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Blue-Sisyphus cooling in cesium gray molasses and antidot lattices

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Abstract. We present an experimental study of the kinetic temperature of cesium atoms interacting with laser beams tuned on the blue side of the $6S_{1/2}(F=3) \rightarrow 6P_{3/2}(F'=2)$ transition. In the case of a three-dimensional four-beam molasses, temperatures as low as 800 nK were found. These low temperatures are compatible with a good capture efficiency. The influence of other hyperfine transitions on the temperature is significant. In the presence of a static magnetic field (antidot lattices), the temperatures are slightly higher but show a much weaker dependence on the other hyperfine transitions.

PACS. 32.80.Pj Optical cooling of atoms; trapping

Increase in the atomic density and decrease in the atomic temperature are constant trends in laser cooling [1]. One very promising technique is to use gray molasses where Sisyphus cooling [2] occurs on the blue side of the atomic transition. Such a cooling scheme can be used on atomic transitions connecting a ground level of angular momentum J to an excited state of angular momentum J' with $J' = J - 1$ or $J' = J$. Because there is at least one linear superposition of the Zeeman substrates that is not coupled to the incident field [3], the lowest optical potential is flat. The atoms tend to be trapped in this *flat* potential surface where they radiate very few photons hence the name gray molasses used in this situation. Actually one-dimensional (1D) [4] and three-dimensional (3D) [5,6] cooling has been observed on the blue-side of the $6S_{1/2}(F=3) \rightarrow 6P_{3/2}(F'=2)$ transition of cesium. These two last experiments, respectively performed with a four-beam [5] and a six-beam [6] molasses, showed that the gray molasses combine low temperatures (in the μK range) with a good capture efficiency. The first aim of this paper is to present a more precise study of the temperature in the case of a four-beam molasses. The lowest temperature (800 ± 100 nK) found in this experiment is, to our knowledge, the lowest value reported so far for a Sisyphus cooling mechanism. This temperature is only four times larger than the recoil temperature (200 nK for cesium). Such low temperatures are still compatible with an excellent capture efficiency because more than 40% of the atoms initially present in the magneto-optical trap are still found in the gray molasses for this temperature. The study of the kinetic temperature T *versus* the molasses beams intensity I and detuning from resonance Δ shows that T is not a function of I/Δ as expected in the usual theory of Sisyphus cooling [2]. We explain this observation by the influence of other hyperfine transitions and in particular the $6S_{1/2}(F=3) \rightarrow 6P_{3/2}(F'=3)$ transition. We also study the variations of the kinetic temperature when a static magnetic field creating a Zeeman shift larger than the light-shift is added to the four-beam molasses. In this situation all the potential surfaces shows a periodic spatial modulation and the description of the medium as a lattice is more appropriate. In fact, for the field configuration used in the experiment, the atoms are trapped in potential surfaces exhibiting antidots hence the name antidot optical lattice [7,8] used for this situation. Here a simple dependence of T *versus* I/Δ is found. This shows that the other hyperfine transitions have a much weaker influence in this case.

1 Experimental set-up

In the first step of the experiment, the cesium atoms are cooled and trapped using a standard magneto optical trap operating on the red side of the $6S_{1/2}(F=4) \rightarrow 6P_{3/2}(F'=5)$ transition (as usually a repumping laser operates on the $6S_{1/2}(F=3) \rightarrow 6P_{3/2}(F'=4)$ transition to avoid the leakage of atoms in $F=3$). The magneto optical trap is realized inside a quartz cell with an antireflecting coating on the external faces. The typical kinetic temperature of the cesium atoms in the MOT is $70\,\mu$K. At a certain time, the inhomogeneous magnetic field and the laser beams of the MOT are switched off and the laser beams of the gray molasses are applied. More precisely we switch on both the cooling beams operating on the blue side of the

