RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 52, NUMBER 5 NOVEMBER 1995

Three-dimensional cooling of cesium atoms in four-beam gray optical molasses

D. Boiron, C. Triché, D. R. Meacher,* P. Verkerk, and G. Grynberg
Laboratoire Kastler Brossel, Département de Physique de l'Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris Cedex 05, France†
(Received 28 July 1995)

We report the observation of three-dimensional cooling of cesium atoms using a four-beam optical molasses tuned to the blue side of the $F_g=3 \rightarrow F_e=2$ hyperfine component of the $6S_{1/2} \rightarrow 6P_{3/2}$ transition. The cooling mechanism is a Sisyphus effect involving atomic states that are nearly uncoupled from the light field. Starting from a magneto-optical trap at 70 μK, the cooling time was on the order of 1 ms with almost 100% capture efficiency and temperature smaller than 5 μK measured. We also present a probe transmission spectrum showing that almost all the atoms are found in the nearly dark states.

PACS number(s): 32.80.Pj

One of the major problems in laser cooling is how to find methods to increase the density of atoms in phase space. The usual starting point of all experiments is the usual magneto-optical trap (MOT) [1]. For example, using cesium atoms, a MOT provides atoms at temperatures of the order of 50 μK with density on the order of $10^{11}-10^{12}$ atoms cm^{-3} [2]. Generally, a molasses phase on the same transition as the one used for the MOT [$6S_{1/2}(F_g=4) \rightarrow 6P_{3/2}(F_e=5)$ in the case of cesium] is employed to decrease the temperature. Indeed, temperatures as low as 2.5 μK were achieved by this method [3] at the expense of a reduced density in real space. In fact, photon-exchange and resonant dipole-dipole interactions between atoms cause limitations to atomic temperature and density [4]. A very clever method, the "dark spot," was recently proposed by Ketterle and co-workers [5] to overcome this limitation. This method makes use of a hole in the repumping light that usually brings back the atoms from the $F_g=3$ ground-state hyperfine sublevel to the $F_e=4$ hyperfine sublevel. As a result, atoms at the center of the MOT can accumulate in the $F_g=3$ sublevel, leading to density higher than 10^{12} cm^{-3} with 10^{10} atoms and with temperature on the order of 100 μK (these figures were achieved with sodium atoms). We present here another method that makes use of the dark states (also called uncoupled states) that exist on any $F \rightarrow F$ or $F \rightarrow F-1$ transition [6]. Once an atom is captured in such an uncoupled state, it almost does not interact with light, and this considerably reduces the atom-atom interaction. However, polarization gradient cooling occurs in these gray molasses only on the blue frequency side of the resonance [7]. Contrary to the usual case of "bright" molasses, which operate on the red side of the atomic resonance and give rise to Doppler and polarization gradient cooling mechanisms, these new molasses correspond to a situation of Doppler heating and polarization gradient cooling. Even if one-dimensional (1D) transverse cooling of an atomic beam has been observed on an $F \rightarrow F-1$ transition [8], the extension to the three-dimensional case is not obvious, particularly with respect to the final temperature and the efficiency of the capture rate. We present here the results of an experiment performed on the $F_g=3 \rightarrow F_e=2$ component of the $D2$ transition of atomic cesium. We show that the cooling can be very efficient, and report temperatures as low as (5 ± 2) μK. The cooling time is very short, its value being typically on the order of 1 ms, starting from atoms having an average temperature of 70 μK in the MOT. The capture rate is also excellent and under optimum conditions all the atoms of the MOT are captured by the gray molasses. We also show and explain the form of probe transmission spectra obtained in these molasses that shows that almost all the atoms are stacked in the uncoupled state that is associated with a flat optical potential. Contrary to the gray lattices [7,9], there is no localization of the atoms inside micrometer-size potential wells here.

