Transverse laser cooling of a velocity-selected sodium atomic beam

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Abstract. The transverse velocity distribution of a sodium atomic beam, laser cooled in one dimension, has been measured with sub-recoil resolution. A velocity-selective detection system was employed to separate the longitudinal and transverse velocity components to provide a direct measure of the transverse velocity distribution. The effects of varying the cooling laser intensity and detuning on the derived transverse temperature are presented, and show a remarkable insensitivity to the laser intensity. Atomic velocities within a factor of two of the recoil velocity are achieved.

1. Introduction

The production of highly collimated atomic beams is of importance for a number of atom optics applications which require low divergence sources, such as atom lithography, atom interferometry or atomic physics collision experiments. One means of producing such highly collimated beams is to reduce the transverse velocity spread of the atomic beam using counterpropagating laser fields perpendicular to the atomic motion and detuned slightly below resonance. This cooling mechanism can be enhanced through the use of polarization gradients, which can be orders of magnitude more efficient than Doppler cooling techniques [1].

Specifically, we consider here the case of polarization gradients induced by two counterpropagating laser fields polarized linearly and orthogonally. Such linear polarization produces a light field whose ellipticity varies in a repeated pattern every half wavelength from linear, to circular, to orthogonal linear, to oppositely circular, back to oppositely linear. The result is that atoms which pass through the generated periodic potential experience a cooling force as a result of the Sisyphus effect [2].

The limits to polarization gradient cooling of the transverse atomic velocity are of considerable interest both theoretically and for the applications mentioned previously. Central to this interest is the dependence of the transverse atomic temperature on the laser intensity. The early analytical treatment of polarization gradient cooling by Dalibard and Cohen-Tannoudji [2] showed that for large intensities, where diffusion effects predominate, the transverse temperature increases linearly with the laser intensity. However, the laser intensity cannot be decreased arbitrarily to produce lower temperatures since at very low intensities the cooling force ceases to be linear with velocity. The result is that a minimum
can be expected in the cooled temperature, which is predicted to be larger than the recoil temperature \( T_r \), defined by

\[
k_B T_r = \frac{\hbar^2 k^2}{2M}
\]

where \( k = 2\pi/\lambda \) (\( \lambda \) is the wavelength), \( M \) is the atomic mass, and \( k_B \) and \( \hbar \) are the Boltzmann and Planck constants, respectively.

A quantum treatment of this problem in the low excitation limit by Castin \textit{et al} [3] confirmed the linear dependence of the transverse temperature at higher intensities. Instead of a temperature, they used the average transverse kinetic energy, which is related to the mean momentum, \( p_{\text{rms}} \) by

\[
E_K = \frac{p_{\text{rms}}^2}{2M}.
\]

The intensity \( I \) is related to the light shift potential \( U_0 \) in the two beams (normalized by the recoil energy \( E_r = h\nu_r \)) by

\[
\frac{U_0}{h\nu_r} = f \frac{\Delta}{\nu_r} G \frac{1 + G}{1 + 4G^2/\Gamma^2}
\]

where \( \nu_r \) is the recoil frequency (24.9 kHz), \( \Delta \) is the interaction laser detuning, \( \Gamma \) is the natural linewidth of the transition and \( G \) is the single-beam saturation parameter \( I/I_0 \) (\( I_0 = 6 \) mW cm\(^{-2} \) is the saturation intensity for the sodium transition). The factor \( f \) is given by [3, 4]

\[
f = \frac{(2F + 1)(F + 1) - 1}{(2F + 1)(F + 1)} = \frac{14}{15} \text{ for the } F = 2 \to F = 3 \text{ transition in sodium}.
\]

Equation (3) is valid in the low excitation limit (\( \Delta \gg \Gamma \)).

At high intensities (\( U_0 \) larger than the value at the minimum kinetic energy) and for the one-dimensional cooling case for sodium considered here, Castin \textit{et al} [3] predict a slope of 0.14 for the transverse kinetic energy as a function of the light potential \( U_0 \). This slope is to be compared with a value of 0.19 from the simple analytical treatment [2].

