EUROPHYSICS LETTERS 1 February 1991

Europhys. Lett., 14 (3), pp. 231-236 (1991)

Laser Cooling below the Doppler Limit in a Magneto-Optical Trap.

A. M. STEANE and C. J. FOOT

Clarendon Laboratory - Oxford OX1 3PU, England

(received 7 September 1990; accepted in final form 16 November 1990)

PACS. 32.80 – Photon interactions with atoms.
PACS. 42.50 – Quantum optics.

Abstract. – We have measured the spring constant, friction parameter, and temperature of the motion of caesium atoms in a magneto-optical trap. The results are very different from those predicted by models based on the scattering force, which have been used up to now. We show that the behaviour can be understood in terms of the sub-Doppler cooling mechanisms which have been observed in molasses, involving atomic motion through a polarization gradient. These mechanisms can operate in a trap because the atoms congregate in a region of low magnetic field. The lowest temperature measured was $(30 \pm 15)\,\mu K$.

Laser cooling of atoms in optical molasses [1] has produced atoms which are much colder than the Doppler cooling limit. We report here the observation of similar ultracold temperatures ($< 10\,\mu K$) for caesium atoms in a magneto-optical trap (MOT), along with measurements of the other parameters of the trapping force.

The temperature at the Doppler cooling limit T_D ($120\,\mu K$ for Cs) is given by $k_B T_D = \hbar\gamma$, where k_B is Boltzmann's constant, $\hbar$ is Planck's constant and γ is the natural width (half-width half-maximum). Mechanisms which allow cooling below this limit rely on the spatial variation of the eigenstates of an atom in a standing-wave radiation field [2]. They are therefore strongly affected by a magnetic field which perturbs the levels more strongly than the radiation. These mechanisms can still work in a MOT, however, since when the intensity of the beams is balanced, the atoms are confined to a region close to the zero of the magnetic field. In this paper we show that the behaviour of atoms in our MOT is very different from that predicted by the original Doppler cooling model, but is in reasonable agreement with a description based on the sub-Doppler theory. We use a model based on one-dimensional theory, then relate the 3D case to this by use of a scaling factor, as in the study of molasses in ref. [3]. A recent paper [4], which concentrates on another feature of the trap, also implies that sub-Doppler temperatures are obtained in a MOT.

Our atom trap was formed by three orthogonal standing waves with the requisite circular polarizations, intersecting at the centre of two coils with opposing currents, as in the original MOT of Raab *et al.* [5]. The trap was loaded from a thermal atomic beam using a counterpropagating laser beam and a small additional Zeeman slowing coil, thus stopping atoms having velocities up to $50\,ms^{-1}$. If we define axes such that the laser beams which form the trap are along the $\pm O\,x, y, z$ directions, then the atomic beam is along the (1, 1, 0) direction and the stopping beam is in the opposite direction. The background pressure was less than 10^{-8} Torr, producing a trap lifetime longer than 0.7 s.

The seven laser beams were split off from the output of a higher-power semiconductor diode laser. This laser was line-narrowed by optical feedback from a confocal Fabry-Perot cavity and set to the required frequency, a few linewidths to the red of the $6S_{1/2}F=4 \rightarrow 6P_{3/2}F'=5$ transition, by means of Doppler-free saturation spectroscopy in a caesium cell. Good beam quality was obtained by sending the beam through a pinhole, with the trap in the far field diffraction region. A second laser, collinear with the first, was used to re-pump atoms from the lower hyperfine state. The alignment and polarizations of the six beams forming the trap, and the balance of intensities in each of the three standing waves, were all carefully adjusted so that the centre of the trapped cloud was within 0.06 G of the zero of the magnetic field. The trap region was imaged, with a resolution of 15 μm, on to a c.c.d. camera. With an additional video amplifier the sensitivity was sufficient to detect the fluorescence from a single atom.

