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Temperatures in 3D optical lattices influenced by neighbouring transitions

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Abstract. A detailed experimental study of the steady-state temperature in a 3D optical lattice for cesium has been performed for a wide range of detunings. Specifically, we have investigated the situation with the cooling and trapping light detuned far red of a ($J_\mathrm{g} \to J_\mathrm{e} = J_\mathrm{g} + 1$)-transition, where the blue detuned interaction with a ($J_\mathrm{g} \to J_\mathrm{e} = J_\mathrm{g}$)-transition can not be neglected. We find that the temperature scales with the optical potential due to the interaction with just the ($J_\mathrm{g} \to J_\mathrm{e} = J_\mathrm{g} + 1$)-transition. This indicates that blue Sisyphus cooling has essentially no effect on the dynamics of the system, when there exists a neighbouring red detuned transition.

PACS. 32.80.Pj Optical cooling of atoms; trapping – 03.75.Be Atom and neutron optics

Optical lattices consist of an array of potential wells, created by the interference of two or more laser beams, where cold atoms can be trapped. Thus, a periodic structure of matter is formed [1,2]. They have for example been used as a general platform to study various fundamental phenomena, as a means of getting very cold samples for precision measurements, as well as for studies of analogues to solid-state physics (*cf.* [1] and references therein). For a near-resonance optical lattice (NROL), the dynamics of the atomic motion is highly influenced by spontaneous emission and optical pumping, which always provides heating, and under favourable conditions also inherent cooling. In the standard situation for a NROL, the optical lattice laser beams are detuned below (red of) a ($J_\mathrm{g} \to J_\mathrm{e} = J_\mathrm{g} + 1$)-transition [1,3], where J_g and J_e are the angular momentum quantum numbers of the ground and excited states of an atom. In contrast, a ($J_\mathrm{g} \to J_\mathrm{e} = J_\mathrm{g}$)-transition requires positive (blue) detuning. This configuration carries the extra attraction that for high enough angular momentum, atoms can be trapped in dark states which in principle means that there is no lower limit for the temperature. In a real physical system, there is usually a manifold of upper levels that can all have important influence on the cooling and heating mechanisms simultaneously. With few exceptions [4,5] the role of neighbouring transitions for red and blue Sisyphus cooling has not been taken into account in previous work. In this paper we present a thorough experimental investigation of the steady-state temperature in a three dimensional (3D) NROL tuned to a range of laser frequencies between the ($F_\mathrm{g} = 4 \to F_\mathrm{e} = 5$)- and ($F_\mathrm{g} = 4 \to F_\mathrm{e} = 4$)-transitions of the D2 line in cesium at 852 nm ($6s\ ^2\mathrm{S}_{1/2} \to 6p\ ^2\mathrm{P}_{3/2}$). These two resonances (the red and the blue transition) are separated by 48.1Γ, where $\Gamma/2\pi = 5.22$ MHz is the natural linewidth of the transition. The third allowed transition ($F_\mathrm{g} = 4 \to F_\mathrm{e} = 3$) is separated from ($F_\mathrm{g} = 4 \to F_\mathrm{e} = 4$) by 38.6Γ. In Figure 1 the upper level hyperfine manifold is displayed.

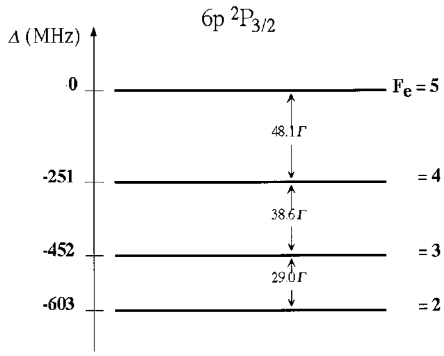

Fig. 1. Hyperfine structure manifold in the excited level $6p\ ^2\mathrm{P}_{3/2}$. The frequency scale is given with $F = 5$ as the origin. The separation between hfs-states is also given in units of the natural linewidth.