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$6S_{1/2}(F = 3) \rightarrow 6P_{3/2}(F' = 2)$ transition and the repumping beams resonant on the $6S_{1/2}(F = 4) \rightarrow 6P_{3/2}(F' = 4)$ transition. These beams originate from two diode lasers. Each beam is divided into four beams that intersect in the region where the cloud of cold atoms is created. The beams located in the $x0z$ plane (resp. $y0z$) make an angle 2θ with $\theta = 38°$. The gray molasses beams located in the $x0z$ plane (resp. $y0z$) have a polarization orthogonal to this plane. This is the usual four-beam lin $\perp$ lin configuration[1] [9]. The $0z$ symmetry axis lays in the horizontal plane. The repumping beams propagate in the same direction as the gray molasses beams but have a crossed linear polarization. To keep the largest number of atoms initially present in the MOT in the gray molasses, we start with gray molasses beams having intensities in the mW/cm^2 range. To reach lower intensities, we decrease the intensity in several steps, each step lasting about 10 ms. The typical lifetime of atoms in the gray molasses is about 0.2 s.

We detect the atomic velocity distribution along the vertical axis by a time of flight method. Actually, we use two probe beams for this measurement, the first one is located 10 cms below the cloud of cold atoms and the second one 30 cms below. These two probe beams have two components: one resonant on the $6S_{1/2}(F = 4) \rightarrow 6P_{3/2}(F' = 5)$ transition and the other one on the $6S_{1/2}(F = 3) \rightarrow 6P_{3/2}(F' = 4)$ transition. The time of flight signal depends both on the velocity distribution and on the size of the atomic cloud. Because these two quantities do not contribute in the same way to the signal for different distances h between the atomic cloud and the probe beam, we can increase the precision on the width of the velocity distribution by comparing the signals for $h = 10$ cms and for $h = 30$ cms. Of course, these signals are recorded separately to avoid that the upper probe beam perturbs the measurements made with the lower probe. This comparison between the two time of flight signals is particularly useful because the fluorescence from the atoms cooled in the gray molasses is very weak, most of the atoms being in the uncoupled states [3]. Thus, a direct measurement of the size of the atomic cloud with a CCD camera is difficult unless one switches on extra beams[2].

[1] This field configuration creates a molasses (atoms in a flat potential) or a lattice (atoms in a spatially modulated potential) depending on the transition and of the possible application of a static magnetic field.

[2] In the case of gray molasses, the influence of the cloud size is significant even for $h = 30$ cms. For this height, an atomic cloud of size $a \approx 2$ mm (total width at $e^{-1/2}$) corresponds to a correction $\Delta T \approx 0.3\,\mu$K. For bright molasses or lattices ($J \rightarrow J+1$ transitions), it is generally possible to make an image of the cloud and to determine a with sufficient precision to avoid the second time of flight. To be confident in the $0.1\,\mu$K precision in gray molasses, it is necessary either to use the second time of flight or to make an image with additional laser beams tuned on a bright transition (such an image would perturb the velocity distribution and should be made independently from the time of flight measurement).

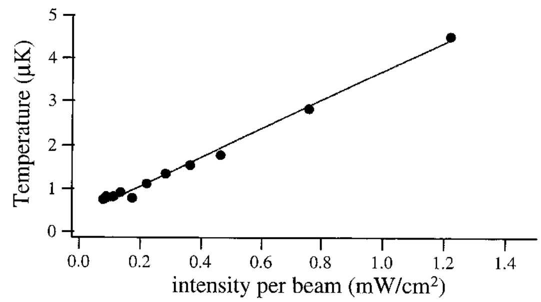

Fig. 1. Kinetic temperature of cesium atoms *versus* laser beam intensity in a gray molasses. The detuning is $\Delta = 4\Gamma$.

From these experiments, we measure both the temperature and the size the cloud of cold atoms. The cloud size is in the mm range as expected (a typical size for the figures presented in the paper is 2.5 mm). From shot to shot, the size fluctuates by about 10%. We tried to use this type of measurements to determine spatial diffusion coefficients in the gray molasses (by measuring the size for different molasses durations). However no detectable variation in the size was found for molasses times comprised between 10 and 100 ms.

