Laser cooling of cesium atoms in gray optical molasses down to 1.1 μK

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We have studied the behavior of cesium atoms cooled in six-beam ''gray'' optical molasses. Cooling occurs for a laser detuned to the blue side of the $6S_{1/2},F=3\rightarrow 6P_{3/2},F'=2$ transition, and a Sisyphus-type effect accumulates the atoms in states not coupled to the light. We measure a minimum temperature of 1.1 ± 0.1 μK at low atomic density. The typical cooling time is on the order of 1 ms. A linear dependence of the temperature versus atomic density is found with a slope of $\sim$0.6 μK/(10^{10} atoms/cm^3). [S1050-2947(96)50806-1]

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I. INTRODUCTION

Laser cooling of atoms in optical molasses and magneto-optical traps (MOT) is now a widespread technique [1]. It relies on Sisyphus cooling using a $J\rightarrow J'=J+1$ cycling transition with red detuned laser beams ($\omega_L<\omega_{\rm at}$). The minimum temperature of the cooled atoms depends on the fluorescence rate and, at high atomic density, on photon multiple scattering [2,3]. For cesium the lowest steady-state temperature measured in six-beam molasses was 2.5 μK [4] and 1.2 μK in four-beam optical lattices [5]. We call these molasses *bright* molasses (BM).

It has recently been proposed to cool atoms using transitions of the $J\rightarrow J$ and $J\rightarrow J-1$ types [6,7], for which some atomic state(s) of the internal ground-state manifold are not coupled to the laser field. The atoms are accumulated with low momenta (on the order of the single-photon momentum $\hbar k$) into these states where their fluorescence is considerably reduced, hence the name ''gray molasses'' (GM) or ''gray lattices.'' This property is at the origin of the interest in gray molasses: the low photon scattering rate is expected to reduce the strength of the interaction between atoms (via reabsorption of fluorescence photons and short-range resonant dipole-dipole interaction). This would allow the production of atomic samples at higher densities than in a MOT.

In Refs. [8] and [9], it was shown experimentally that four-beam or six-beam optical lattices using $J\rightarrow J-1$ transitions produced efficient cooling and accumulation of the atoms in uncoupled states, but temperatures no lower than 5 μK were found. We show here that cesium six-beam gray molasses can provide temperatures as low as 1.1 ± 0.1 μK at low atomic density. We study the behavior of GM as a function of the laser parameters and of the density of atoms. In spite of the fact that the fluorescence rate in GM is strongly reduced, we observe an increase of temperature when the atomic cloud becomes denser. This increase is linear in atomic density and, surprisingly, is found to be similar to that occurring in bright molasses.

The cooling mechanism in GM has already been described in Refs. [6–10]. It relies on a Sisyphus effect between coupled states which have spatially modulated light shifts and uncoupled states which experience no light shift. For $\delta=\omega_L-\omega_{\rm at}>0$, the optical potentials of the coupled states lie above the flat potential of the uncoupled states. Motional coupling between both types of states [11] is position dependent. It leads to a position-dependent transition rate from the uncoupled states to the coupled states that is maximum when the light intensity is minimum, i.e., when the light shift of the coupled states is minimum. The transition rate from the coupled states to the uncoupled ones is proportional to the light intensity, as a regular optical pumping rate, so that atoms are pumped back into uncoupled states preferentially in points where the light shifts are maximum; in this case they have climbed a hill of potential energy before returning to the uncoupled states. Kinetic energy is thus extracted from the atoms.

II. EXPERIMENTAL SETUPS

Because of the blue detuning of the laser beams, the GM are not able to capture directly the atoms from a cesium vapor. For loading the GM, we first use a standard MOT in a low vapor pressure cell ($\approx 10^{-6}$ Pa) with laser beams tuned to the red side of the $F=4\rightarrow F'=5$ cesium transition. In our experiments, two different setups were used. In the first one, two extended cavity lasers with an emission linewidth of the order of 100 kHz provide the $F=4\rightarrow F'=5$ (MOT and bright molasses) and $F=3\rightarrow F'=2$ circularly polarized cooling beams (gray molasses). The repumping lasers are tuned to the transitions $F=3\rightarrow F'=4$ and $F=4\rightarrow F'=4$, respectively. The vapor cell is surrounded by a μ-metal chamber to shield external magnetic fields to less than 1 mG.

