EUROPHYSICS LETTERS 15 August 1990

Europhys. Lett., 12 (8), pp. 683-688 (1990)

Laser Cooling of Cesium Atoms below 3 μK.

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(received 31 May 1990; accepted in final form 26 June 1990)

PACS. 32.80P – Optical cooling of atoms; trapping.
PACS. 42.50 – Quantum optics.

Abstract. – We have measured the temperature of cesium atoms released from optical molasses. For a wide range of laser intensity and detuning from resonance, the temperature depends only on the intensity-to-detuning ratio. The lowest temperature achieved is $(2.5 \pm 0.6)\,\mu$K, which corresponds to an r.m.s. velocity of 12.5 mm/s or 3.6 times the single-photon recoil velocity. This is, to our knowledge, the coldest kinetic temperature ever measured for three-dimensional (3D) cooling.

The reduction of kinetic motion of atoms using momentum and energy exchange with laser fields has produced extremely low kinetic temperatures in recent years [1]. Here we report new measurements on laser-cooled cesium atoms which show that the temperature is a simple, nearly linear function of the ratio of laser intensity I and detuning δ from resonance, in agreement with recently developed theoretical models [2, 3]. We have also determined the range of I and δ for which the cooling works. For large detuning, a minimum and constant ratio of I/δ is required and the corresponding lowest temperature is $(2.5 \pm 0.6)\,\mu$K.

We use a configuration of three pairs of mutually orthogonal laser beams, called optical molasses by the Bell labs group that performed the first 3D laser cooling of neutral atoms in 1985 [4]. At that time it was believed that the laser cooling in optical molasses was due simply to differential radiation pressure induced by Doppler shifts [5]. The lower limit of this Doppler cooling is given [6] by $k_B T_{Dop} = \hbar\Gamma/2$, where Γ^{-1} is the radiative lifetime of the

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excited state (30 ns for the $6P_{3/2}$ state of Cs, giving $T_{\mathrm{Dop}} = 125\ \mu\mathrm{K}$). In 1988, a group at NIST measured temperatures much lower than this Doppler cooling limit [7]. Soon after, new mechanisms for laser cooling were proposed independently by a group at ENS in Paris and a group at Stanford [2, 3]. These mechanisms use the multilevel structure of the ground state of alkali atoms and the laser polarization gradients unavoidable in these 3D experiments. Differential light-shifts of the various Zeeman sub-levels lead to a much stronger cooling than in the two-level case, and therefore much lower temperatures.

An important prediction of the theory [2] is that for $|\delta| \gg \Gamma$ and $\Omega \ll |\delta|$:

$$k_{\mathrm{B}} T \approx C\hbar\Omega^2/|\delta|\,, \tag{1}$$

where C is a numerical factor on the order of 0.1, the detuning $\delta = \omega_{\mathrm{L}} - \omega_{\mathrm{A}}$ is negative, and $\Omega = 2\boldsymbol{d}\cdot\boldsymbol{E}/\hbar$ is the Rabi frequency describing the coupling between the atomic dipole moment and the electric field vector $\boldsymbol{E}$. By convention, Ω refers in the following to the Rabi frequency of a single travelling wave. When decreasing the laser intensity, eq. (1), which shows the proportionality of the temperature to the light shift, is expected to hold until the intensity is too low for the new mechanism to work.

Our experimental set-up (see fig. 1*a*)) has been described previously [8, 9]. A cesium atomic beam is first slowed by a counterpropagating laser beam. Some of the nearly stopped atoms ($|v| \lesssim 3$ m/s) then load the molasses where the strong laser cooling provides viscous confinement. The molasses beams are derived from a stabilized ring dye laser (Coherent 699-21) and are tuned below the $6S_{1/2}\,F = 4 \rightarrow 6P_{3/2}\,F' = 5$ transition. A «repumping» diode laser beam tuned to the $6S_{1/2}\,F = 3 \rightarrow 6P_{3/2}\,F' = 4$ transition is combined with one or two of