The minimum in the kinetic energy is again predicted, yet it appears to occur at a normalized potential that is relatively independent of the atomic species, at around \( U_0 \sim 100E_r \) (for sodium, at \( U_0 \sim 105E_r \)). Below this value, the kinetic energy increases rapidly with decreasing intensity. The minimum kinetic energy was shown to be relatively independent of laser detuning for \( \Delta \gg \Gamma \), and for sodium yields a value of \( E_K \sim 40E_r \).

The question arises as to whether the mean kinetic energy can be used to assign a temperature to the cooled atoms. As Castin \textit{et al} point out, if the momentum distribution is a Gaussian then a temperature can be assigned, since in this case \( p_{\text{rms}}/M \) is equal to the half width of the velocity distribution at the \( 1/\sqrt{e} \) point. However, both in their quantum Monte Carlo calculations and in their analytical calculations, these quantities diverge, with the result that the minimum in the \( 1/\sqrt{e} \) width of the velocity distribution (as opposed to the \( p_{\text{rms}} \) curve) occurs at a value for \( U_0 \sim 25E_r \) in the case of caesium. The minimum velocity width at this value of \( U_0 \) for a detuning of \( \Delta = -15\Gamma \) is \( v_{\text{min}} \sim 3\nu_r \), i.e. an energy of \( \sim 9E_r \).

A number of experiments using trapped atoms with long interaction times and at large detunings have verified the theoretical predictions of these models, confirming, for the case of three dimensions, a linear dependence of the temperature on the light potential [5–7]. Experiments on one-dimensional cooling of trapped atoms have also demonstrated the expected linear dependence on the light potential [8, 9].
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However, the situation is less conclusive for the one-dimensional transverse cooling of a thermal atomic beam. The width of the transverse velocity distribution has not shown the expected dependence on the light potential in experiments using a rubidium atomic beam [10]. This experiment revealed a lower slope for $E_K$ versus $U_0$ than expected from the previously mentioned theoretical predictions: indeed an almost flat behaviour for the transverse kinetic energy at higher intensities was observed.

However, as was pointed out by Bergeman [4] and later by Doery et al [11], there are a number of complicating factors in beam experiments which inhibit the interpretation of such results. Firstly, in contrast to atom trap studies, the interaction time for atomic beam experiments is usually limited by the maximum available laser power, which determines the maximum interaction length. Typical atomic beam interaction times are less than a few thousand natural lifetimes. In such situations the transverse velocity distribution seldom reaches the steady-state limit (particularly where large transverse velocities are present). Consequently, careful quantum Monte Carlo modelling is required to determine the expected final spatial distribution in the atomic beam [4, 11].

The difficulties of including other non-ideal experimental effects such as the shape of the initial velocity distribution, the laser intensity distribution and the interaction transit time, must be addressed. The result is that a decisive comparison between experiment and theory is very difficult.

The work reported here provides data for the transverse cooling of a sodium atomic beam, using counterpropagating laser beams with lin.Llin polarization. Various laser polarization configurations were also studied, but orthogonal linear polarizations were found to produce the most effective cooling.

A distinguishing feature of the present experiments is the use of a longitudinal velocity-selective detection system which enables a direct determination of the transverse velocity distribution. This technique simplifies interpretation of the experimental results due to the elimination of one of the non-ideal conditions, namely the existence of multiple interaction times.

In the present experiments, the detection region was illuminated using a second laser incident at an angle to the atomic beam in order to select a single longitudinal velocity group. The spatial profile of the resulting laser-induced fluorescence then yielded a direct measure of the transverse velocity profile, with sub-recoil resolution. By placing a knife edge immediately following the interaction region, the divergence of the atomic beam downstream from the knife edge was used to determine the transverse velocity distribution of the cooled atoms. The transverse temperature was therefore derived directly due to the separation of the longitudinal and transverse velocities.

The results reported here for the case of one-dimensional cooling of sodium are again at variance with current polarization gradient theory. Indeed, despite the existence of other non-idealized conditions that include finite interaction times, non-uniform laser field intensity distributions and optical pumping processes in a multilevel system, we managed to achieve transverse temperatures more than an order of magnitude less than the minimum predicted by infinite interaction time models [2, 3]. Once more the experiments reveal a very weak dependence of the transverse temperature on the laser intensity.