In the commonly accepted semi-classical model for the cooling process in a NROL (Sisyphus cooling) [3], atoms climb sinusoidal potential wells, thus losing kinetic energy and gaining potential energy. The higher they climb, the bigger the probability gets that they will be optically pumped into a magnetic substate with lower potential energy. In this way kinetic energy is extracted from the atoms so efficiently that they can become cold enough to get trapped in local minima of the light shift potential. The steady-state temperature is predicted to scale linearly with light shift ($k_\mathrm{B}T \propto U \propto I/|\Delta|$ where U is the

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modulation depth of the light shift potential, I is the intensity, and Δ is the detuning from resonance), which has been confirmed experimentally in optical molasses without spatial order [6] as well as in controlled optical lattices [7,8]. According to the model referred to, this comes about because the steady-state temperature is assumed to emerge from a balance between cooling and heating effects. The cooling rate is independent of intensity, whereas the heating scales as the scattering rate ($\propto I/\Delta^2$), and thus the temperature will decrease linearly as the intensity is lowered. In this work, as in most other experimental investigations (*e.g.* [7,8]) the optical lattice actually operates in the so-called oscillating regime, and the theoretical dragged-atom model of [3] may not be appropriate. Nevertheless, the linear scaling of the temperature with light shift still holds.

For red Sisyphus cooling on a ($J_\mathrm{g} \rightarrow J_\mathrm{e} = J_\mathrm{g} + 1$)-transition, the atoms will be preferentially pumped into the magnetic sublevel $M_{J_\mathrm{g}} = J_\mathrm{g}$ around points where the polarization is σ^+ [3]. This state couples stronger to the σ^+-field than it does to the σ^--field. Therefore optical pumping will at all positions tend to transfer atoms to the lowest local potential, and thus extract energy from the system. Also for blue Sisyphus cooling on a ($J_\mathrm{g} \rightarrow J_\mathrm{e} = J_\mathrm{g}$)-transition, the atoms will again be pumped into $M_{J_\mathrm{g}} = J_\mathrm{g}$ around a σ^+-site. Once there the atom can only interact with the σ^--light. Since this field has a minimum at this point, the light shift has to be positive in order to make this into a potential minimum, and thus the detuning has to be blue. One main interest in blue Sisyphus cooling stems from the fact that atoms are pumped into a state where the interaction with the light field is minimized. Thereby temperature and density limiting effects should be less severe. Blue Sisyphus cooling has been used in various configurations [9–11], but to our knowledge no detailed experimental study and comparison to red Sisyphus cooling has been made.

For most cases the actual situation is one where both cooling schemes may coexist. Consider for example a situation where the laser is detuned between a ($J_\mathrm{g} = 1/2 \rightarrow J_\mathrm{e} = 3/2$)- and a ($J_\mathrm{g} = 1/2 \rightarrow J_\mathrm{e} = 1/2$)-transition. If one follows the derivation of the friction coefficient and of the diffusion constant in [3] and adds terms corresponding to the added interaction with an extra level, one gets the following expression for the steady state temperature:

$$k_\mathrm{B}T \propto \frac{D}{\alpha} \propto \frac{\hbar\Omega^2}{8} \frac{\dfrac{\Delta_{1/2}}{2\Delta_{3/2}} + \dfrac{\Delta_{3/2}}{2\Delta_{1/2}}\chi^2 + \chi}{\Delta_{1/2} + \chi\Delta_{3/2}} \,. \tag{1}$$

Here Ω is the Rabi frequency at the center of a potential well, defined as $\Omega^2 = (\Gamma^2/2)(I/I_0)$, I is the intensity, I_0 is the saturation intensity, $\Delta_{3/2}$ and $\Delta_{1/2}$ are the detunings from the respective upper levels, and χ is the relative strength of the two transitions. In the standard situation where $\Delta_{3/2} \ll \Delta_{1/2}$ this reduces to the familiar $k_\mathrm{B}T \propto I\Omega^2/\Delta_{3/2}$. Similarly, close to the blue transition we get $k_\mathrm{B}T \propto I\Omega^2/\Delta_{1/2}$. For higher angular momenta red Sisyphus cooling has been found to retain the temperature scaling from the simplified model in [3]. For that reason, an intuitive assumption from the simplistic model above is that close to any transition, for blue as well as for red Sisyphus cooling, the temperature should scale as the intensity divided with the detuning to the close transition. For the present experiment this suggests that when we start close to the ($F_\mathrm{g} = 4 \rightarrow F_\mathrm{e} = 5$)-transition and tune further and further away, towards ($F_\mathrm{g} = 4 \rightarrow F_\mathrm{e} = 4$), the previously confirmed [6–8] relation $k_\mathrm{B}T \propto I\Omega^2/\Delta_5 \propto U_5$ (where U_5 is the modulation of the light shift potential taking only the red transition into account, and Δ_5 is the detuning from the red transition) might no longer hold. Instead the temperature should get a more complicated dependence on the laser frequency, which subsequently turns into $k_\mathrm{B}T \propto I\Omega^2/\Delta_4 \propto U_4$ as the next hyperfine transition is approached. An even more straightforward assumption would be that the temperature is always proportional to the modulation depth of the total optical potential, $k_\mathrm{B}T \propto U_\mathrm{tot} = U_5 + U_4 + U_3$.