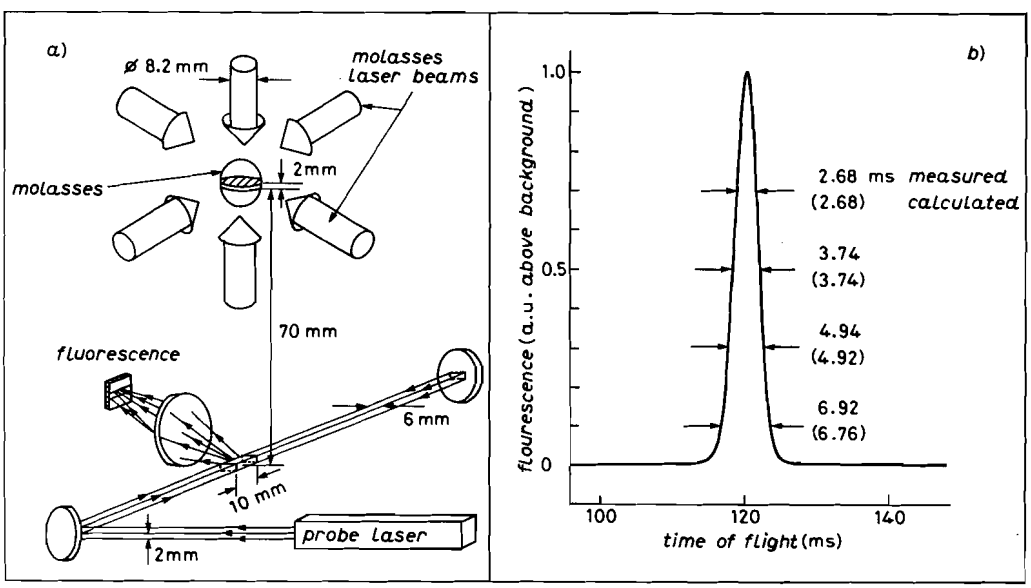

Fig. 1. – *a*) Apparatus: atoms from a laser-cooled atomic beam (not shown) are further cooled and confined at the intersection of three pairs of mutually orthogonal, counterpropagating laser beams. Cold atoms from a 2 mm high slice of the molasses are dropped into the probe. The probe-induced fluorescence is collected by a lens, imaged onto a photodiode, and recorded *vs.* time. *b*) Experimental time-of-flight spectrum for the lin $\perp$ lin configuration with $|\delta|/2\pi = 52$ MHz and $\Omega^2/\Gamma^2 = 0.22$, $T = 2.5\ \mu$K. By comparing the measured widths of the TOF spectrum at various fractions of its full height with the calculated ones, we confirm that the initial velocity distribution is closely Maxwellian and can be assigned a temperature.

the pairs of molasses beams to prevent optical pumping into the $F = 3$ ground state. The residual magnetic field in the molasses region is $\approx 1\,\mu$T.

The molasses laser beams are apertured to 8.2 mm diameter, with the intensity uniform over this diameter to better than 15%. We have used two different polarization configurations: i) lin ∥ lin, where the polarization vector in each counterpropagating beam pair is linear and orthogonal to that of the other pairs; ii) lin ⊥ lin, where each travelling wave has a linear polarization orthogonal to that of the counterpropagating wave. The maximum intensity used for these experiments is 4 mW/cm^2 per wave. ($\Omega = \Gamma$ for 2.25 mW/cm^2 on the $F = 4$, $m_F = 4 \rightarrow F' = 5$, $m_{F'} = 5$ transition.) With this intensity, the observed mean confinement time of an atom in the molasses is 0.35 s for lin ∥ lin and 0.70 s for lin ⊥ lin at a detuning of -10 MHz, *i.e.* about two linewidths. After loading the molasses at these laser parameters for 1.5 s and achieving a density of about 10^8 atoms/cm^3, we turn off the slowing laser. We then rapidly (< 2 ms) switch the detuning and lower the intensity of the molasses laser. After the switching we allow 100 ms for the atoms to reach a constant temperature. By this technique we can measure temperatures at intensities as low as 0.04 mW/cm^2 or at detunings as great as -240 MHz, while still maintaining the high density obtained with the optimal loading parameters given above([1]).