A second setup was designed to be simpler than the first one. It employs only two DBR laser diodes (distributed Bragg reflector) for capture and GM cooling. We use the fast frequency tunability offered by the diode current to switch the laser frequencies between the capture values and the GM values. The measured linewidth of the DBR laser diodes is $\simeq$8 MHz. Atom capture is performed as in the first setup. For the GM phase, the frequency locking loops are quickly opened and the $F=4\rightarrow F'=5$ laser is switched to the

$F=4\rightarrow F'=4$ transition, whereas the $F=3\rightarrow F'=3$ laser is switched to the blue side of the $F=3\rightarrow F'=2$ transition. When the GM cooling sequence is complete, the lasers are brought back to resonance and are automatically relocked. Coils are used for compensating external stray magnetic fields.

In the first setup, we determined the minimum temperature of atoms in gray molasses as follows. After a capture of about 2×10^7 atoms, the magnetic field is switched off, leaving the atoms in a 60-ms-long BM phase. This phase guarantees the full decay of the magnetic field inside the magnetic shield. In a second step the $F=4\rightarrow F'=5$ cooling beams are switched off and the six GM beams are applied. The duration of the GM can be changed between 0 and 500 ms.

After turning off the GM beams rapidly ($\leqslant 1$ μs), the temperature and the number of cooled atoms are measured by a time-of-flight technique. The atoms fall through a probe beam located 14 cm below the atom cloud. This beam has a vertical Gausssian profile with a $e^{-1/2}$ radius of 640 μm. It contains two frequencies, one resonant with the $F=4\rightarrow F'=5$ transition, and one resonant with the $F=3\rightarrow F'=4$ transition. The atomic fluorescence is then simply collected on a low noise photodiode and the temperature of the atoms along the vertical is then deduced from the width of the time-of-flight peak. A small correction factor is applied to these measurements to include the effect of the geometrical broadening of the peak due to the finite height of the probe and of the initial atom cloud. This latter height is measured using a charge-coupled device camera by applying a 5-ms pulse of bright molasses light. We have checked that, with such a short pulse, spatial diffusion of the cloud is negligible as compared to its diameter. This technique thus provides an instant picture of the spatial distribution of atoms in GM. The horizontal (vertical) spatial profile is well fitted by a Gaussian profile with an $e^{-1/2}$ radius of 0.7 mm (0.6 mm), leading to a temperature correction of ~ 0.1 μK. The 5-ms-long fluorescence signal is also used to deduce the number of atoms and the density in the gray molasses cloud.

III. RESULTS

When switching on the GM (6 $\sigma^+\sigma^-$ beams with a diameter of 1 cm, a Rabi frequency per wave $\Omega=0.5\Gamma$, and a detuning $\delta=+4.5\Gamma$ where $\Gamma=2\pi\times5.3$ MHz), the amount of fluorescence decreases to less than 1% of the MOT fluorescence operating at a detuning of -3Γ and a Rabi frequency of $\Omega=\Gamma$. From the time-of-flight results, we find that more than 98% of the atoms are in the $F=3$ hyperfine level. The $F=4\rightarrow F'=4$ beam (Rabi frequency of 0.5Γ) is tuned to resonance and has little influence on temperature and capture efficiency. Moreover, no stable GM is observed on the red side of the $F=3\rightarrow F'=2$ transition ($1/e$ lifetime less than 5 ms), whereas the GM lifetime for blue detuning exceeds 100 ms. This observation is also valid when the laser is tuned to $F=3\rightarrow F'=3$, although in that case the $F=4\rightarrow F'=4$ beam is no longer a repumper and has to be tuned to the blue side of the transition (the $F=3\rightarrow F'=3$ transition is no longer closed). All these remarks are in agreement with our theoretical analysis and consistent with the fact that atoms are mostly in uncoupled states.

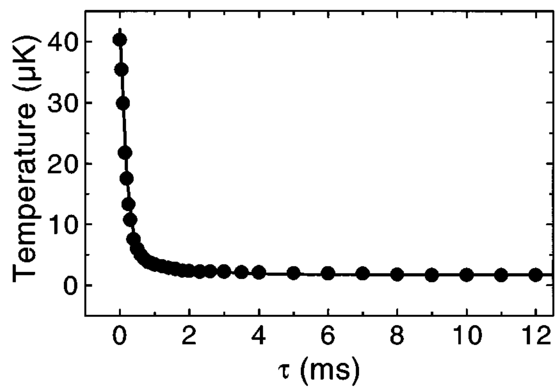

FIG. 1. Evolution of the temperature as a function of the gray molasses time τ. At $\tau=0$, 2×10^7 atoms are released from bright optical molasses at a temperature of 40 μK into gray molasses with $\Omega=0.5\Gamma$, $\delta=+4.5\Gamma$. At 2 ms the temperature is 2.3 μK and levels off at 1.6 μK beyond 8 ms.