We describe first the principle of the cooling mechanism for a transition for which there is a nearly dark state. We consider initially the one-dimensional case of an atom with a ground-state angular momentum $F_g>1$ interacting with two counterpropagating laser beams that give rise to a light field appropriate for polarization gradient cooling, such as the well known lin$\perp$lin configuration, where the two beams have linear orthogonal polarizations [10]. We assume that the frequency of the light is tuned to the blue side of an $F \rightarrow F$ or $F \rightarrow F-1$ resonance. In this case, there are one or two uncoupled states for which the corresponding optical potentials are independent of position and into which the atoms are optically pumped. However, motional coupling can cause the transfer of atomic population from an uncoupled to a coupled state. Because this coupling is most effective when the energy difference between the states involved is a minimum and because the coupled state has a space-dependent light shift (Fig. 1), a Sisyphus cooling mechanism can result, as has been described in [7,11]. The resulting cold molasses emits little fluorescence, hence the designation "gray or nearly dark molasses."

The generalization of the 1D configuration to three spatial dimensions can be performed by dividing the two beams of the 1D case into pairs of beams propagating in orthogonal planes [12,13]. In the present experiment we employ two different extensions of the 1D lin $\perp$ lin configuration. In the first, denoted $\perp$ in the following, the two beams propagating

*Present address: Clarendon Laboratory, Parks Road, Oxford OX1 3PU, England.

†Laboratoire de l'Ecole Normale Supérieure et de l'Université Pierre et Marie Curie associé au CNRS.

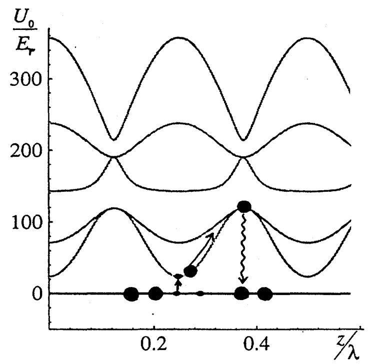

FIG. 1. Light shift potential energies for a 1D lin$\perp$lin configuration. The energy is plotted in units of the recoil energy $h^2/2m\lambda^2$ as a function of z/λ. The laser beams are tuned to the high-frequency side of an $F_g=3\rightarrow F_e=2$ transition. The two levels lowest in energy correspond to the nearly dark states and their light shifts are zero. The dots represent the atomic population of these levels. Atoms can be transferred to coupled levels with higher energies, by the motional coupling. Then they climb the potential hill before being optically pumped at the summit to an uncoupled state.

in the xOz plane are polarized along the Oy direction, whereas those propagating in the yOz plane are polarized along Ox. In the second case, denoted $\|$, each pair of beams has its polarization vectors in the plane of propagation (defined by the two wave vectors). These two configurations, studied in Secs. III B 1 and III B 2 of [13], give rise to a polarization gradient identical to the one obtained in the 1D case along lines parallel to Oz, but exhibit significant differences. In the $\perp$ configuration the light polarization is always perpendicular to Oz and therefore contains only σ^+ and σ^- photons. On the other hand, π photons are also present in the $\|$ configuration. Furthermore, there are lines parallel to Oz on which the electric field vanishes in the $\perp$ case, whereas there is π polarized light in the $\|$ case. π photons appear in the latter case also on the diagonal lines in the xOz plane on which the light has constant circular polarization in the $\perp$ configuration.

In the experiment, carried out on atomic cesium, the molasses beams are tuned to the blue side of the $F_g=3\rightarrow F_e=2$ hyperfine component of the $6S_{1/2}\rightarrow 6P_{3/2}$ transition. Note that the splitting between the $F_e=3$ and $F_e=2$ levels is 150 MHz. The blue detunings used in the experiment are in the range 10–40 MHz and remain small compared to the hyperfine splitting. However, a few atoms are pumped into the $F_g=4$ hyperfine sublevel. To avoid this optical pumping, an additional beam of intensity 0.4 mW/cm^2, nearly resonant with the $F_g=4\rightarrow F_e=4$ transition, is mixed with each of the molasses beams. The angles between the pairs of molasses beams are given by $2\theta_x=40°$ and $2\theta_y=50°$. The kinetic temperature of atoms along the Ox direction is measured using a time-of-flight method: two sheets of light, resonant respectively for the $F_g=4\rightarrow F_e=5$ and $F_g=3\rightarrow F_e=3$ transitions, cross each other 3 cm below the location of the molasses. The source of cold atoms is a magneto-optical trap, which produces atoms at a kinetic temperature of typically 70 μK. To load the gray molasses, the MOT magnetic and light fields are switched off and the four