We measure the velocity distribution of the atoms by a time-of-flight (TOF) method [7]. The atoms confined in the molasses are released by suddenly turning off the molasses laser beams using an acousto-optic modulator (< 10 μs fall time to an extinction of 10^{-5}) followed within 2 ms by a mechanical shutter. The atoms then travel ballistically to a 2 mm high probe laser beam, centered at 70 mm below the molasses centre, where they are detected by fluorescence. The probe is derived from a frequency stabilized diode laser tuned to the $6S_{1/2}F = 4 \rightarrow 6P_{3/2}F' = 5$ transition, has an intensity of 0.33 mW/cm^2, is σ^+ polarized, retroreflected and is detuned half a linewidth below resonance to minimize longitudinal heating. Each atom scatters an average of $\sim 10^4$ photons, providing efficient detection.

The distribution of detection times (TOF spectrum) is determined by the initial, thermal spread of vertical atomic velocities and by the molasses and probe geometry. In order to reduce the molasses geometry contribution, we «slice» the molasses: just after the molasses beams are turned off, we irradiate the atoms with a horizontal, unidirectional beam in the middle of which is a sharp, 2 mm high shadow. After 7 ms of irradiation, all of the atoms except those in a 2 mm high slice are given enough transverse momentum that they fall to the side of the probe.

We use a Monte Carlo simulation to take account of the molasses and probe geometry and of the effect of the slicing operation on the TOF spectrum. We have checked that most of the measured TOF signals are compatible with a Maxwellian distribution of velocities by comparing the widths at 0.1, 0.3, 0.5, and 0.7 of full height for experimental and calculated spectra (see fig. 1*b*)). Therefore, we have assigned to each TOF spectrum a temperature determined from the 0.5 width, provided that the other widths differ by less than 5% from the calculated ones.

These measured temperatures, plotted *vs.* laser intensity at various laser detunings, are shown in fig. 2*a*) for the lin ∥ lin configuration. The intensity is given in units of Ω^2/Γ^2. Ω^2 is calculated for the $F = 4$, $m_F = 4 \rightarrow F' = 5$, $m_{F'} = 5$ transition and is the average of Ω^2 for the 6 beams. (The 6 intensities are generally equal to better than 10%.)

For a given detuning, the temperature decreases with decreasing intensity and is well represented by a straight line for most of the range, in agreement with eq. (1). However, for

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([1]) At a detuning of -250 MHz the laser is resonant with the $F = 4 \rightarrow F' = 4$ transition. TOF signals are not seen for tunings below this resonance, but reappear at tunings just below $F = 4 \rightarrow F' = 3$.

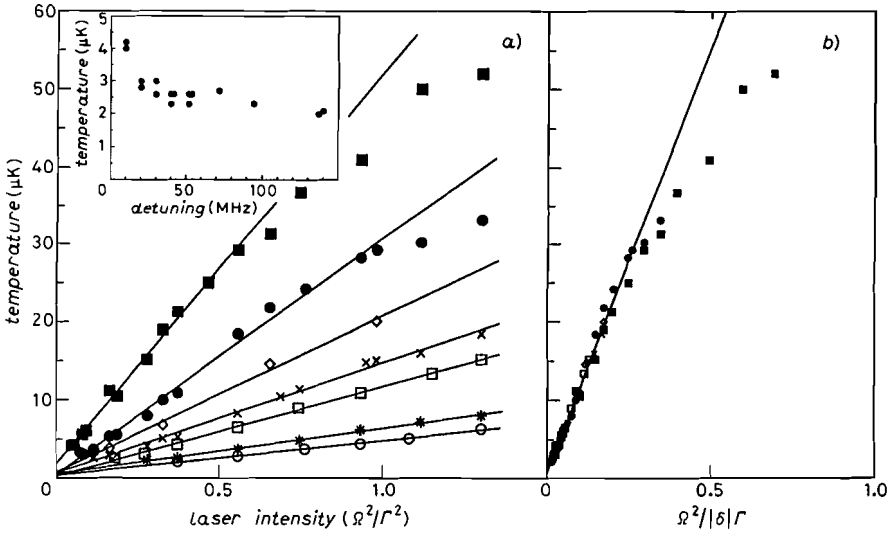

Fig. 2. – Temperature as a function of laser intensity and detuning. *a*) The lines are least-squares fits to those points which for a given detuning are within the range of validity of eq. (1). Insert: lowest temperature achieved as a function of detuning, for both polarization configurations. For $|\delta| \gg \Gamma$ ($\Gamma/2\pi = 5.3$ MHz) the lowest temperature is essentially constant. *b*) Temperatures of *a*) plotted against $\Omega^2/|\delta|\Gamma$. The straight line is a fit to the points with small $\Omega^2/|\delta|\Gamma$. $|\delta|/2\pi = 10$ MHz (■), 20 MHz (●), 30 MHz (◇), 40 MHz (×), 54 MHz (□), 95 MHz (*), 140 MHz (○).