Because the atomic temperature shows a dramatic increase with the magnetic field at low field [7,8], it is important to cancel the field with a very good precision. Actually the most accurate method we found was precisely to minimize the atomic temperature. The intensity in the three pairs of compensating coils is thus changed until a minimum for the kinetic temperature is found.

2 Experimental results for the four-beam gray molasses

We present in Figure 1 the variation of the kinetic temperature T *versus* the intensity per beam I for a detuning $\Delta = 4\Gamma$ ($\Gamma = 5.2$ MHz is the natural width of the upper level, $\Delta = \omega - \omega_0$ where ω and ω_0 are respectively the beam and atomic frequencies). For $I < 0.2$ mW/cm^2, the temperature is less than $1\,\mu$K, the minimum being $0.8 \pm 0.1\,\mu$K. Even at these low temperatures, an important fraction (≈ 0.4) of the atoms initially in the MOT are still present in the molasses. Although this temperature is slightly lower than the temperature found in a six beams molasses ($1.1\,\mu$K) [6], the capture efficiency is also lower (40% at $0.8\,\mu$K instead of 85% at $1.25\,\mu$K). In the four beam molasses a 85% capture efficiency is found at higher temperatures ($1.6\,\mu$K). The variation of T *versus* I is linear. The rapid increase of T at low intensity generally encountered in Sisyphus cooling (and often called "decrochage") is not found on the curve. However for the lowest values of the intensity, the atoms fall from the molasses before the gray molasses beams are switched off (see Fig. 2). This is probably because at low intensity the capture velocity is not enough to cope with the vertical velocity due to gravity.

We can express the data in Figure 1 as a function of the light-shift Δ' (more precisely we define Δ' as the light-shift found for the same values of I and Δ for a transition

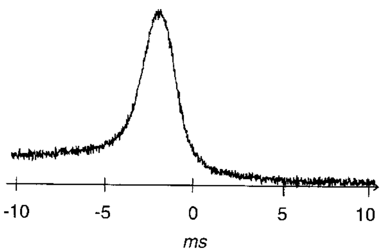

Fig. 2. Time of flight signal for $I = 0.1$ mW/cm^2 and $\Delta = 4\Gamma$. The asymmetry is due to the atoms falling from the gray molasses before the molasses beams are switched off.

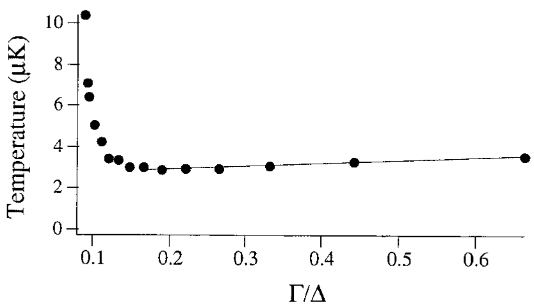

Fig. 3. Kinetic temperature of cesium atoms *versus* Γ/Δ for a fixed value of the laser beam intensity ($I = 0.8$ mW/cm^2).

