Bimodal Speed Distributions in Laser-Cooled Atoms

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We report a bimodal speed distribution for sodium atoms cooled in "optical molasses." The temperatures of the two velocity groups differ in their dependence on laser detuning, sensitivity to beam misalignment and imbalance, polarization, and the presence of static magnetic fields. We believe that this behavior is evidence for two distinct cooling mechanisms.

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Since the three-dimensional laser cooling of atoms, "optical molasses," was first demonstrated,[1] many of its properties have been measured to be different from the predictions of the theory for cooling two-level atoms.[2] The alignment and intensity imbalances of the beams are less critical to the atomic confinement time than predicted.[3] In fact, some skewed alignments give factor-of-50 longer confinement times than precise retroreflection.[4] More recently, the NBS group has shown that the temperature of sodium atoms in optical molasses is 6 times colder than the theoretical "Doppler limit," and that the minimum temperature occurs when the laser is tuned $\simeq 3\Gamma$ (Γ = FWHM of the atomic resonance) below the atomic resonance, not at $\Gamma/2$ as the two-level theory predicts.[5] These measurements have been confirmed by our group for Na[6] and the Ecole Normale group has observed similar anomalously cold temperatures for Cs.[7] The accumulated evidence implies that the cooling mechanism in real molasses with large detunings depends on the 3D, multilevel nature of the atoms.[6] By identifying two velocity distributions with different properties, the results we report here indicate that there are at least two distinct cooling forces in optical molasses and that these forces are most effective in different velocity regimes.

Our apparatus is similar to that described in Ref. 1. The optical molasses consists of three orthogonal, orthogonally polarized, counterpropagating, Gaussian beams (waist=0.45 cm) produced by a cw dye laser with rf sidebands at ± 856.2 MHz from the carrier frequency in order to excite the $3S_{1/2}, F=1 \rightarrow 3P_{3/2}, F=2$ and $3S_{1/2}, F=2 \rightarrow 3P_{3/2}, F=3$ transitions in Na. Unless otherwise noted, the reported measurements were taken at between -10 and -12-MHz detuning and with 1.7 mW per sideband per beam. Atoms are loaded into the molasses region from a continuous atomic beam slowed by a light beam chirped by 600 MHz every 1.5 ms. We measure temperature using a time-of-flight (TOF) method of Lett *et al.*,[5] but modified by using a double shutter. After loading the molasses for 200 ms, the slowing laser beam is turned off for times between 5 and 100 ms. The laser beams are then shut off using an acousto-optic modulator, which extinguishes the light by $\simeq 65{:}1$ within 75 ns. A mechanical shutter in series with the acousto-optic modulator begins to close 1 μs later and completely blocks the light in 4 μs. This procedure avoids adiabatic cooling of atoms confined in standing-wave potential-well minima and spurious effects due to incomplete extinction of the molasses beams.[6] We observe the fluorescence of the atoms as they fall through a portion of two counterpropagating, horizontal, Gaussian probe beams (waist=0.2 cm), each with 0.13 mW per sideband, positioned 2.5 cm below the molasses center. Before the molasses beams are shut off, the sodium atoms are cleared from the region between the cooling volume and the probe with a 10 mW/cm^2 per sideband light beam. This beam helps reduce an initial fluorescent signal due to earlier losses from the molasses or stray atoms from the slowed atomic beam.

Figure 1 shows the fluorescence of the atoms as they fall through the probe region. At -25-MHz detuning, the TOF signal is similar to the signals reported by Lett *et al.*, but at smaller detunings a second peak appears.

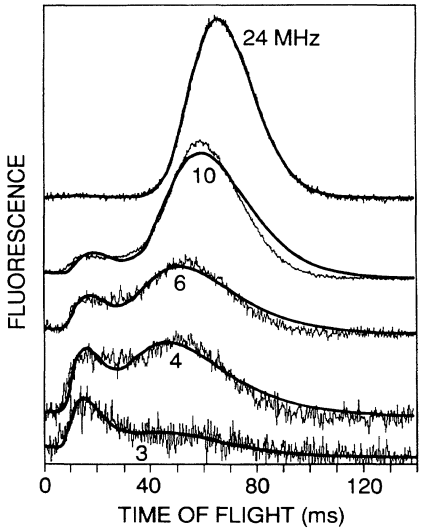

FIG. 1. The time-of-flight signal for various detunings of the laser from the D_2 resonance. The solid lines are a computer fit by the sum of two Boltzmann velocity distributions.