each detuning, there is a lower limit to the intensity for which the molasses can function. As the intensity is decreased toward this limit, we observe a «disintegration» of the molasses which manifests itself as a dramatic decrease in the size of the TOF signal and the appearance of wide wings on the TOF spectrum. The signal finally disappears at an intensity which is nearly linear in detuning, and approximately given, to within about 15% for a given laser intensity calibration (see below), by $\Omega^2/|\delta|\Gamma = (0.6 + 2.5\Gamma/|\delta|) \cdot 10^{-2}$. At high intensity and for the smallest detunings, we observe a deviation from the linear law mentioned above; in this domain, the temperature increases more slowly than the laser intensity.

In order to further illustrate the agreement with eq. (1), we have replotted in fig. 2*b*) the temperature as a function of $\Omega^2/|\delta|\Gamma$. This strikingly demonstrates that the temperature depends only on this single parameter and is quite linear for small values of $\Omega^2/|\delta|\Gamma$. We determine C of eq. (1) by calculating $C(\delta) = |\delta|(\partial T/\partial I)$ for each δ. Excluding the $\delta = -10$ MHz data, these $C(\delta)$ are, as expected from eq. (1), independent of δ, to within a standard deviation of 5%. Expressing T in units of $\hbar\Gamma/k_B$, and detuning and Rabi frequency in units of the natural width Γ, C is dimensionless, and for lin ∥ lin we find the average $C_\parallel = 0.45$. The lin ⊥ lin data are similar and give $C_\perp = 0.35$.

The lowest measured temperature is (2.5 ± 0.6) μK. As shown in the insert of fig. 2, it is nearly independent of detuning for $|\delta| > 2\Gamma$ and we find that it is also independent of the polarization choice of the experiment. The corresponding r.m.s. velocity along the vertical axis $v_{\text{r.m.s.}} = (2k_BT/M)^{1/2}$ is only 12.5 mm/s or 3.6 times the single photon recoil velocity $v_{\text{rec}} = \hbar k/M$. Still narrower TOF peaks with «T» < 2 μK have been obtained but showing significantly non-Gaussian character in the wings.

The uncertainty (standard deviation) of 0.6 μK includes the following contributions. Uncertainty in vertical thickness of the slice and the probe: 0.3 μK; uncertainty in the calculated effect of the slicing: 0.3 μK; statistical fluctuations in the measured TOF widths: 0.3 μK; heating by the probe beam, which affects the time an atom spends in the probe:

0.1 μK. Other effects, such as uncertainty in the distance between the slice and the probe, each contribute less than 0.1 μK. At higher temperature the uncertainty in T is dominated by 5% statistical fluctuations and a 10% uncertainty due to the slicing. $C_{\parallel}$ and $C_{\perp}$ have in addition a 20% intensity calibration uncertainty for a total of 25%. Their ratio (1.29) is uncertain only by a statistical 7% and therefore differs significantly from unity.

Finally, we note that, while we have measured the temperature along a single vertical axis, considering the symmetry of the optical molasses, we have no reason to believe that the velocity distribution is anisotropic. Furthermore, we have checked that for intensity variations up to 30% in the vertical beams, the resulting temperature still depends only on the average of the intensity of the six beams. This suggests that such intensity anisotropies do not significantly alter the isotropy of the velocity distribution.

We now compare our experimental results with theoretical predictions. First, we emphasize that we know of no quantitative theoretical predictions for the temperature expected in three dimensions for a $F = 4 \rightarrow F' = 5$ transition. Theory has considered simpler transition schemes in one dimension [2, 3]. For 1D counterpropagating waves, two polarization gradient mechanisms giving sub-Doppler-limit temperature have been identified: ellipticity gradient where orthogonal linear polarizations produce cooling by a «Sisyphus mechanism», and rotation of polarization where σ^+-σ^- polarizations lead to cooling by velocity-induced radiation pressure imbalance.

