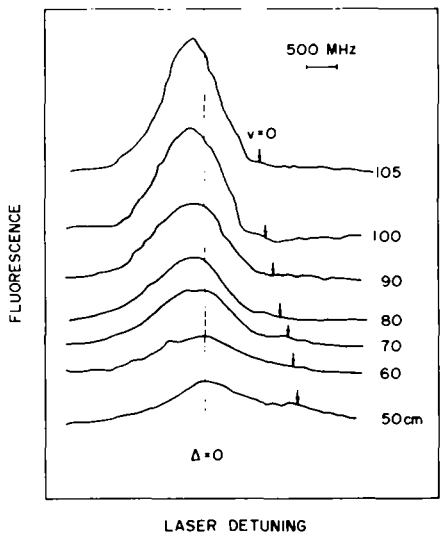

Fig. 2. Fluorescence intensity as a function of laser detuning for different positions of the detector. The marker $v=0$ indicates the resonant frequency for zero velocity atoms at each position. The $\Delta=0$ line corresponds to the atomic resonance at zero velocity and zero magnetic field (reference marker).

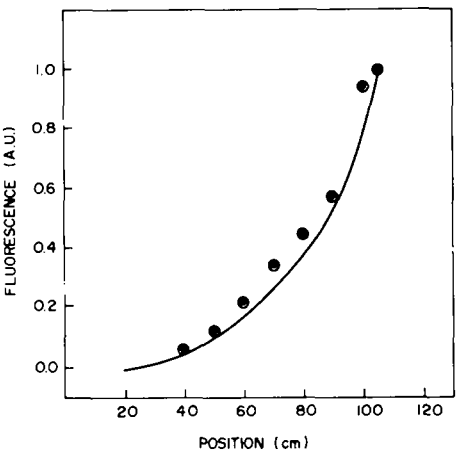

Fig. 3. Fluorescence intensity at $\Delta=0$ laser detuning, as a function of the detector position, with the background subtracted. The solid line is the result of the calculation (eq. (13)), with only one adjustable multiplicative constant.

ing a cooling process (less than 10 ms). On each scan we have indicated the frequency corresponding to resonance for zero velocity atoms. It has been determined by shifting the resonance marker of the reference beam by a quantity equal to the Zeeman effect calculated at this position. It is important to realize that these curves do not reflect directly the velocity distribution in a given situation. However, we show now that their interpretation is straight forward and yields important information.

According to the analysis of section 2, an atom is captured in the deceleration process at z if its velocity is $V_c(z)=v_r^{(0)}+\gamma' z$ (see eqs. (3) and (9)). The atoms participating to the deceleration process at z correspond to a range of initial velocities between $V_c(z)$ and $V_c(z_M)$, where $V_c(z_M)$ is the captured velocity at the maximum of the magnetic field. This range has thus a width depending on the position z, and it is shifted towards low velocities when

the laser frequency increases. The global increase of the signal when z increases is thus readily interpreted as a consequence of a wider range of captured velocities. On the other hand, the variation of the signal with the laser frequency at a given position reflects a change of the overlap of this captured velocities range and of the initial velocities distribution. There is also an increase when the velocity decreases, because the signal is proportional to the atomic density, which is inversely proportional to the velocity at a given flux.

To make this reasoning quantitative, we assume a maxwellian initial velocity distribution

$$\mathrm{d}\Phi/\mathrm{d}V = A\,V^3 \exp(-\beta V^2)$$

with

$$\beta = M/2k_B T,$$

and we calculate the total fluorescence of the captured atoms at point z. The calculation is quite simple in our case where the divergence of the atomic beam exactly matches the focusing of the laser, and neglecting the transverse heating of the atoms due to the cooling process. One finds

$$S(z) = S_0 \epsilon(z) \frac{V_c(z_M)}{V_c(z)} \times \{\exp[-\beta V_c^2(z)][1+\beta V_c^2(z)] - \exp[-\beta V_c^2(z_M)][1+\beta V_c^2(z_M)]\}, \quad (13)$$

with $\epsilon(z)$ a factor resulting from the averaging of the collection efficiency of the detector at position z over the interaction region. The result relies on the assumption that $V_c(z)$ varies very little in the region where the detection efficiency is not negligible. Due to the geometry of the detectors, it is also reasonable to assume that $\epsilon(z)$ is constant with z, since the transverse dimension of the interaction region remains small compared to the distance to detectors.