2. Experiment

The experimental configuration was similar to that used in previous experiments in this laboratory [12] and is shown in figure 1. A sodium atomic beam was produced by a thermal oven source operating at a temperature of 400–450 °C and with an exit aperture
of 1 mm diameter. After passing through a skimmer, the beam was apertured by a 1 mm (height) $\times$ 3 mm (width) slit located 350 mm downstream from the oven, that also served as the entrance port for the differentially pumped interaction chamber. The 1 mm atomic beam height restriction was used to minimize the variation of the interaction laser intensity across the atomic beam in the vertical direction. The 3 mm width (combined with the 1 mm oven aperture) provided a broad range of transverse velocities for the cooling experiment. The interaction chamber itself was located within a full set of Helmholtz coils to minimize the effect of stray magnetic fields (residual magnetic field $B < 1 \mu T$).

Light from a stabilized ring dye laser (the interaction laser—a Spectraphysics 380D operated with R6G) formed the transverse cooling beam. The beam passed through an 856 MHz electro-optic modulator and the two first-order sidebands were used to generate the cooling and repumping laser frequencies. Each of these sidebands contained $\approx \frac{1}{3}$ of the total laser power. An anamorphic prism pair was used to magnify the horizontal dimension of the laser beam by a ratio of 4:1. A telescope system was employed to further increase the dimensions of the interaction laser beam, and was also used to collimate the laser to $< 0.5$ mrad. The intensity in the interaction region could be varied by rotation of a half wave plate placed before a linear polarizer. The maximum laser intensity averaged over the interaction region was 13 mW cm$^{-2}$ ($\frac{1}{3}$ of the total intensity). This corresponds to a maximum, single beam, on-resonance saturation parameter of $G \sim 2$ at the centre of the beam.

An aperture with a 15 mm horizontal width was placed in the laser path prior to the interaction region at a distance of 75 mm from the atomic beam (outside the interaction chamber). The edges of the aperture defined the length of the interaction region. The collimated laser beam intensity profile was measured very precisely using a 25 $\mu$m pinhole and a power meter mounted on a micrometer-driven translation stage on the far side of the interaction region. The pinhole was scanned horizontally across the laser beam, and the resulting profile is shown in the inset to figure 1.

The structure in the measured laser intensity profile results from diffraction and interference effects. This structure may also be present in similar experiments elsewhere,
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but may not be noticeable unless measured using such a high-resolution, two-dimensional technique. The translating slit method often employed averages out variations in one dimension and may smooth out such spatial structure.

In the present experiment, the structure could not be eliminated easily without the use of spatial filtering, which would have reduced the laser intensity to impractical levels. The period of the structure, however, is very small compared to an atomic oscillation period in an optical potential well, and the structure is therefore believed to have only minor implications for the cooling results (see discussion). The rising/falling edge of the light field had a width of 300 $\mu$m, which was made as small as possible to minimize the effect of adiabatic cooling.

Upon passing through the interaction region the laser was retro-reflected from a rotatable mirror located outside the interaction chamber 100 mm from the atomic beam. Depending upon the cooling method used, polarizing elements could be placed between the mirror and the exit window to define the interaction field. The polarization schemes used were $\sigma^+ - \sigma^-$, $\sigma^+ - \sigma^+$, linear and orthogonal linear (lin.lin—the configuration shown in figure 1).

The laser beam entering the interaction region was aligned horizontally to within a few mrad. Perpendicular alignment to the atomic beam axis is achieved by using a corner cube reflector on the far side of the interaction region to produce a second fluorescence spot in the atomic beam. By detuning the laser frequency appropriately, the relative brightness and spatial distribution of the fluorescence spots could be monitored, a symmetric behaviour indicating that perpendicular alignment of the incoming laser had been achieved. The perpendicularity of the laser beam reflected from the rotatable mirror was achieved by ensuring that the cooled atomic beam profile was spatially symmetric with respect to the centroid of the uncooled beam.