In Fig. 1, we give the evolution of the temperature of atoms initially prepared at 40 μK, when switching on at $\tau=0$ the GM. Within 2 ms, the temperature drops down to 2.3 μK and levels off at 1.6 μK beyond 8 ms, showing the efficiency of this cooling with gray states. If we repeat this experiment with a lower GM intensity, the final temperature is lower but at the expense of a severe loss of atoms: the GM capture velocity becomes smaller than the width of the initial velocity distribution. In order to reach smaller temperatures without atom loss, we first turn on the GM at high intensity ($\Omega=0.7\Gamma$) and then reduce the intensity in 13 ms to an adjustable final value. If we maintain the intensity constant at this final value for longer times, the temperature no longer evolves. Atom losses in this process never exceed 15% in the first 20 ms of GM. We present in Fig. 2 the measured temperature as a function of the light-shift parameter ($\Omega^2/\delta\Gamma$) for various detunings and final intensities. For a peak atomic density of 4×10^9 atoms/cm^3, the minimum temperature is

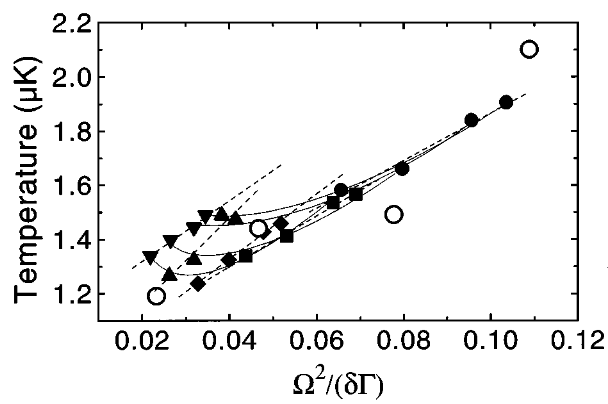

FIG. 2. Temperature of atoms in gray molasses as a function of the light-shift parameter $\Omega^2/\delta\Gamma$ at $n_{\mathrm{peak}}=4\times10^9$ atoms/cm^3 for different intensities and detunings: dashed lines at constant detunings, from left to right, δ/Γ = 6.8, 5.7, 4.5, 3.4, and 2.3; solid lines at constant intensities, from top to bottom, Ω^2/Γ^2 = 0.25, 0.22, 0.18, and 0.16. For a given intensity, there is a clear optimum in detuning. Open circles: numerical results of a 3D quantum Monte Carlo calculation at a fixed detuning of $+5\Gamma$.

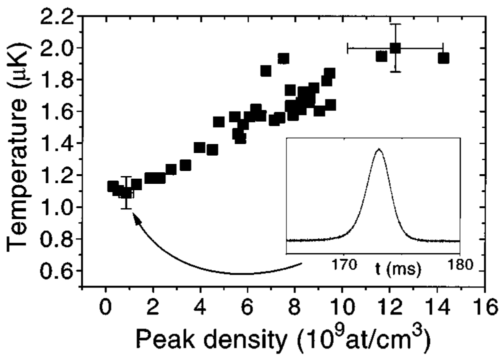

FIG. 3. Temperature of atoms in gray molasses as a function of peak atomic density for $\delta=4.5\Gamma$, $\Omega^2=0.16\Gamma^2$. The absolute density is known to a factor of 2. Inset: time-of-flight signal corresponding to a temperature of 1.1 ± 0.1 μK ($v_{\rm rms}=8.3$ mm/s).

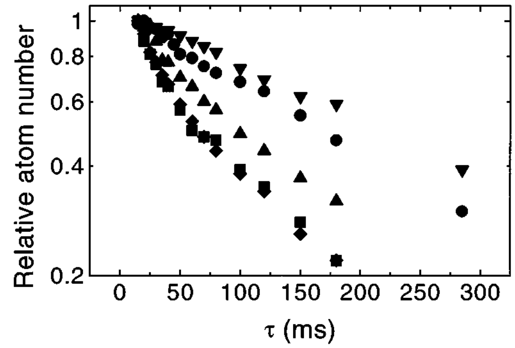

FIG. 4. Relative number of cold atoms in gray molasses as a function of time τ. The gray molasses beam intensity is kept constant for $\tau\geqslant13$ ms (from top to bottom: Ω^2/Γ^2 = 0.49, 0.36, 0.25, and 0.16). The two lower curves at $\Omega^2=0.16\Gamma^2$ were obtained at two background pressures of Cs which differ by 30%. For a MOT lifetime of 1 s, $1/e$ time constants in GM are, respectively, 290, 220, 127, and 92 ms (from top to bottom).