With high angular momenta the ground state sublevels are coupled through stimulated Raman transitions. Including this in the analysis makes the interaction Hamiltonian non-diagonal and a solution yields the so-called adiabatic potentials [1,2,12]. Especially for blue Sisyphus cooling, this changes the nature of the cooling process. Here, the lowest state will be decoupled from the radiation field, independent of position. There is still a slight probability that the atom will get optically pumped to another potential though, and this will primarily happen where the upper potential has a minimum. Before the atoms is pumped back to the uncoupled state, it will have to move uphill, and thus, there will be a friction mechanism even for this configuration. This was examined in [11] for a blue-detuned ($J_\mathrm{g} \rightarrow J_\mathrm{e} = J_\mathrm{g} - 1$)-transition, where the temperature was found not to scale as the intensity divided by the detuning to the blue transition.

In the original Sisyphus cooling scheme, the atom has to be energetic enough to make it up one half period of the diabatic potential (where the above mentioned coupling can be ignored) in order to be optically pumped and cooled. Therefore one could assume that the adiabatic potentials are irrelevant (see [12] for a detailed discussion). Even if this hypothesis is true for hot (untrapped) atoms (the jumping regime), the fact that the cooling continues even when the atoms are very well localized at the bottom of the potential wells (the oscillating regime), suggests that there may be additional cooling mechanisms for cold (trapped) atoms. There have been speculations about different *local* cooling mechanisms [12]. For example, for a multilevel system an atom oscillates on the lowest potential curve, and near its classical turning point, the probability for the atom to get optically pumped into the second lowest potential is as high as it will get. If it is pumped, it will then slide back on a more shallow potential towards the trap center, where the probability for it to be optically pumped back to the lowest potential is very high. In this model, the cooling rate, and the steady-state temperature ought to be related to the difference in curvature