The interaction laser was tuned to the sodium $\{3s\}^2S_{1/2} (F = 2) \rightarrow \{3p\}^2P_{3/2} (F = 3)$ transition at 589.1 nm. The laser frequency was referenced to the signal from a sodium absorption cell. The zero detuning of the laser could also be determined to within $\pm 1$ MHz by the rapid change from cooling to heating effects as the laser goes through resonance. A high-finesse spectrum analyser with a 1.5 GHz free spectral range and a stability of $\pm 2$ MHz over the observation period was then used to measure the interaction laser detuning with a repeatability of $< 0 / 4$.

The spatial profile of the atomic beam was measured by a velocity selective laser fluorescence system located in a separate vacuum chamber 1.64 m from the interaction region. The system consisted of a second, independently tunable laser (a single-mode Coherent 699-21 operated with R6G) which was tuned to the transition between the $\{3s\}^2S_{1/2} (F = 2)$ hyperfine ground state and an excited state. The laser-induced fluorescence (LIF) produced as the atoms decayed into both the $\{3s\}^2S_{1/2} (F = 2)$ and $\{3s\}^2S_{1/2} (F = 1)$ states yielded a signal proportional to the number of atoms entering the detection region in the $F = 2$ state. (Strictly speaking, there are three accessible upper hyperfine levels, but the fluorescence signal is dominated by the $F = 3 \rightarrow 2$ transition.) This state selective detection system is therefore used to detect only those atoms which interacted with the cooling laser field.

In order to provide velocity selectivity, the detection laser crosses the atomic beam at 74$^\circ$ to the propagation axis of the atomic beam. For sufficiently low detection laser powers (below saturation), the longitudinal velocity resolution is determined by the atomic linewidth (9.7 MHz) which was much greater than the laser bandwidth ($\sim 1$ MHz). The combination of intersection angle and detection bandwidth yields a longitudinal velocity resolution of $\pm 10$ m s$^{-1}$. The detection laser was detuned by 320 MHz to select a longitudinal velocity of 700 m s$^{-1}$. This was just below the peak of the Maxwellian velocity distribution in order
to detect slower atoms with a longer interaction time, while at the same time providing reasonable signal levels.

The LIF was detected by a linear, 1024-element Reticon photodiode array via a dual-lens achromat imaging system with unity magnification. The detection laser was focused in the horizontal direction using a cylindrical lens to provide a fluorescence region with a small depth of field (and hence sharper image) for the detection system.

The size of the detector pixels (25 µm) determines the spatial resolution of the apparatus. The Reticon was parallel to the detection laser beam, i.e. at 74° to the atomic beam axis, and the 1024-element linear array was aligned horizontally. The distance to the interaction region yields an angular resolution for each pixel of ~15 µrad. This corresponds to a transverse velocity resolution of 1 cm s\(^{-1}\) (~\(\frac{1}{2} \hbar k\)) for a longitudinal atomic velocity of 700 m s\(^{-1}\).

The position of the detector relative to the fluorescence region can be adjusted using a two-axis positioning system to focus and translate the detector in the horizontal direction. In order to optimize the focus, a slit ~15 µm wide and ~1 mm high can be moved into the atomic beam immediately upstream of the detection region. The image of the resulting 15 µm wide fluorescence region can then be optimized using the focusing mechanism, yielding a FWHM of 3 pixels. Given that the fluorescence region is itself ~1 pixel wide, this measurement determines the instrument resolution of the entire detection system due to all sources of systematic error to be better than ±1 pixel (±\(\frac{1}{3} \hbar k\)).

The detector array accumulates signal from the detection region and the output is sampled after an integration time of 2 s. A sequence of five traces is stored and the result averaged to improve the signal-to-noise ratio. Background subtraction techniques are further employed to reduce systematic contributions to the noise level. Detailed spatial profiles of the transversely cooled atomic beam in the far field were then obtained using this system.

In general, the spatial distribution consisted of a well defined peak of transversely cooled atoms on a broad background of atoms which had experienced significantly less interaction with the cooling laser field. To determine the transverse velocity distribution of the cooled atoms, we used a knife edge to partially block the atomic beam 160 mm downstream from the laser cooling region [13]. After the knife edge, the atoms traversed 1.48 m until they were illuminated by the detection laser.