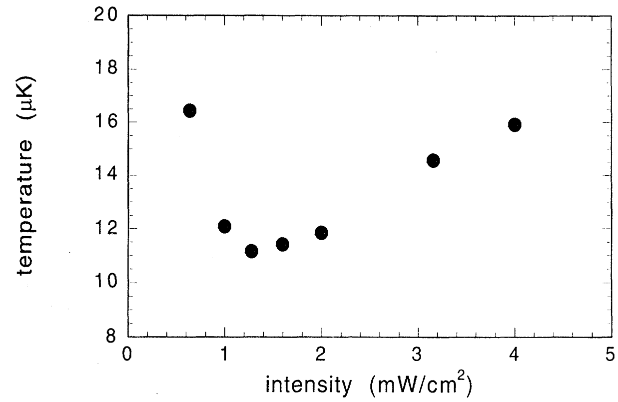

FIG. 2. Variation of the temperature of the atoms with the intensity of the gray molasses beams. The detuning from resonance is $\Delta=3\Gamma$. This figure was obtained for the $\perp$ configuration but that for the $\|$ configuration is similar.

molasses beams are simultaneously switched on. They remain illuminated for a time τ, after which they are extinguished and the temperature of the remaining atoms measured. The cooling in the gray molasses appears to be very efficient since a molasses phase of duration 1 ms suffices to decrease the temperature from 70 μK to one on the order of 10 μK. After this abrupt decrease the temperature remains practically constant. A typical variation of the final temperature of the atoms with the intensity of the gray molasses beams is shown in Fig. 2.

Using a molasses beam intensity of 1.5 mW/cm^2 per beam and a detuning of 5Γ, temperatures as low as (5 ± 2) μK were measured in these gray molasses after elimination of stray magnetic fields. We believe that this temperature is not a limit but is mainly due to experimental imperfections [14]. No systematic difference was found between the $\perp$ and $\|$ configurations. The time-of-flight signal was also used to give a measure of the number of atoms in the molasses and the proportion of atoms in each hyperfine sublevel. First, the

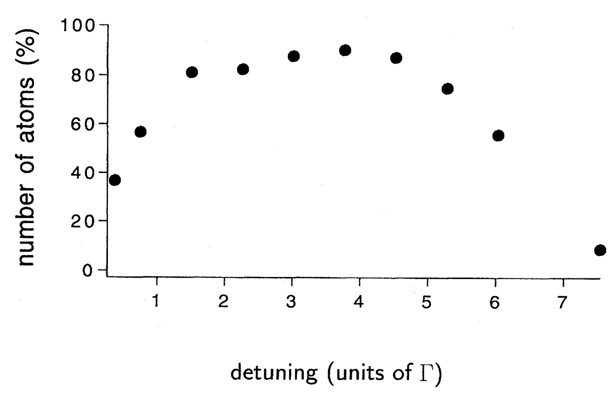

FIG. 3. Variation of the number of atoms captured from the MOT in the gray molasses with the detuning from resonance Δ $(\Delta=\omega-\omega_0)$. The molasses beam intensity was $I=2$ mW/cm^2 per beam. For this recording the maximum capture efficiency is 90%. This figure was obtained for the $\perp$ configuration but that for the $\|$ configuration is similar.