The force on an atom may be written, to first approximation, $\boldsymbol{F} = -\kappa \boldsymbol{r} - \alpha \boldsymbol{v} + \boldsymbol{A}(t)$, so that κ is a spring constant, α a friction coefficient, and A depends on a diffusion constant D. In fact the trapping force is not central, and is twice as large in the vertical direction (along the symmetry axis of the coils), producing an elliptically shaped cloud of trapped atoms. This will not concern us here, however, since we will consider mainly the motion in a horizontal plane. If one ignores sub-Doppler cooling mechanisms, a rough value for α may be obtained from the one-dimensional theory of the $J=0 \rightarrow J=1$ case given by Dalibard *et al.* [6]. We will refer to this value as α_D. In the low-intensity limit, α_D tends to the result obtained by adding the radiation pressures of a pair of beams independently. Including the Zeeman effect, with a constant field gradient dB/dx, one obtains for the spring constant

$$\kappa_D(p) = \alpha_D \frac{p\mu_B}{\hbar k} \frac{dB}{dx}, \tag{1}$$

where $k = 2\pi/\lambda$, and p is a parameter describing the size of the Zeeman shift (Lande g-factor).

A more accurate approach, for a multilevel atom, is to solve the optical Bloch equations numerically. Raab *et al.* [5] did this for sodium (ignoring polarization gradient effects) to obtain the steady-state populations of the various Zeeman sublevels. The resulting value for α is $0.8\alpha_D$, at low intensity. The value they obtained for κ implies $p = 0.56$—this is approximately an average of the Zeeman effect of all the possible transitions between the various sublevels, weighted by the populations and transition probabilities—one would expect a value less than 1.

The theory described so far («Doppler theory») would be accurate in the absence of polarization gradients in the radiation field. However, in the MOT these gradients are significant since the light shifts, of order $8\gamma^2 I/(I_s \delta) = 5 \times 2\pi$ MHz are much greater than the Zeeman shifts for atoms in the trapped cloud, of order $\mu_B B/\hbar \simeq 0.1 \times 2\pi$ MHz. (For caesium, the saturation intensity $I_s = 2.2\,\text{mW}\,\text{cm}^{-2}$, and $\gamma = 2.6 \times 2\pi$ MHz. I is the intensity of each beam, and δ is the laser detuning. The field $B = B_0 + r\,dB/dx$, with $B_0 < 0.06$ G, cloud radius $r = 50\,\mu\text{m}$ when $dB/dx = 5\,\text{G}\,\text{cm}^{-1}$.) Therefore one expects sub-Doppler cooling, for which two mechanisms have been identified: motion-induced orientation in the σ^+-σ^- field, and a «Sisyphus» mechanism involving optical pumping to the state with the largest light shift [2]. In the latter case, adiabatic movement to other states will be due both to motion through the polarization gradient and to Larmor precession in the magnetic field [7]. The radiation field in the trap contains all types of polarization and also nodes and antinodes, so that both the cooling mechanisms will be present.

To allow for sub-Doppler cooling in the theory of the trap, we compare our measurements with values of α and temperature given by the calculations for 1D molasses [2, 7, 8]. We model the spring constant of the trap, κ, as follows. The effect of a magnetic field on orientation cooling in 1D is calculated simply by adding the real field to the fictitious field already present in the model for this case [2]. A population difference, proportional to the field, is produced in the ground-state Zeeman sublevels, along with the usual Zeeman shifts. We will consider two ground-state sublevels, writing their populations $\Pi_\pm = \{1/2 \pm \xi X\delta/(\delta^2 + \gamma_2)\}$, where $X = x(\mu_B/\hbar)\,\mathrm{d}B/\mathrm{d}x$, and ξ is a parameter which will express the size of the deviation from Doppler theory. This approximation is reasonable since for an $F = 4 \rightarrow F' = 5$ transition as in caesium, the optical pumping and the Clebsch-Gordan coefficients are such that most of the σ^+ photons are scattered from the $M_F = 4$ level, and most of the σ^- photons from the $M_F = -4$ level. The Zeeman effects of the two transitions involved are $g'M_{F'} - gM_F = \pm 1$. We will use the saturation parameter