For large $|\delta|$ and small velocity the force for Sisyphus cooling is larger than for σ^+-σ^- by a factor of $|\delta|/\Gamma$. This more efficient cooling is accompanied by a similarly stronger heating due to the fluctuations of the light shift gradient force which are not present in a pure σ^+-σ^- case. This leads for both mechanisms to nearly equal temperatures given by (1) with $C \approx 0.1$. Our observations confirm very well this prediction, but with $C \approx 0.4$. This difference may well result from the fact that in 3D, for a given intensity per beam (Ω^2), the average intensity is three times larger than in 1D and also from the fact that the prediction is for simpler transition schemes than in Cs.

In our experiment, the two mechanisms are clearly mixed up since both types of polarization gradient occur in the molasses. While one might suppose that the Sisyphus mechanism is dominant at large detuning, at first sight we have a problem in interpreting our experiment in terms of this single mechanism. As calculated in [2] for the Sisyphus mechanism, there is a critical velocity v_c, varying as I/δ^2; below v_c the cooling force $f(v)$ increases linearly with v, while above v_c it decreases as $1/v$. It would seem that eq. (1) is valid for Sisyphus cooling only over the range $v_{\text{r.m.s.}} < v_c$. However, for most of our experimental points the measured $v_{\text{r.m.s.}}$ is greater than v_c, and yet we observe excellent cooling (2). Fortunately this apparent contradiction is lifted because, as shown in [10], the momentum diffusion due to the fluctuations of the gradient force also decreases for $v > v_c$. It turns out that eq. (1) remains valid for Sisyphus cooling over a different range given by $v_{\text{r.m.s.}} < v_c(|\delta|/\Gamma)$, much larger than the range of linearity of $f(v)$. Only when this new condition is violated do we expect the appearance of wide wings in the velocity distribution. This occurs for a constant ratio of $\Omega^2/|\delta|\Gamma$, corresponding to $v_{\text{r.m.s.}}$ equal to a few recoil velocities [10]. This prediction is in good qualitative agreement with the experimental parameters for molasses disintegration at $|\delta| \gg \Gamma$ and with our minimum temperature. We note that at disintegration, where $v_{\text{r.m.s.}} \approx v_c(|\delta|/\Gamma)$, the Sisyphus cooling force is reduced to the level of the σ^+-σ^- force, so that one probably has to take into account both mechanisms in order to calculate quantitatively the exact conditions for disintegration.

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(2) Furthermore, requiring $v_{\text{r.m.s.}} < v_c$ leads to a lower limit of $v_{\text{r.m.s.}} > v_{\text{rec}}(|\delta|/\Gamma)$, while we find $v_{\text{r.m.s.}} = 3.6 v_{\text{rec}}$ even when $|\delta|/\Gamma = 26$.

Let us also point out that the average kinetic energy of the atoms is on the order of the light shifts of the atomic energy levels. Thus a significant fraction of the atoms may be trapped in the wells formed by the spatial modulation of these shifts. Such trapping may well have already been seen in Na molasses [11].

In conclusion, we have made detailed temperature measurements on laser-cooled cesium atoms, exploring a wide range of laser intensity and detuning. The lowest measured temperature of $(2.5 \pm 0.6)\,\mu K$ is 50 times lower than the Doppler cooling limit and corresponds to an r.m.s. velocity of 3.6 times the single-photon recoil velocity. This can be compared to a similar result of about three recoils found for Na in a 3D molasses [12]. The corresponding deBroglie wavelength is of the order of $0.2\,\mu m$, which opens the way for new experiments exploring the wave nature of these atoms. Also, such a cold and dense sample of atoms will be an ideal tool for frequency metrology and ultra-precise physical measurements.

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We wish to thank A. ASPECT, C. COHEN-TANNOUDJI and L. HOLLBERG for helpful contributions and discussions. WDP expresses his thanks to C. COHEN-TANNOUDJI, A. ASPECT, the Laboratoire de Spectroscopie Hertzienne, the Département de Physique de l'ENS, the CNRS and the Université de Paris VI for their hospitality and support during his stay in Paris, and to NIST and ONR for their support. This work was supported in part by Collège de France, DRET, and BNM.

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