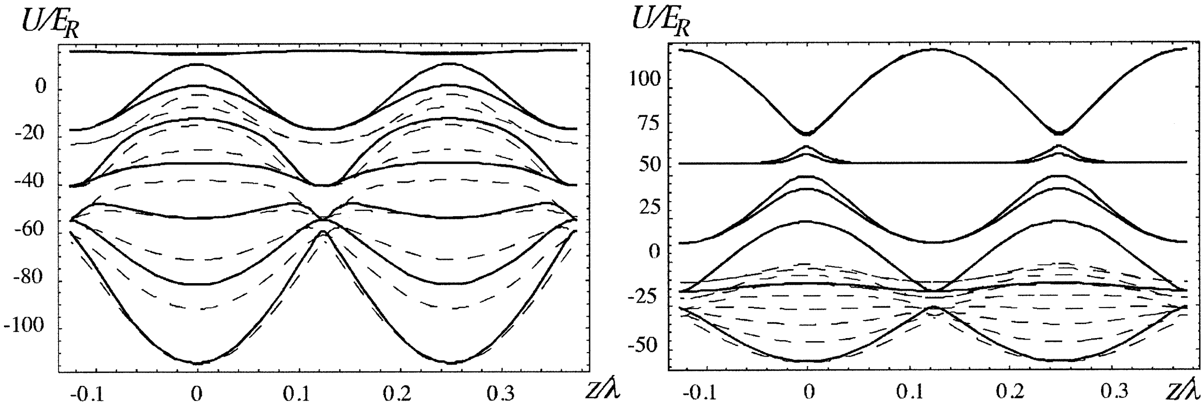


Fig. 2. The adiabatic potentials for all nine sub-levels of $F_g = 4$ at a detuning from the ($F_g = 4 \rightarrow F_e = 5$)-transition of (a) $\Delta_5 = -20\Gamma$ and (b) $\Delta_5 = -40\Gamma$. The full lines show the potential when all allowed transitions have been taken into account in the derivation, whereas the dashed lines show the potentials due only to the ($F_g = 4 \rightarrow F_e = 5$)-transition.

between the lowermost potentials. Close to the red transition, this quantity scales as U_5 and previous measurements do not disagree with the hypothesis. As the blue transition is approached though, the lowest adiabatic potential of the U_{tot}-manifold is still almost identical to the lowest U_5-potential, whereas all higher potentials change dramatically. This is illustrated in Figure 2, and can easily be understood from the fact that the lowest state in a pure ($J_g \rightarrow J_e = J_g$)-transition is decoupled from the light, and thus the blue transitions contribution to the lowermost adiabatic potential is minimal. So, if this local Sisyphus model accurately describes the cooling process, U_5 ought not to be a correct scaling parameter for the temperature as the detuning is increased. On the other hand, if the equilibrium temperature is determined solely by the curvature of the lowest potential, the temperature should scale essentially as U_5 through the whole investigated interval. For a single red transition, the adiabatic and diabatic potentials have the same curvatures and the same vibrational quantization close to the bottom. In our mixed case however, the curvature of the total adiabatic potential will agree with U_5, rather than U_{tot}, within the level of our experimental uncertainties. This is illustrated in Figure 3, which shows a plot (for the 1D-case) of calculated curvatures, as a function of detuning, in terms of the squares of the oscillation frequencies in an harmonic oscillator approximation.

In our experiment a magneto-optical trap (MOT) is loaded from a chirp-slowed atomic beam. The MOT is formed by 3 mutually orthogonal pairs of laser beams (1 cm diameter, 20 and 10 mW power). The magnetic field gradient is 0.1 T/m in the central region of the trap. The number of atoms in the initial MOT are about 2 millions, the 1/e-diameter is 0.4 mm, and the density is in the order of 5×10^{10} cm^{-3}. After about two seconds of loading, the magnetic field is switched off and the atoms are further cooled for about 15 milliseconds in a 3D optical molasses, yielding a temperature of 3–4 μK. The molasses beams are then switched off and the optical lattice beams are switched on simultaneously. The lattice is a 3D general-