The knife edge was aligned vertically using diffraction from a helium neon laser to produce a diffraction pattern that was horizontal to better than a few mrad, which was all that was needed to ensure parallelism of the knife edge with the 25 × 1000 µm vertical elements of the photodiode array.

The knife edge provides the effect of a point source. If we take the angular distribution of the cooled beam as \(f(\alpha)\), where \(\alpha\) is the angle to the atomic beam axis, then the spatial profile can be written as

\[
I(x) = \int_{\alpha_{\min}}^{\pi/2} f(\alpha) \, d\alpha
\]

where \(I(x)\) is the fluorescence intensity at distance \(x\) from the beam axis and \(\alpha_{\min} = \tan^{-1}(x/1.48)\), assuming the knife edge blocks the atomic beam for \(x < 0\). Taking the derivative of this profile then provides the angular distribution \(f(\alpha)\).
Because we have selected a single longitudinal velocity group, then the divergence angle is linearly related to the transverse velocity. That is, an atom following a path at angle $\alpha$ to the beam axis at longitudinal velocity $v_l$ must have transverse velocity $v_l \alpha$. Hence, from $f(\alpha)$ we have the transverse velocity distribution directly, because $f(v_l) = f(\alpha)$. The width of the derivative of $I(x)$ (i.e. $f(\alpha)$) is a measure of the width of the transverse velocity distribution.

The knife edge was placed at the peak of the cooled atomic spatial distribution. By differentiating the resulting spatial profile for atoms detected in a specific longitudinal velocity group (defined by the detection laser frequency), the transverse velocity distribution of the cooled atoms in that group could be measured directly.

### 3. Results

The spatial distributions of atoms near the peak of the longitudinal velocity distribution ($v_l = 700 \text{ m s}^{-1}$) were measured as a function of laser polarization, intensity and detuning. The most efficient cooling polarization was found to be lin.$\perp$lin, and it is the results of these measurements that are presented here.

An example of the spatial profile measured in the experiments is shown in figure 2(a).
The profile consists of a sharp peak of cooler atoms on a broad background, and the peak is cut by the knife edge with the penumbral region falling off to the left. In order to minimize the effect of noise on the differentiation of the spatial profile, the penumbral region for the cold peak is fitted by a combination of error functions (for which the derivative is a Gaussian) using a least-squares fitting routine.

The first iteration used two error functions, one to simulate the cooler beam with the other representing the broad, hotter background. However, in order to achieve a good fit, it was found necessary to introduce a further error function. The three individual error functions are shown in figure 2(b) and their resultant fit is shown in figure 2(a).

The derivative for the fitted curve is shown in figure 2(c) together with the derivative of the raw data. As can be seen, the main Gaussian fits the narrow central peak reasonably well, while the small secondary peak fits the shoulder on the left-hand side. The broad Gaussian corresponding to the hotter atoms is not evident as it is much flatter on this scale.

The results of the calculations by Castin et al [3] indicate that such velocity distributions may not always be Gaussian, and hence cannot always be characterized by a temperature. Depending upon whether a compact (small $p_{\text{rms}}$) momentum distribution or a narrow central peak (small $1/\sqrt{\varepsilon}$ half width) is used as a fitting criterion, both the optimal value of $U_0$ and the minimum energy/temperature may vary by a factor of four as mentioned previously.

However, as can be seen from figure 2(c), a Gaussian fit to the narrow central peak is a good approximation. The $1/\sqrt{\varepsilon}$ half width of the spatial profile for the cooled atoms is then converted to transverse velocity half widths $v_t$ directly using the pixel calibration from the previous section. The temperature $E_K = \frac{1}{2} M v_t^2$ is then plotted as a function of the light potential, and is shown in figure 3. Also shown is the area under the derivative curve (proportional to the total number of cooled atoms) as a function of the light potential.