$$s_\pm(I, X) = \frac{2I/I_s}{(\delta \mp X)^2/\gamma^2 + 1}, \tag{2}$$

where I is again the intensity of each beam. Then, for $s \ll 1$, the trapping force is $\hbar k\gamma(\Pi_+ s_+ - \Pi_- s_-)$, which, for small X, gives $\kappa = (1 + \xi)\kappa_D$ ($p = 1/2$). For large ξ, this reproduces the 1D sub-Doppler result for a $J = 1 \rightarrow 2$ transition (2, adapting eq. (5.14)) if

$$\xi = \frac{30}{17}\left(\frac{\delta^2 + \gamma^2}{\delta^2 + 5\gamma^2}\right)\frac{1}{s_0}, \tag{3}$$

where $s_0 = s_\pm(I, 0)$.

For the 3D case, the situation is more complicated since Sisyphus cooling can also cool towards a finite velocity when a magnetic field is present [7]. It is not clear what effect this may have for the geometry and polarizations obtaining in a trap.

In order to simplify the interpretation of our measurements, we concentrated on the simplest case of low laser intensities ($s_0 < 0.2$) and low atomic densities ($< 10^{10}\,\mathrm{cm}^{-3}$). We measured the spring constant of the trap by two (related) methods. First, the intensities of the vertical pair of laser beams were unbalanced and the resulting displacement of the trap centre was measured using the video camera. If the two beam intensities are I_1 and I_2, then the trap centre will be at the position given by $\Pi_- s_-(I_1, X) = \Pi_+ s_+(I_2, X)$, which gives, for small X, a displacement $(1 + \xi)$ times smaller than the Doppler theory result. At $I = 1.8 I_s$ and $\delta = 4\gamma$ the displacement *vs.* imbalance measurements implied $\xi = 3 \pm 0.5$. The trap is thus comparatively insensitive to intensity imbalance. Equation (3) gives $\xi = 6.7$ for the 1D case. The factor of 2.2 difference can probably be explained by the effects of optical pumping by the other beams. For a quantization axis along a given pair of beams, the other beams produce mostly π transitions and so will tend to reduce the atomic orientation.

More extensive measurements of κ were made by pushing the trap off-centre with a seventh laser beam. This pushing beam was the one already used for slowing atoms from the oven, it had an intensity half that of the trapping beams. We found that the cloud of atoms was pushed two or more times further away from the trap centre when the pushing beam was polarized σ^+ than when σ^-, where σ^- is the polarization suitable for a trapping beam if one were propagating in the pushing direction. This represents evidence for the field-induced orientation: when σ^+, the pushing beam is interacting mainly with the more populated ground-state sublevel and so exerts a stronger force. The orientation and optical pumping effects mean that it is difficult to calculate accurately the force exterted by the pushing beam (the force consistent with our model is $\hbar k\gamma\Pi_- s_-$). This may produce a systematic error in the measurements of κ. The problem could be avoided by switching the pushing and trapping beams on and off alternately. The cloud was pushed typically 0.3 mm when $dB/dx = 9\,G\,cm^{-1}$, it therefore remained in the low-field region in the trap. Our preliminary measurements, summarized in fig. 1, indicate that the spring constant is larger than that predicted by Doppler theory, and has a dependence on detuning nearer to that predicted by the sub-Doppler model. For $I = I_s$, the measured κ may be obtained by reducing ξ by a factor 6 ± 1 from the value given in (3). Our measurements appear to indicate that κ retains a dependence on intensity larger than is implied by (3), however. These differences are not surprising considering the approximations involved in using the 1D theory to describe the 3D case.