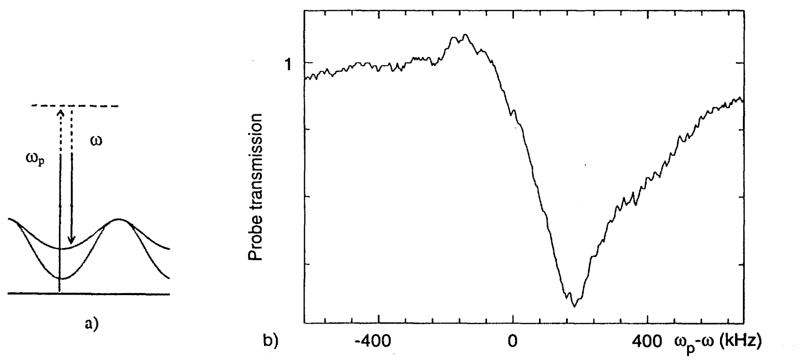

FIG. 4. (a) Scheme of the stimulated Raman process with absorption of a photon from the probe. (b) Transmission spectrum of a probe linearly polarized along Ox of intensity 0.2 mW/cm^2 with $\Delta=5\Gamma$; the molasses intensity is $I=2$ mW/cm^2 per beam. The spectrum exhibits a broad resonance in absorption due to transitions from an uncoupled to a coupled state. The position 1 on the vertical axis corresponds to 100% transmission. The maximum absorption is on the order of 5%. This spectrum was obtained for the $\perp$ configuration but that for the $\parallel$ configuration is similar.

lifetime of the molasses, on the order of 500 ms, was similar to those observed in bright molasses and lattices under the same conditions [12] and was probably limited by collisions with the background gas. Second, from the comparison of the areas of the time-of-flight signals obtained by releasing atoms from the molasses or directly from the MOT, it was deduced that the number of atoms in each was similar. This demonstrates the excellent capture efficiency of the gray molasses for atoms having kinetic temperatures of less than 100 μK. A more detailed study (see Fig. 3) showed that the capture efficiency was maximum for a detuning from resonance of the molasses waves, $\Delta=4\Gamma$ ($\Delta=\omega-\omega_0$, where ω_0 is the resonance frequency, ω the frequency of the molasses beams, and Γ the natural width of the $6P_{3/2}$ state). For $\Delta=8\Gamma$ the proportion of captured atoms had decreased by a factor of 10. When the molasses field was tuned to the red side of the resonance where one has Doppler cooling and Sisyphus heating, there was no evidence for the formation of a molasses. In the absence of the MOT, we also observed no evidence of the direct formation of a molasses. By switching off the $F_g=3\rightarrow F_e=3$ repumping light mixed with the time-of-flight probe beam, we were able to obtain an estimate of the relative populations of the $F_g=3$ and $F_g=4$ hyperfine sublevels. Surprisingly it was found that the two populations were similar and that the temperatures of the two classes of atoms were approximately equal. This observation might be associated with the existence of another uncoupled state of the $F_g=4\rightarrow F_e=4$ transition which prevents atoms falling in this state from being rapidly pumped to the $F_g=3$ sublevel. Finally, we want to emphasize that, contrary to what is found with bright molasses, the fluorescence from the gray molasses is so weak that its direct observation on a charge-coupled-device camera was not possible. We have not made a quantitative estimate of the reduction factor, but its value is at least 100. As a consequence, the adjustment of the molasses beams was made by an indirect (and destructive) method, i.e., by optimizing the time-of-flight signal.