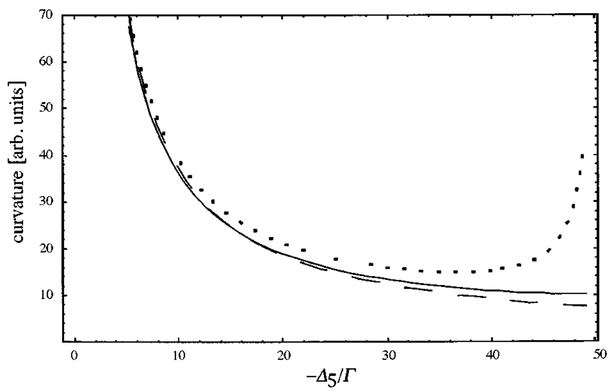
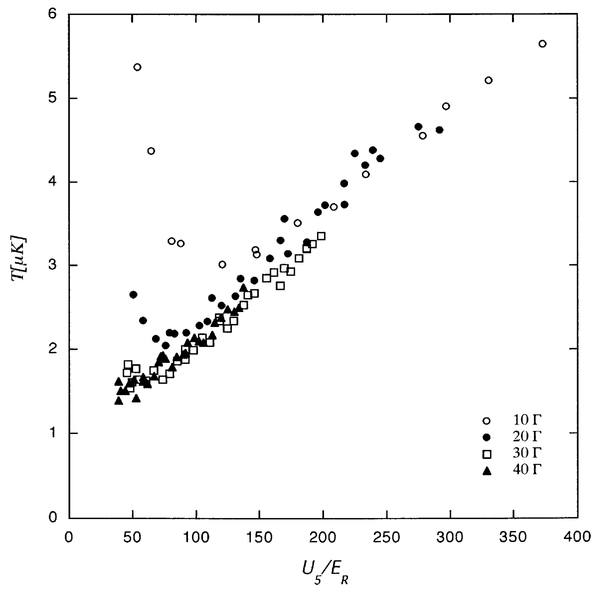
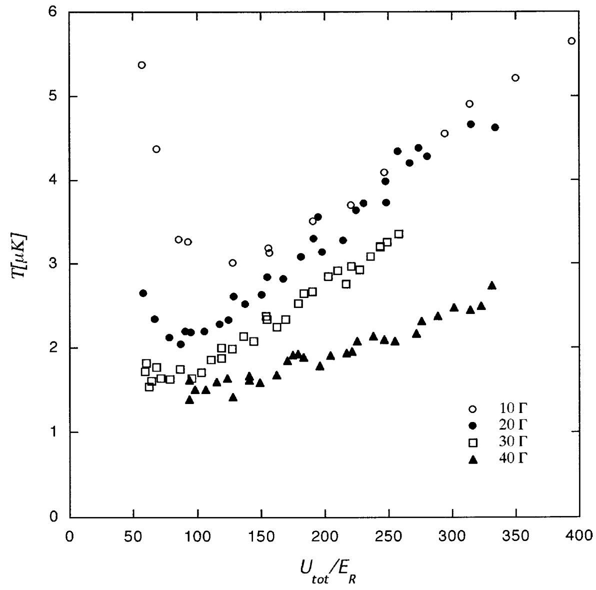


Fig. 3. The curvature at the bottom of the lowest potential as a function of detuning from the ($F_g = 4 \rightarrow F_e = 5$)-transition at a constant intensity. The dashed line refers to the diabatic potential due to the ($F_g = 4 \rightarrow F_e = 5$)-transition, U_5, the dotted line to the total diabatic potential, $U_{tot} = U_5 + U_4 + U_3$, and the full line to the total adiabatic potential.

ization of the 1D lin $\perp$ lin configuration created by two orthogonally polarized pairs of laser beams that propagate in the yz- and xz-plane respectively. The angle between the beams of each pair is 90°, and each beam forms an angle of $\theta = 45°$ with the (vertical) quantization (z-) axis. This results in a tetragonal structure with alternating sites of pure σ^+- and σ^--light, where potential minima are formed. The lattice constants are $a_z = \lambda/2\sqrt{2}$ and $a_{x,y} = \lambda/\sqrt{2}$. The lattice beams are spatially filtered with an optical fiber. Their profile is made flat-top with a diameter of 2 mm by imaging a pinhole in the interaction region. The beam intensities range from 0.4 mW/cm^2 to 3 mW/cm^2. After letting the atoms equilibrate for typically 10–15 ms, the lattice beams are switched off and the Gaussian velocity distribution along the z-axis is measured with a time-of flight technique. The probe beam (height 0.5 mm) is placed 5 cm below the lattice. The laser frequency of the lattice beams is detuned red of the ($F_g = 4 \rightarrow F_e = 5$)-transition. This detuning is varied



(a)



(b)

Fig. 4. Kinetic temperature for four different detunings (see inset) as a function of light shift, U_5, due to the ($F_{\rm g} = 4 \rightarrow F_{\rm e} = 5$)-transition, and (b) as a function of the light shift of all allowed transitions, $U_{\rm tot} = U_5 + U_4 + U_3$. The light shift is given in units of the Cs recoil energy.

between $\Delta_5 = -3\Gamma$ and $\Delta_5 = -47\Gamma$. For detunings between $\Delta_5 = -40\Gamma$ and $\Delta_5 = -47\Gamma$ we notice a destructive effect of the lattice light on the MOT if the lattice light is kept on during loading and precooling. This effect peaks at approximately $1/2\Gamma$ to 1Γ blue of the ($F_{\rm g} = 4 \rightarrow F_{\rm e} = 4$)-transition and we attribute it to blue Doppler heating. For each detuning the temperature is measured as a function of laser intensity. The repumper mostly operates at the ($F_{\rm g} = 3 \rightarrow F_{\rm e} = 4$)-transition. For detunings between $\Delta_5 = -40\Gamma$ and $\Delta_5 = -47\Gamma$ we have also tried to tune the repumper to the ($F_{\rm g} = 3 \rightarrow F_{\rm e} = 3$)-transition, without seeing any significant change in temperature. The laser beam intensity is derived by measuring the power and the diameter of the optical lattice beams.