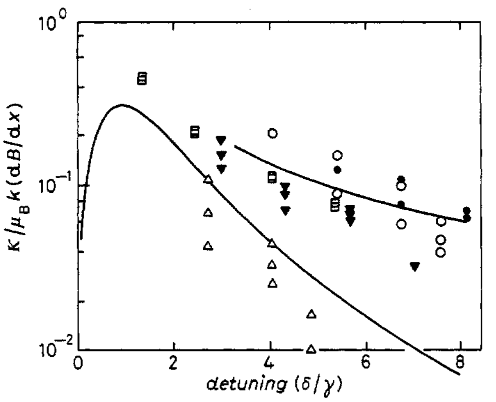

Fig. 1. – Pushing measurements, for $I/I_s = 1.77$ (●), 0.82 (▼), 0.73 (○), 0.5 (□), 0.11 (△). Lines are for $I/I_s = 1$: upper line using eq. (3) divided by 6 (*i.e.* scaled so as to fit our data); lower line is eq. (1) at $p = 1$ (*i.e.* the largest reasonable value for Doppler theory).

If the pushing beam is shut off suddenly (< 1 ms), the cloud of atoms will move back to the trap centre. We found this motion to be strongly overdamped, so that it follows an exponential decay with time constant α/κ. We measured the time constant by recording the motion on a video tape, at 50 frames per second. At $dB/dx = 5\,G\,cm^{-1}$, for example, the Doppler theory (1) predicts $\alpha/\kappa = 3.4$ ms, for $p = 0.5$. Our measured values, however, were in the region of 20 to 50 ms (fig. 2). Using our measured value for κ (fig. 1), this implies that the friction coefficient is up to 50 times larger than the Doppler result α_D, but agrees reasonably well with the predictions of orientation and Sisyphus cooling [2]. We have argued above that the orientation is reduced in 3D. The high α/κ therefore indicates that the friction is dominated by Sisyphus cooling.

Finally, we measured the radius of the trapped cloud, from its image on the video tape, in order to deduce its temperature, from $k_B T = \kappa\langle x^2\rangle$. The cloud had a Gaussian profile with typical radius $\sqrt{\langle x^2\rangle} = 50\,\mu m$. Using again the measured κ, our temperature measurements are summarized in fig. 3. We obtain the two main features of sub-Doppler cooling: a temperature going down with increasing detuning and with decreasing intensity. The temperatures are 6 ± 2 times larger than the 1D sub-Doppler theory, for a given intensity per beam, agreeing with more accurate measurements on pure molasses [3]. Here, we are using eq. (1) from [3], noting that although this equation is only strictly valid for $|\delta| \gg \gamma$, their measurements show that it is accurate for the parameter values obtaining at most of our data points. At the lowest intensities of the trapping beams, $0.25\,mW\,cm^{-2}$, the temperature no longer falls off with intensity. This may be evidence of the Zeeman shifts

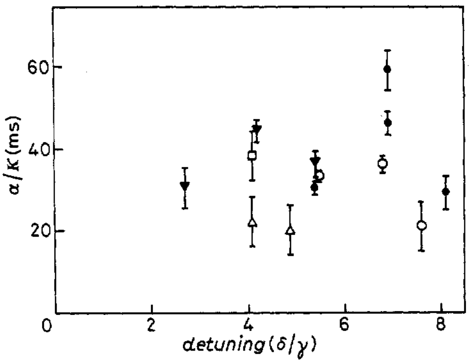

Fig. 2.

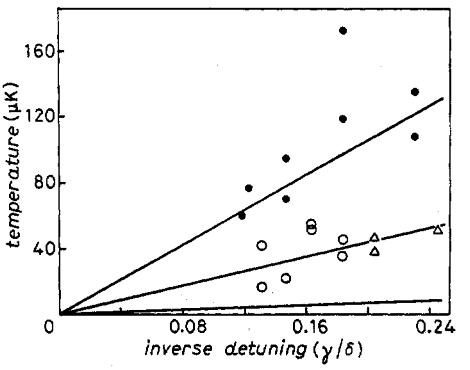

Fig. 3.

Fig. 2. – Measurements of β/κ at $dB/dx = 4.5$ G/cm, symbols as in fig. 1.