The size of the fast peak relative to the slow peak decreases by about 30% in the first 25 ms after the molasses loading is stopped, and then stabilizes. In order to more clearly illustrate the fast peak and to have a larger signal, the measurements shown were taken 5 ms after the molasses loading was stopped. The solid lines in Fig. 1 show least-squares fits of the data by a model of the TOF signal. The model assumes an initial Gaussian spatial distribution of atoms which are divided between two separate isotropic Boltzmann velocity distributions and a small exponentially decaying number of background atoms. This model fails to fit the data around the fast peak closely, so it is clear that our two-temperature parametrization is only a convenient approximation to the velocity distribution. The model also does not fit the slow peak at detunings ≤ 20 MHz because the slowest atoms undergo excessive scattering in the probe beam and do not follow their assumed ballistic trajectory. Attenuation of the probe beam improves the fit, but decreases the already small fast-peak signal.

The drag force $F(v)$ as a function of velocity and the diffusion of momentum D_p determines the velocity distribution of the atoms cooled in optical molasses. Setting aside for the moment details of a theory of laser cooling that would give the observed velocity distribution, we first examine the velocity distribution that one would expect for a given form of $F(v)$. For a gas of particles of mass m subject to a purely velocity-dependent force and to momentum diffusion, conservation of particles gives

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial v}\left[\frac{D_p}{m^2}\frac{\partial n}{\partial v} - \frac{nF(v)}{m}\right],$$

where $n = n(v,t)$ is the particle distribution function. The general steady-state solution is

$$n(v) = \left[c_1 + m^2 c_2 \int \frac{e^{-\int (mF/D_p)dv}}{D_p} dv\right] e^{\int (mF/D_p)dv},$$

and with the condition of no flux at infinity, the c_2 term equals 0. For $F(v) = -\alpha v$ and D_p independent of v (conditions expected for the two-level theory at low intensity and in the Doppler-limited velocity range) the solution is a thermal distribution $n(v) = c_1 \exp(-mv^2/2kT_a)$, where the temperature is $kT_a = K_p/\alpha$.

Now suppose the drag force is $F = -\alpha v$ for $v < v_c$ and $F = -\alpha v_c - \beta(v - v_c)$ for $v \geq v_c$. The distribution will be Gaussian with mean velocity $\bar{v} = 0$ and a width $kT_\alpha = D_p/\alpha$ only up to $v = v_c$. For $v \geq v_c$ the distribution is again Gaussian, but with $\bar{v} = (1 - \alpha/\beta)v_c$ (the v intercept of the force for $v > v_c$ projected back to the v axis) and width $kT_\beta = D_p/\beta$. This velocity distribution will make the time-of-flight signal bimodal. Computer solutions of the optical Bloch equations for the $3P_{3/2}$, $F = 3$, to $3S_{1/2}$, $F = 2$ levels have allowed us to calculate $F(v)$ according to a generalization of the two-level treatment of Gordon and Ashkin.[2] In the low-velocity range appropriate for atoms cooled in optical molasses and at detunings where a clear bimodal signal has been observed, we find that $F(v)$ can be approximated by a two-slope function such as the one discussed above. This work will be discussed thoroughly in a later publication.

We now discuss the velocity distribution as we change experimental parameters such as laser detuning, beam imbalance and misalignment, laser polarization, and magnetic field. In all these measurements, the fast atoms respond differently to changes in the experimental conditions as compared to the slow atoms.