Figure 4a shows data for various detunings ($\Delta_5/\Gamma = -10, -20, -30, -40$), where the kinetic temperature is plotted against U_5, the modulation depth of the red transition, normalized to the recoil energy, $E_{\rm R} = \hbar\omega_{\rm R} = \hbar^2k^2/2m$ ($\omega_{\rm R}/2\pi = 2.07$ kHz and $m = 133$ u is the atomic mass for Cs). Here we ignore the contributions of other transitions and obtain this diabatic potential by just keeping the diagonal elements of the effective ground state Hamiltonian. The light shift potential (excluding saturation) is

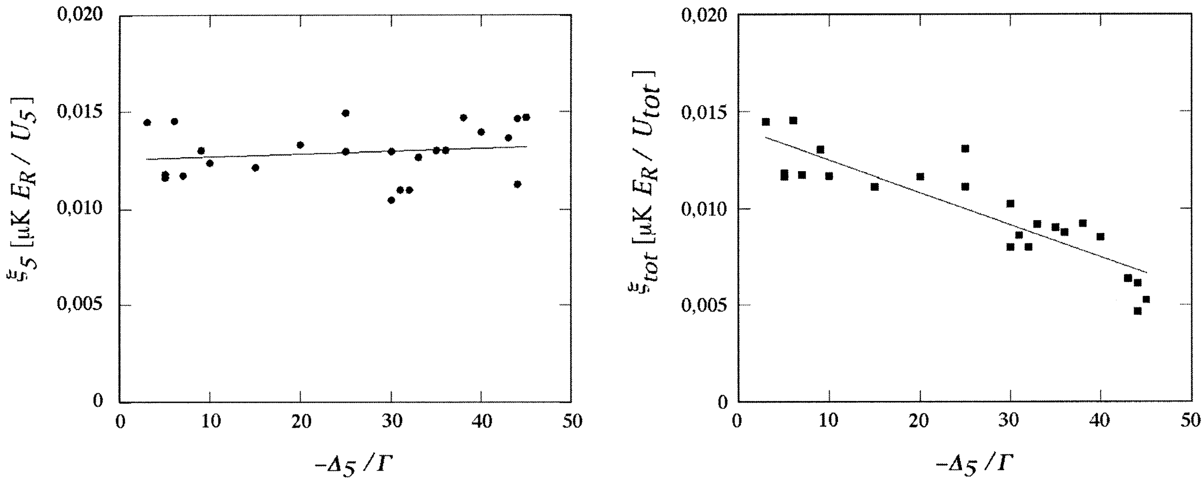
$$U_5 = \frac{\hbar\Delta_5}{2}\left(\frac{44}{45}\right)\frac{\Omega^2}{2\Delta_5^2} = \frac{\hbar}{2}\left(\frac{44}{45}\right)\frac{\Gamma^2 I}{4I_0\Delta_5} \qquad (2)$$

where $I = 8I_{\rm beam}$ is the laser intensity at pure σ^+/σ^--sites and $I_0 = 1.1$ mW/cm^2 for the D2-line in Cs. The factor 44/45 originates from the difference of the squares of the Clebsch-Gordan coefficients (CGC) connecting $M_{F_{\rm g}} = \pm 4$ to $M_{F_{\rm e}} = \pm 3$ and $M_{F_{\rm e}} = \pm 5$. We see that the temperature scales linearly with light shift in a wide range even close to the blue transition. After reaching a minimum, the temperature increases rapidly at low intensities. The same data is plotted in Figure 4b, this time scaled with the total diabatic potential $U_{\rm tot} = U_5 + U_4 + U_3$. U_4 and U_3 are the diabatic light shift potentials due to the ($F_{\rm g} = 4 \rightarrow F_{\rm e} = 4$) and ($F_{\rm g} = 4 \rightarrow F_{\rm e} = 3$)-transitions and are

$$U_4 = \frac{\hbar\Delta_4}{2}\left(\frac{7}{60}\right)\frac{\Omega^2}{2\Delta_4^2}, \qquad (3)$$

$$U_3 = \frac{\hbar\Delta_3}{2}\left(\frac{21}{84}\right)\frac{\Omega^2}{2\Delta_3^2}\,. \qquad (4)$$