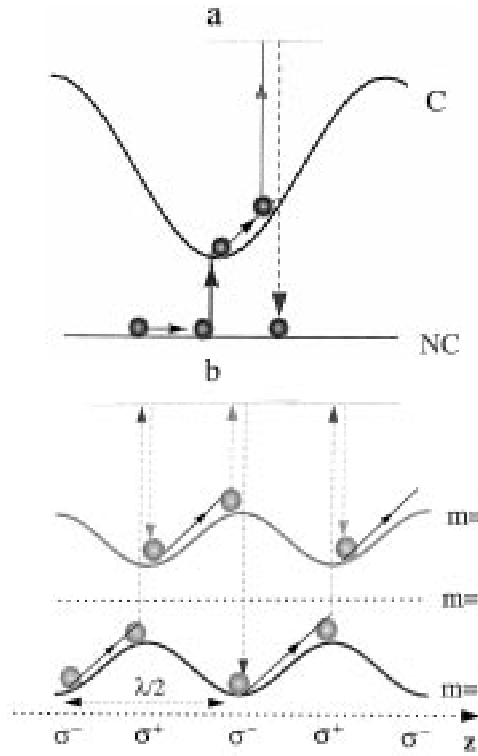

Fig. 4. Sisyphus cooling in a gray molasses (a) and in an antidot lattice (b). In the absence of magnetic field (a), an atom moving in the uncoupled state (NC) is transferred towards a coupled sate (C) by motional coupling. In this state, it climbs a potential hill before being optically pumped in the uncoupled state. In the case of a large magnetic field (b), the atom climbs a hill associated with a Zeeman sublevel potential before being optically pumped into another Zeeman sublevel where it also climbs potential hills. The figure (b) corresponds to the case of a $1 \to 1$ transition but the principle is the same for the transition studied in the paper.

having a Clebsch-Gordan coefficient equal to 1 at a lattice point where the light is circularly polarized. In the present situation, the relation between Δ', I and Δ is $\Delta' = (I/I_{sat})(\Gamma^2/\Delta)$ where $I_{sat} = 1.1$ mW/cm^2). We find that the slope $k_BT/\hbar\Delta'$ is 5×10^{-2} in Figure 1. Contrary to what is expected in the usual Sisyphus cooling theory [2], the slope changes with the detuning Δ. In fact, the variation of the kinetic temperature *versus* Γ/Δ for a fixed value of the intensity ($I = 0.8$ mW/cm^2) looks different from Figure 1. In this case (Fig. 3) we find a curve exhibiting a minimum for a detuning $\Delta \cong 6\Gamma$. For small values of Γ/Δ there is a rapid increase in T. For large values of Γ/Δ there is a slow increase. As a function of the light-shift we find an asymptotic slope $k_BT/\hbar\Delta' \approx 7 \times 10^{-3}$, *i.e.* a value almost ten times smaller than the value deduced from Figure 1.

This nonintuitive behaviour is not expected for a pure $F = 3 \to F' = 2$ transition. Actually a 1D calculation using the band model [10] performed by Petsas [11] for the lin $\perp$ lin configuration gives a slope $k_BT/\hbar\Delta' = 5 \times 10^{-3}$ independent of Δ. We attribute the experimental observations to the influence of the other hyperfine transitions and in particular the $6S_{1/2}(F = 3) \to 6P_{3/2}(F' = 3)$ transition. Although this transition is not very close from the $6S_{1/2}(F = 3) \to 6P_{3/2}(F' = 2)$ transition (the distance is 30Γ) its influence can be quite significant because the cooling mechanism on the $6S_{1/2}(F = 3) \to 6P_{3/2}(F' = 2)$ transition relies on a process starting from an uncoupled transition (Fig. 4a). In the absence of other transitions, the optical potential is flat and the optical pumping originates from motional coupling between the uncoupled and coupled states. Actually, the friction coefficient induced by this process can be shown to be much weaker than the friction coefficient for a $F \to F + 1$ transition [12,13]. Even a small perturbation due to the coupling with another transition induces level shifts and optical pumping rates having a magnitude similar or even larger than the ones originating from the $F = 3 \to F' = 2$ transition. Although the eigenstates are still determined by the $F = 3 \to F' = 2$ transition, the heating caused by the other transitions is less and less balanced when $|\Delta|$ increases by the small friction due to the $F = 3 \to F' = 2$ transition. A more accurate evaluation shows that the heating overcomes the cooling when $|\Delta| \geq 10\Gamma$ for this cesium transition [13]. Such an estimate is in reasonable agreement with the experimental observation (Fig. 3).