Fig. 3. – Temperature measurements. The lines give 6 times the 1D sub-Doppler theory for the values of intensity per beam $I/I_s = 1.77$ (●), 0.73 (○), 0.11 (△).

beginning to limit the cooling when the light shifts are small, or of collisional limitation of the cooling (see below). We have not yet made an independent measurement of the temperature by another technique such as time of flight. However, if the temperatures are actually higher than we estimate, then this would imply that κ is larger. Using our unambiguous measurement of σ/κ, this would imply that α is also large, so that clear evidence for sub-Doppler cooling is still obtained.

Since we obtain very low temperatures, some of the scatter in our results will be due to a further complication of the atomic motion, namely trapping of the atoms in the optical potential wells formed by the light field [4, 9]. This is the main subject of the work of Bigelow and Prentiss [4]. If an interference pattern were to create optical well large enough to contain the whole trapped cloud, then our measurements of the trap parameters would be significantly affected. We have seen structures in the fluorescence from the trap which are probably due to such interference patterns. For the present work, we aligned the trapping beams until there was no evidence of fringes as large as the cloud. This was checked by moving the zero of the magnetic field so as to move the cloud across the laser beams.

The first experiments on the MOT all reported temperatures consistent with the Doppler theory. This may be due to the fact that they concentrated on the regime of small detuning, where the temperature is comparable with the Doppler value. Also, our experiments involved unusually low numbers of trapped atoms (< 4000) in order to examine the low-density regime before moving to higher densities. The temperatures reported previously may have been higher than our results due to collisional effects which limit the cooling process [10]. We intend to investigate this possibility further.

To conclude, our experiments show that polarization gradient cooling is significant in the magneto-optical trap. We have described a first approach to modelling the behaviour, but a more accurate theory and further experiments are clearly needed. We have measured temperatures down to $(30 \pm 15)\,\mu$K [11], where the uncertainty is mainly from the measurement of the spring constant. Thus one can obtain temperatures below the Doppler cooling limit, along with the higher densities and longer confinement times possible in a trap.

* * *

We would like to acknowledge useful discussions with W. PHILLIPS, K. MOLNER, J. DALIBARD and C. SALOMON at the recent Les Houches summer school on quantum optics.

REFERENCES

[1] LETT P. D., PHILLIPS W. D., ROLSTON S. L., TANNER C. E., WATTS R. N. and WESTBROOK C. I., *J. Opt. Soc. Am. B*, **6** (1989) 2084.
[2] DALIBARD J. and COHEN-TANNOUDJI C., *J. Opt. Soc. Am. B*, **6** (1989) 2023.
[3] SALOMON C., DALIBARD J., PHILLIPS W. D., CLAIRON A. and GUELLATI S., *Europhys. Lett.*, **12** (1990) 683.
[4] BIGELOW N. P. and PRENTISS M. G., *Phys. Rev. Lett.*, **65** (1990) 29.
[5] RAAB E. L., PRENTISS M. G., CABLE A. E., CHU S. and PRITCHARD D. E. *Phys. Rev. Lett.*, **59** (1987) 2631. See also RAAB E. L., Ph.D. Thesis, MIT (1988) unpublished.
[6] DALIBARD J., REYNAUD S. and COHEN-TANNOUDJI C., *J. Phys. C*, **17** (1984) 4577.
[7] SHANG S.-Q., SHEEHY B., VAN DER STRATEN P. and METCALF H., *Phys. Rev. Lett.*, **65** (1990) 317.
[8] UNGAR P. J., WEISS D. S., RIIS E. and CHU S., *J. Opt. Soc. Am. B*, **6** (1989) 2058.
[9] WESTBROOK C. I., WATTS R. N., TANNER C. E., ROLSTON S. L., PHILLIPS W. D. and LETT P. D., *Phys. Rev. Lett.*, **65** (1990) 33.
[10] SMITH A. M. and BURNETT K., submitted to *J. Opt. Soc. Am. B*.
[11] We note, after consultation with the authors, that the 30 μK quoted on p. 1572 of MONROE C., SWANN W., ROBINSON H. and WIEMAN C., *Phys. Rev. Lett.*, **65** (1990) 1571, is a misprint and should read 300 μK.