The factors 7/60 and 21/84 are due to the CGC and the relative ratio of the reduced dipole moment d_i between the transitions d_5:d_4:d_3 = 12:7:3. Figure 4b clearly shows that $U_{\rm tot}$ does not provide a global scaling parameter. In Figure 5 we plot slopes of the linear parts of curves such as the ones in Figure 4, as a function of detuning Δ_5. The points scatter around a constant value of $\xi_5 = 12.6(1.4)$ nK/$E_{\rm R}$ when the temperature is scaled against U_5 (Fig. 5a) even for detunings close to the ($F_{\rm g} = 4 \rightarrow F_{\rm e} = 4$)-resonance ($\Delta_5 = -48.1\Gamma$). This is not the case in Figure 5b where instead $U_{\rm tot}$ has been applied. The error of 12% in the slopes is the sum of the maximum possible systematic errors (dominated by the uncertainty in the absolute value of the intensity of 10%) and the run to run scatter in temperature measurements.



(a) (b)

Fig. 5. Measured slopes of temperature *versus* light shift, as a function of detuning; (a) is obtained by using U_5, and (b) by using U_{tot}, as a scaling parameter for the temperature. The solid line is a linear fit that here mainly serves the purpose of a guide for the eye.

Our measured value of ξ_5 is smaller than the one reported by Gatzke *et al.* ($\xi_5 = 24(2.8)$ nK/E_{R}) [7] by approximately a factor of 2 even though the lattice configuration is identical. This could be explained by the fact that in contrast to the work by Gatzke *et al.* we measure the kinetic temperature parallel to the quantization axis z. In our $\theta = 45°$ configuration the lattice spacing in the z-direction is half as big as in the transverse direction which could lead to an anisotropy in temperature. To our knowledge there has been no previous experimental indications of different temperatures in different direction, however theoretical investigations show that such differences may occur [13,15].

The fact that the U_5 appears to provide a global scaling through the whole interval indicates that there is no effect on the dynamics of the atoms from blue Sisyphus cooling for the relevant range of parameter. Even very close to the blue transition, where the red transition is detuned by almost 50 linewidths, the latter is the one that matters. The regular behaviour with U_5 also excludes the local Sisyphus model. In themselves, our measured temperature scalings do not disagree with a hypothesis that it is the curvature of the total adiabatic potential that determines the steady-state temperature. That would also explain different temperatures along different directions. However, the curvature along the z-axis is a factor of $\sqrt{2}$ higher that along the transversal directions, but our measured slopes of temperature-*versus*-intensity-curves are a factor of two lower than those in [7]. Therefore, we also exclude the curvature as a scaling parameter for the temperature.

In conclusion we have measured the steady-state temperature in a 3D optical lattice for laser frequencies detuned between the ($F_{\mathrm{g}} = 4 \rightarrow F_{\mathrm{e}} = 5$) and ($F_{\mathrm{g}} = 4 \rightarrow F_{\mathrm{e}} = 4$)-transitions within the D2-line in Cs. We find that the temperature does not scale as the modulation depth of the total diabatic potential. Instead the data indicate that the temperature in a particular direction is determined solely by the intensity and the detuning from the ($F_{\mathrm{g}} = 4 \rightarrow F_{\mathrm{e}} = 5$)-transition and that the appearance of neighbouring transitions has no direct influence. Furthermore, our measured value of ξ_5 suggests that there is an anisotropy in temperature for the used configuration. The reported results can not easily be explained by conventional semiclassical models of laser cooling [3,16]. We hope that this work stimulates a thorough theoretical investigation of the cooling process for the setup we presented. A rigorous quantum Monte Carlo simulation [13] could possibly clarify the somewhat confusing results.

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