We now describe the transmission spectrum that is obtained for a weak probe beam that traverses the trapped atoms in the Oz direction when its frequency ω_p is tuned around that, ω, of the molasses waves. This spectrum, which is shown in Fig. 4(b), consists predominantly of a resonance in absorption for the probe, the form of which we now explain. In general, Raman processes are possible, which scatter a photon from the molasses to the probe fields or vice versa. However, because most of the atoms are in an uncoupled state, $|\Psi_{NC}\rangle$, and because $\mathbf{d}\cdot\mathbf{E}_m|\Psi_{NC}\rangle=0$ (where $\mathbf{d}$ is the electric dipole moment and $\mathbf{E}_m$ is the electric field associated with the molasses waves), it is not possible to leave an uncoupled state by absorbing a photon from the molasses beams. As a result the dominant processes are transitions from an uncoupled to a coupled state by the *absorption* of a *probe* photon and the stimulated emission of a photon into the molasses field [Fig. 4(a)]. The corresponding resonances then occur at a frequency detuning $\omega_p-\omega$ equal to the difference in light shifts of the levels involved, and their widths are of the order of the optical pumping rates of the coupled states. For this reason the resonance of Fig. 4(b) is relatively broad. From the relative magnitudes of the absorptive part of the spectrum of Fig. 4(b) and the part corresponding to probe gain, one can estimate the proportion of atoms in the uncoupled states. As is clear from Fig. 4(b), the fraction of atoms in a nearly dark level in the steady state is at least 0.9. In all the experiments described above no significant differences were found between the $\perp$ and $\parallel$ configurations.

In conclusion, we have observed the 3D cooling of atoms in a gray optical molasses and showed that this cooling is more efficient than that found in conventional bright molasses. The two three-dimensional configurations investigated yielded no significant differences in spite of the fact that the patterns of the polarization gradients are quite different. All the results obtained so far confirmed the naive picture of a gray molasses as an ensemble of weakly interacting atoms at low temperature. The excellent cooling efficiency and the very good capture rates are clearly demonstrated in our experimental work. We thus believe that these gray molasses can be quite useful in many experiments where one needs both low temperatures and high density. Because the present density is limited by the MOT density it might be quite interesting to see if the density in real space can be increased without modification of the temperature in the presence of an additional dipole trap [15].

We should like to express our thanks to S. Guibal for his assistance. This work was supported in part by NEDO (Japan) and the EU. D.R.M. is grateful to EPSRC (UK) for support.

[1] E. Raab *et al.*, Phys. Rev. Lett. **59**, 2631 (1987).
[2] M. Drewsen *et al.*, Appl. Phys. B **59**, 283 (1994).
[3] C. Salomon *et al.*, Europhys. Lett. **12**, 683 (1990).
[4] T. Walker, D. Sesko, and C. Wieman, Phys. Rev. Lett. **64**, 408 (1990); C. J. Cooper *et al.*, Europhys. Lett. **28**, 397 (1994).
[5] W. Ketterle *et al.*, Phys. Rev. Lett. **70**, 2253 (1993); K. B. Davis *et al.*, Phys. Rev. Lett. **74**, 5202 (1995).
[6] G. Alzetta *et al.*, Nuovo Cimento B **36**, 5 (1976).
[7] G. Grynberg and J.-Y. Courtois, Europhys. Lett. **27**, 41 (1994).
[8] C.Valentin *et al.*, Europhys. Lett. **17**, 133 (1992); R. Gupta *et al.*, J. Opt. Soc. Am. B **11**, 537 (1994).
[9] A. Hemmerich *et al.*, Phys. Rev. Lett. **75**, 37 (1995).
[10] C. Cohen-Tannoudji, in *Fundamental Systems in Quantum Optics*, Les Houches, Session LIII, 1990, edited by J. Dalibard, J. M. Raimond, and J. Zinn Justin (North-Holland, Elsevier Science Publishers, Amsterdam, 1992).
[11] M. S. Shahriar *et al.*, Phys. Rev. A **48**, 4035 (1993).
[12] P. Verkerk *et al.*, Europhys. Lett. **26**, 171 (1994); D. R. Meacher *et al.*, Phys. Rev. Lett. **74**, 1958 (1995).
[13] K. I. Petsas, A. B. Coates, and G. Grynberg, Phys. Rev. A **50**, 5173 (1994).
[14] By extending our method to the case of a six-beam molasses and by carefully eliminating all stray magnetic fields, two groups, one at the ENS (D. Boiron, A. Michaud, and C. Salomon) and another one at LPTF (A. Clairon and co-workers) have recently obtained temperatures smaller than 1.5 μK (unpublished).
[15] S. Chu *et al.*, Phys. Rev. Lett. **57**, 314 (1986).