In the course of these experiments we also studied the variation of the fraction of atoms captured in the gray molasses. This number f is deduced from the the comparison between the area of the time of flight signal for the gray molasses and the MOT. Fixing $\Delta = 4\Gamma$, we find $f > 80\%$ for $I > 0.5$ mW/cm^2 (no decrease of f is found in the range up to $I = 1.4$ mW/cm^2 studied experimentally). Fixing $I = 0.8$ mW/cm^2 we find $f > 80\%$ for $2\Gamma < \Delta < 5\Gamma$. In the best conditions, we find $f \approx 1$

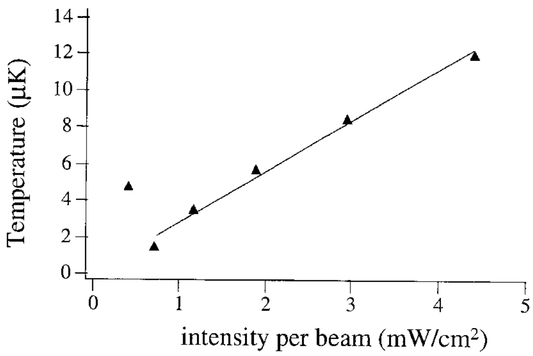

Fig. 5. Kinetic temperature of cesium atoms *versus* laser beam intensity in an antidot lattice. The detuning is $\Delta = 4\Gamma$ and the magnetic field $B_0 = 8.7$ G.

which means that most of the atoms that were initially present in the MOT were captured and cooled by the gray molasses[3].

3 Experimental results for an antidot lattice

Another simple situation is found when a static magnetic field leading to a Zeeman shift large compared to the light-shift is applied on the atoms [14]. In the case of a 3D beam configuration, this often leads to an optical potential exhibiting antidots [7,8]. However this is not an absolute rule and one can also find potential wells in some field configurations [15]. In our experimental situation (four beam lin $\perp$ lin configuration and a magnetic field $\mathbf{B}_0$ along $0z$), we find an antidot lattice [7].

We present in Figure 5 the variation of the kinetic temperature *versus* I for a detuning $\Delta = 4\Gamma$ and a magnetic field $B_0 = 8.7$ G. The curve presents a minimum for a temperature which is slightly less than $2\,\mu$K and an asymptote with a slope $k_BT/\hbar\Delta' \approx 5 \times 10^{-2}$. A similar curve with the same asymptote is found for a different value of Δ ($\Delta = 8\Gamma$) and the same magnetic field. The situation here is thus markedly different from the one of the gray molasses[4] and corresponds to what is expected for Sisyphus cooling on an isolated transition. The change comes from the absence of uncoupled states when the static magnetic field differs from 0. For large B_0 the Sisyphus cooling, the principle of which is recalled in Figure 4b, does not differ from the usual Sisyphus mechanism [2] and the friction coefficient is expected to be much larger than in zero magnetic field. As a result, the effect of the distant hyperfine transitions is much weaker. We note also that a computation for the 1D lin $\perp$ lin configuration and a large B_0 field gives a slope $k_BT/\hbar\Delta' \approx 8 \times 10^{-2}$ in the case of a $F = 3 \rightarrow F' = 2$ transition [8]. Because of the different dimensionalities, the agreement with the experimental result is satisfactory.

We also checked that the temperatures do not show significant variations with B_0 (5 G $\leq B_0 \leq$ 9 G) for I and Δ fixed. This observation valid for a Zeeman splitting larger than the light-shift is consistent with theory [8] and with an earlier experiment[5] [7].

4 Conclusion

We have presented temperature measurements on gray molasses and lattices. We believe that the main result is the demonstration that a large number of atoms can be captured in a gray molasses and cooled to temperatures on the order of $1\,\mu$K. By comparison with similar data obtained with bright molasses or lattices operating on a $F \rightarrow F + 1$ transition, the temperature is about three times smaller in a gray molasses. A phase of gray molasses cooling can thus be a useful step to increase density in phase-space by purely optical methods.

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[3] In fact, at the maximum we even found an area slightly larger (by 10%) for the gray molasses than for the MOT. This result could be related to the presence of hot atoms in the MOT whose trajectories do not cross the probe beam for the time of flight measurement.

[4] The fact that the slopes in Figures 1 and 5 are nearly equal is not associated with a basic physical process. For a different value of Δ, the slopes are different.

[5] The range of values of B_0 for which such experiment can be performed is however limited. We want B_0 sufficiently large to have a Zeeman splitting larger than the light-shift but not too large because the Zeeman splitting should remain small compared to the frequency detuning Δ.