1.25 μK. We observe a linear dependence of the temperature as a function of the intensity (dashed lines) and a linear dependence as a function of $1/\delta$ for detunings smaller than $+4\Gamma$. The open circles in Fig. 2 are theoretical predictions for the mean kinetic energy obtained by a three-dimensional (3D) Monte Carlo wave function calculation for cooling on a $J=3\rightarrow J'=2$ transition, for a detuning $\delta=+5\Gamma$, and for fixed relative phases between the three standing waves $(0,\pi/3,2\pi/3)$. The numerical implementation closely follows that of Ref. [12]. The agreement between theory and experiments is good considering the theoretical (0.2 μK) and experimental (0.1 μK) uncertainties. From this agreement, we deduce an excited-state population on the order of 3×10^{-4}.

A deviation from the universal intensity-detuning law appears for $\delta\geqslant5\Gamma$ and becomes more and more pronounced as the detuning increases. We attribute this heating effect to a destabilization of the uncoupled states by a parasitic excitation of the $F=3\rightarrow F'=3$ transition which is indeed only at $+150$ MHz (i.e., $+28\Gamma/2\pi$) from the $F=3\rightarrow F'=2$ transition. Generally none of the two uncoupled states associated with the $F=3\rightarrow F'=2$ transition coincides with the uncoupled state associated with the $F=3\rightarrow F'=3$ transition.

Another interesting result deals with the density dependence of the minimum temperature, presented in Fig. 3. For $n\leqslant10^9$ atoms/cm^3, the temperature is as low as 1.1 ± 0.1 μK. The corresponding rms velocity is 8.3 mm/s or 2.4 times the single-photon recoil velocity. We noticed that the minimum temperatures measured with the second setup using the DBR lasers are higher by 0.4 μK than those found in the first one (narrow linewidth lasers). When increasing the density up to 1.5×10^{10} atoms/cm^3, the temperature increases linearly to 2 μK. The density variations are obtained either by increasing the MOT magnetic-field gradient or by changing the diameter of the MOT beams without modifying the GM beams. We attribute this heating effect to photon multiple scattering within the GM atomic cloud. The surprising feature of these measurements is that the temperature in GM as a function of density has nearly the same slope (0.6 μK/10^{10} atoms/cm^3) as that of the $F=4\rightarrow F'=5$ bright molasses for a detuning of -10Γ, an intensity of $\Omega^2=0.23\Gamma^2$, and a temperature at low density of 3.5 μK. In this case the one-beam excitation rate is $6\times10^{-4}\Gamma$, resulting in an excited-state population of $\sim4\times10^{-3}$ [13]. The atoms in GM being mostly in uncoupled states, one would indeed expect a much-reduced heating effect in GM than in BM. The theoretical interpretation of this heating, which is a crucial point in attempts to build an atom laser, will be published in a future paper and is only sketched here. The equilibrium temperature in molasses results from a balance between a cooling power from the Sisyphus mechanism and the spontaneous emission (and stimulated) heating. From Fig. 1 we deduce an effective cooling time ≈20 times longer than that of bright molasses [3], resulting in a cooling power 20 times weaker in GM than in BM. It is thus sufficient to have 20 times less fluorescence emission to produce an excess temperature in GM similar to that of BM.

Finally, we have investigated the lifetime of GM as a function of the beam intensity at a detuning of $\delta=+4.5\Gamma$ (Fig. 4). At relatively high intensity ($\Omega=0.7\Gamma$, $T=2.0$ μK), the $1/e$ lifetime is 290 ms, a factor of 3 shorter than that of the MOT. At lower intensities this lifetime shortens considerably, indicating that GM possesses a loss mechanism. We have not yet studied this loss in detail (anomalous spatial diffusion, Doppler heating, etc.), but we have checked that it is not dependent on the background gas pressure in the chamber.

IV. CONCLUSION

We have shown here that gray molasses yields lower temperatures than bright optical molasses and that it can be very simply implemented with only two DBR laser diodes. The minimum temperature is 1.1 ± 0.1 μK, similar to that of bright optical lattices [5]. Gray molasses cools the atoms in the lowest hyperfine state and has a reduced fluorescence rate. This opens the way to produce atomic samples with higher densities than in a MOT but, as we have shown, at the expense of an increase in temperature. A first possibility that we are presently investigating is to superimpose on the GM a far off resonance dipole trap [14] or a crossed dipole trap [15] to create an additional confining force. We foresee several other applications of these gray molasses; for instance, in atomic fountain clocks where it is desirable to get a colder cloud of atoms [16]. The cold and dense sample (peak density $\sim 2\times 10^{10}$ atoms/cm^3) produced by this technique has a phase space density $1/2n\Lambda^3 = 2\times 10^{-5}$, where $\Lambda = h/(2\pi M k_B T)^{1/2}$ is the thermal de Broglie wavelength and where the factor 1/2 accounts for the two uncoupled states. This is a very simple source for further cooling such as Raman or evaporative cooling in order to reach the Bose-Einstein condensation [17].

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