![Figure 3](image.png)

**Figure 3.** Temperature of cooled atoms (full squares) normalized to the photon recoil energy ($E_r$) and the area under the cooled peak (circles) as a function of $U_p$ ($\Delta = -0.67\Gamma$). The chain line represents a best linear fit to the temperature points for $U_p > 70 E_r$. Note that the Doppler limit $E_D = 100 E_r$ for sodium.
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Figure 4. Temperature of cooled atoms as a function of $U_p$ for a series of detunings at three laser saturation values $G$. The detunings range from $-0.6\Gamma$ in steps of $-0.6\Gamma$ from right to left.

The laser intensity is expressed in normalized units for the light shift potential divided by the recoil energy. However, at the small detunings employed in the present experiment ($\Delta \sim \Gamma$) the previous expression for the light shift $U_0$ is not valid. A more correct expression for the normalized light shift potential in this parameter range has been derived for the case of a two-level atom by Gordon and Ashkin [14]:

$$\frac{U_p}{\hbar \nu_r} = \frac{\Delta}{\nu_r} \ln[1 + G/(1 + 4\Delta^2/\Gamma^2)].$$ (6)

Note that the expression in (6) is twice the single laser potential, as is also the case for $U_0$ in (3). However, the logarithmic term in (6) takes into account the excited state character of the atomic wavefunction near resonance. This is usually neglected at large detunings by omitting ‘ln’ from the expression, as is done by Castin et al [3] in the weak excitation limit ($\Delta \gg \Gamma$). By contrast, equation (6) gives a better approximation at small detunings ($\Delta \gg \Gamma$) and in the adiabatic limit.

The detuning dependence of the normalized temperature is shown in figure 4. Here, a sequence of detunings is performed at three different laser saturation values $G$, and the temperature plotted as a function of $U_p(G, \Delta)$. As was the case for figure 3, the vertical error bars are obtained from the least-squares fitting routine.

4. Discussion

The results shown in figure 3 confirm the measurements obtained elsewhere for chromium [13] and rubidium [10], namely that the cooling efficiency (number of cooled atoms) increases monotonically with intensity, and that the transverse temperature is remarkably insensitive to laser intensity. Over the range of normalized potentials from $U_p = 70–140E_r$, there is only a slight increase in temperature. At low values of the potential ($U_p < 70E_r$) the temperature rises sharply with decreasing potential. In this regard, the results are in
As indicated by the discussion in [3], the minimum turning point occurs at a value of the potential for which $U_0 = 105E_r$ or $25E_r$, depending upon whether the velocity distributions can be represented by a single Gaussian or otherwise. Here, we fit the velocity distributions (figure 2(c)) to a sum of three Gaussians. We therefore need to compare the temperature (as derived from the half width at the $1/\sqrt{e}$ point, of the cold part of the measured velocity distribution) to the latter theoretical value for which the minimum turning point is $25E_r$.

The quantitative comparison is not very good. The slope of the straight line fitted to the experimental curve for $U_p > 70E_r$ is 0.007, much smaller than the theoretical value of 0.14. The experimental turning point value for $U_p$ is $\sim 70 E_r$, cf $25E_r$. The discrepancy may be caused by the fact that the theoretical curve was calculated for large detunings ($\Delta = -15\Gamma$), whereas the measurements in figure 3 were obtained at small detunings ($\Delta = -0.6\Gamma$).

The effect of different combinations of laser intensity and detuning leading to the same value for $U_p$ is illustrated in figure 4. At large detunings ($\Delta \gg \Gamma$), the extent of cooling should simply scale on a single curve with $U_p$. However, at the small detunings used here, figure 4 indicates that this is not the case. At varying laser intensities, the dependence of $E_K$ on $U_p$ is different. The expected minimum in temperature occurs at $U_p \approx 50E_r$, except at the lowest intensity, for which a minimum was not measured. The slope changes dramatically, from 0.09 for $G = 0.9$ to 0.02 for $G = 2.2$. Consequently, it is difficult to compare the theoretical results, obtained at large detuning, and plotted against $U_0$, to the present data, plotted against $U_p$.

The most remarkable result, however, is that the minimum temperatures obtained are much cooler than predicted by earlier theories [2, 3]. The lowest temperature observed here is $\sim 1.8E_r$, which is more than an order of magnitude less than the minimum theoretical temperature as determined from $p_{rms}$ ($40E_r$), and a factor of $\sim 5$ less than the narrow central peak criterion [3]. The lowest velocity widths achieved (4 cm s$^{-1}$) are approaching the recoil velocity (2.95 cm s$^{-1}$), which is as low as has been achieved by, for example, adiabatic cooling [15].