With these assumptions, we have plotted $S(z)$ with only one arbitrary multiplicative constant adjusted to fit best the experimental data. The good agreement between this curve and the experimental data shows that the main physical aspects have been taken into account, and that the approximations made here are reasonably well fulfilled. This agreement indicates that there are no noticeable losses in the explored region. For an imperfect circular polarization, the method allows to evaluate the losses. It would be very interesting to push the observation to the point where atoms are stopped (this was not possible here for mechanical reasons). It is clear that formula (13) fails at this point (the signal cannot be infinite), which means that it is no longer possible to neglect the transverse expansion of the beam due to heating and to the mismatch between the laser focusing and the atomic beam divergence.

5. Conclusion

We have tested a method allowing to follow the capture process along the deceleration path, without perturbing the deceleration process. Although it has been presented for a magnetic field following the law of eq. (2), the method can easily be generalized to different field profiles, provided that it is possible to write an equation similar to (6) with γ varying slowly (in a time scale given by τ_D, eq. (10)). One then just needs to know the exact profile of the field in order to extract information about the losses in the decelerating process. The analysis will be generalized by use of a similar change of frame of reference in order to transform to an equation where the methods used in bistability studies can be applied [13]. In this context, note that the effect of perturbations such as "ripples" of the magnetic field or such as the laser jitter are similar to the effect of noise on bistable systems [16].

Acknowledgement

This work has been supported by FAPESP, CNPq, FINEP and Secretaria de Ciencia e Tecnologia do Estado de Sao Paulo. The authors are grateful to Vladir Colussi and Euclydes Marega Jr. for their technical assistance, and to C. Salomon for very useful comments on the manuscript.

References

[1] S.V. Andreev, V.I. Balykin, V.S. Letokhov and V.G. Minogin, Pis'ma Zh, Eksp. Teor. Fiz. 34 (1981) 463 [JETP Lett. 34 (1981) 442];

V.I. Balykin, V.S. Letokhov and A.I. Sidorov, Optics Comm. 49 (1981) 248.
[2] W.D. Phillips and H. Metcalf, Phys. Rev. Lett. 48 (1982) 596;
J.V. Prodan, W. Phillips and H. Metcalf, Phys. Rev. Lett. 49 (1982) 1149.
[3] W. Ertmer, R. Blatt, J.L. Hall and M. Zhu, Phys. Rev. Lett. 54 (1985) 996.
[4] S. Chu, L. Hollberg, J.E. Bjorholm, A. Cable and A. Ashkin, Phys. Rev. Lett. 55 (1985) 48.
[5] A. Aspect, J. Dalibard, A. Heidmann, C. Salomon and C. Cohen-Tannoudji, Phys. Rev. Lett. 57 (1986) 1688.
[6] A. Migdall, J.V. Prodan, W. Phillips, T. Bergman and H. Metcalf, Phys. Rev. Lett. 54 (1985) 2596.
[7] S. Chu, J. Bjorkholm, A. Ashkin and A. Cable, Phys. Rev. Lett. 57 (1986) 314.
[8] V.S. Bagnato, G. Lafyatis, A. Martin, E. Raab and D. Pritchard, Phys. Rev. Lett. 58 (1987) 2194.
[9] P.L. Gould, G.A. Ruff and D. Pritchard, Phys. Rev. Lett. 56 (1986) 827;
P.J. Martin, B.G. Oldaker, A. Miklich and D. Pritchard, Phys. Rev. Lett. 60 (1988) 515.
[10] P.L. Gould, P.D. Lett, P.S. Julienne, W.D. Phillips, H.R. Thorsheim and J. Wiener, Phys. Rev. Lett. 60 (1988) 788.
[11] P.D. Lett, R.N. Watts, C. Westbrook, W.D. Phillips, P.L. Gould and H.J. Metcalf, Phys. Rev. 61 (1988) 169.
[12] G. Lafyatis, A. Martin, K. Helmerson and D. Pritchard, Phys. Rev. A, to be published.
[13] A. Aspect, R. Bonifacio, F. Casagrande and L.A. Lugiato, Europhys. Lett. 7 (1988) 499.
[14] W.D. Phillips, J.V. Prodan and H.J. Metcalf, J. Opt. Soc. Am. B2 (1985) 1751.
[15] C. Salomon and J. Dalibard, C.R. Acad. Sci. Paris, 306 I (1988) 1319.
[16] E. Arimondo, D. Dangoisse and L. Fronzoni, Europhys. Lett. 4 (1987) 287.