The two fitted temperatures as a function of laser detuning are shown in Fig. 2 along with the prediction of the two-level theory for our intensity.[2,8] Note that the temperature of the fast atoms is minimized at a small detuning as the two-level theory predicts, while the temperature of the slow atoms continues to decrease at large detunings and is smaller than the "Doppler limit" of 240 μK by a factor of 6. The minimum temperature of the fast atoms is larger than the two-level theory prediction for our intensity by a factor of 3, but this temperature drops from 1.7 to 1.1 mK (at a detuning of -10 MHz) if the TOF measurement is delayed for 55 ms after the molasses loading is stopped.

The TOF fast-peak signal is very sensitive to beam imbalance and misalignment, and this dominates the ± 1-mK uncertainty in our absolute temperature measurements. Intensity imbalances of 10% between counterpropagating beams lead to factor-of-2 changes in the slow-to-fast-peak ratio, primarily due to changes in the fast-peak magnitude. Also, if the beam collimation is worse than 3 mrad, then the fast peak ceases to be discernible as a clear peak. Data taken with an approximately uniform beam-intensity profile are not significantly different from data taken with Gaussian beams.

The temperature of the slow peak is very sensitive to

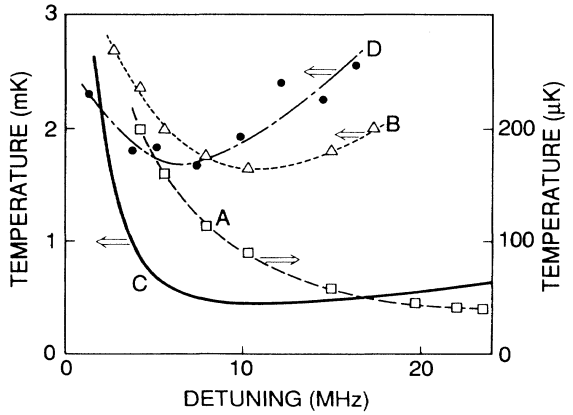

FIG. 2. The temperature vs detuning of, curve a, the D_2 slow-velocity component; curve b, the D_2 fast-velocity component; curve c, the theoretical temperature of a two-level atom with the experimental parameters used for a; curve d, the D_1 molasses temperature.

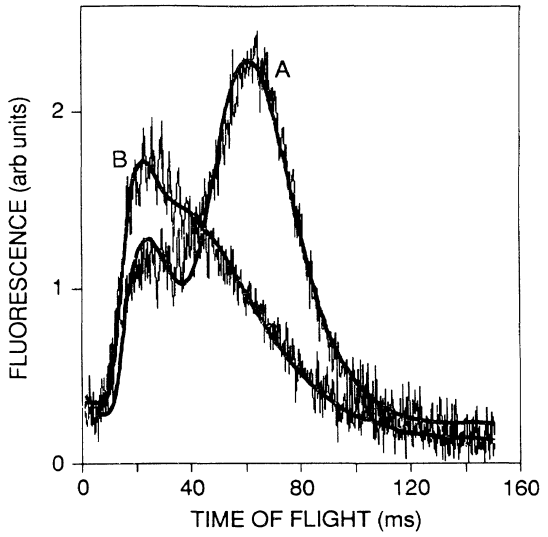

FIG. 3. The time-of-flight signal for, curve *a*, orthogonally polarized beams and, curve *b*, when the polarization of one of the horizontal beams is parallel to that of the vertical beam.

the orientation of the polarization of the molasses beams. Figure 3, curve *a* shows the TOF signal at -6-MHz detuning for mutually orthogonal linear polarizations while Fig. 3, curve *b* shows the signal when one of the *horizontal* beams is polarized parallel to the *vertical* beam. The velocities of atoms along the vertical axis increase by a factor of 1.7 while there is no significant change in the fast peak. The apparent change in the ratio of the *number* of slow to fast atoms between curves *a* and *b* in Fig. 3 is exaggerated by the measurement since the faster atoms spend less time in the probe region. When the polarizations of both horizontal beams are parallel to each other, the temperature of the slow peak increases slightly, but the peak is 8 times smaller. Since the time-of-flight method is primarily sensitive to the temperature in the vertical direction, these measurements make it clear that the velocity distribution ceases to be isotropic. These data also suggest that the mechanism that cools the slow atoms requires a changing electric field orientation in the atoms direction of motion. The temperature of the slow atoms rises sharply with increasing magnetic field. For example, at a detuning of -12 MHz and an intensity of 5 mW per sideband per beam, the temperature rises from 0.18 mK at $B \leq 0.1$ G to 1.0 mK in a 2.1-G field. On the other hand, the temperature of the fast atoms when the linear polarizations are configured to suppress the slow peak is relatively less sensitive to magnetic fields, rising from 2.4 to 3.2 mK for the same change of field.