The question then arises as to whether adiabatic cooling can contribute to the low temperatures observed in the present experiment. The result of a simple estimate shows this to be unlikely.

The potential indicated by the laser intensity profile shown in the inset to figure 1 decreases at the edge of the aperture over a distance of $\sim 300 \mu$m, which for 700 m s$^{-1}$ atoms gives a transit time $t_t \sim 400$ ns.

To satisfy adiabaticity one must have $|\dot{\omega}|/\omega = \epsilon \omega$ [16], where $\epsilon \ll 1$ and $\omega$ is the oscillation frequency of atoms in the potential wells, given by

$$\omega = \frac{E_r}{\hbar} \sqrt{\frac{4\hbar|\Delta|G}{E_r(1 + 4\Delta^2/\Gamma^2)}}.$$  \hspace{1cm} (7)

In our case, we have an upper limit for $\omega \sim 4 \times 10^6$, leading to $\epsilon > 0.3$. The values for $\epsilon$ considered by Kastberg et al [16] to be necessary for adiabatic cooling are in the range $0.02 < \epsilon < 0.2$. The upper limit for $\omega$ above corresponds to at most one full oscillation period during the transit time through the falling edge.

Consequently, we believe that in the present experiment there is insufficient time for the atoms to experience adiabatic cooling. Similar arguments can be made to discount adiabatic cooling in the structure evident on the laser intensity profile, for which the length scales are even smaller. While a complete Monte Carlo calculation of the atomic trajectories is required to account fully for the effects of spatial inhomogeneity, the indications are that adiabatic cooling is not responsible for the low temperatures observed.
Comparison with the full quantum Monte Carlo treatment of Bergeman [4] is difficult, since the case of sodium was not considered. However, similar calculations for rubidium for similar interaction times (1300s⁻¹) yield temperatures approaching the lowest values measured here in sodium. A direct comparison of theoretical calculations with the measured velocity distributions under the current experimental conditions is therefore needed.

Finally, it remains to consider the existence of the third but much smaller Gaussian required to fit the experimental velocity distributions. This suggests the presence of a third (transverse) velocity group of atoms, slightly displaced from the central peak of cooled atoms, and also significantly cooled (with widths of a few \( v_t \)). This shoulder on the transverse velocity distribution may arise from a slight imbalance in the laser intensity, introduced by the optical elements through which the laser beam passes before being retroreflected. For the \( \sigma^+\sigma^- \) polarization configuration these effects have been discussed extensively by Werner et al [17], and yield similar shoulders in the velocity distribution.

5. Conclusion

Measurements have been performed with sub-recoil resolution on the transverse cooling of a longitudinally velocity-selected sodium atomic beam in a lin⊥ lin laser field. A minimum temperature occurs as a function of \( U_p \), in qualitative agreement with theoretical predictions.

However, at the small detunings used, the expected scaling with \( U_p \) appears to be complex, which makes quantitative comparison with theory difficult. At a fixed, small detuning, the temperature nevertheless appears to be less sensitive than expected for values of \( U_p \) larger than the value at the minimum temperature.

Furthermore, the lowest kinetic energies obtained (\( E_K \sim 1.8E_r \), i.e. \( v_t \sim 1.4v_r \)) are significantly lower than expected. It is unlikely that adiabatic cooling effects are responsible for such low temperatures.

However, quantum Monte Carlo calculations for other atomic species do indicate similar temperatures for polarization gradient cooling. These calculations also suggest that careful account needs to be taken of the effects of variations in the spatial intensity and velocity distributions in the calculation of the cooled atomic distributions [4, 11].

Finally, there is some experimental evidence of a second cooled transverse velocity group, possibly the result of imbalance in the counterpropagating laser beams.

In order to make a direct comparison with all features of the present data, a full quantum mechanical Monte Carlo calculation of the atomic trajectories using a polarization gradient model for sodium under the same experimental conditions is required.

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References