We have studied optical molasses near the D_1 line ($3S_{1/2} \rightarrow 3P_{1/2}$), using the $F=1 \rightarrow 2$ and $F=2 \rightarrow 1$ transitions. In order to circumvent optical pumping into a nonabsorbing (dark) $F=2$ ground state during the initial slowing process, we scrambled the polarization continuously from linear to circular polarization at a 4-MHz rate. The frequency dependence of the single temperature associated with D_1 molasses is shown in Fig. 2, curve *d* (7 mW per sideband per beam for these measurements) and is very similar to the fast-velocity component of the D_2 molasses. Moreover, the temperature dependence on misalignment, polarization, and magnetic field is also much like that of the fast atoms in D_2 molasses. These results suggest that the cooling mechanism responsible for the fast D_2 peak is similar to the one that causes the D_1 peak, while the process responsible for the slow D_2 peak is not present in the D_1 molasses.

Although it is comforting that the solutions to the optical Bloch equations can give nonthermal velocity distributions, the physical reason for the velocity dependence of the force must be determined. Given the accumulated evidence, it is tempting to separate the cooling mechanism into two parts. We wish to identify the cooling mechanism responsible for the hot velocity group as the standard molasses due to photon recoil first envisioned by Hansch and Schawlow.[9] The sensitivity of the temperature of the fast peak to misalignment, intensity imbalance, and detuning and the insensitivity to magnetic field and polarization is consistent with the behavior of recoil cooling. The only discrepancy is that the temperature is slightly higher than expected. A tentative explanation of the cooling mechanism responsible for the slow velocity group has been proposed by us and independently by Dalibard and Cohen-Tannoudji.[10] The mechanism uses the fact that an atom excited from F to $F+1$ angular momentum states will tend to optically pump into the lowest energy Zeeman sublevels of the ground state. Nonadiabatic motion of the atom to a region of space where the local electric field is pointing in a different direction causes a population mixing with higher energy m_F levels. Thus, the kinetic energy of the atom is converted into its internal energy. Subsequent optical pumping completes the cooling cycle by returning the atom back to the optically pumped distribution of states. This explanation appears to explain the qualitative behavior of the slow atoms described in this paper and in Ref. 5. Furthermore, the rough calculation of the damping force based on this physical argument[10] agrees with the solution to the optical Bloch equations to 30%.

The velocity dependences of the two postulated cooling forces also provide an explanation of why the two cooling mechanisms seem to act on separate velocity groups. Both forces are linearly proportional to velocity for very low velocities, but then each force reaches a maximum for a different $v_{\rm crit}$ before becoming less effective for large velocities. The orientational cooling force reaches a maximum when the atom moves a distance $\simeq\lambda$ in roughly two optical cycling times. At low intensities, $v_{\rm crit}({\rm slow}) = \lambda/2\tau$, where $\tau = \tau_{\rm atom}/p$, $\tau_{\rm atom} = 16$ ns, and p is the saturation parameter.[2] For an intensity of 2.6

mW/cm^2 and -12-MHz detuning, $v_{crit}(slow) \simeq 50$ cm/s. On the other hand, the photon recoil force has $v_{crit}(fast) = c\Omega/v \simeq 700$ cm/s, where $h\nu$ is the energy of the photons and Ω is the laser detuning. The combination of these two forces should give the velocity dependence of the damping force calculated from the solution of the optical Bloch equations.

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[7]C. Cohen-Tannoudji (private communication).

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