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Study of laser cooling in deep optical lattice: two-level quantum model

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Abstract. We study a possibility of laser cooling of ^{24}Mg atoms in deep optical lattice formed by intense off-resonant laser field in a presence of cooling field resonant to narrow $(3s3s)\,^1S_0 \to (3s3p)\,^3P_1$ ($\lambda = 457$ nm) optical transition. For description of laser cooling with taking into account quantum recoil effects we consider two quantum models. The first one is based on direct numerical solution of quantum kinetic equation for atom density matrix and the second one is simplified model based on decomposition of atom density matrix over vibration states in the lattice wells. We search cooling field intensity and detuning for minimum cooling energy and fast laser cooling.

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1. Introduction

Nowadays deep laser cooling of neutral atoms is routinely used for broad range of modern quantum physics researches including metrology, atom optics, and quantum degeneracy studies. The well-known techniques for laser cooling below the Doppler limit, like sub-Doppler polarization gradient cooling [1], velocity selective coherent population trapping [2, 3] or Raman cooling [4, 5] are restricted to atoms with degenerated over angular momentum energy levels or hyperfine structure. However, for atoms with single ground state ^{24}Mg, ^{40}Ca, ^{88}Sr, ^{174}Yb are of interest for developing optical time standard these techniques can not be applied directly. For example, for ^{24}Mg atoms with the ground state $^1S_0$ the Doppler cooling temperature ($k_B T_D \approx \hbar\gamma/2$) can be reached on closed singlet transition $^1S_0 \to {}^1P_1$ ($\lambda = 285.3$ nm). For lower temperature additional cooling on $^3P_2 \to {}^3D_3$ optical transition with degenerated over angular momentum energy levels can be applied [6, 7]. However, the experimental realization of laser cooling on $^3P_2 \to {}^3D_3$ optical transition does not result significant progress. The atoms were cooled to temperature $T \approx 1\,mK$ is about Doppler limit only [7]. The quantum simulation of laser cooling are also shows the limitation of cooling temperature to about Doppler limit in conventional MOT, formed by laser waves with circular polarization [8].

An alternative way of deep laser cooling of these elements is to use narrow lines and "quenching" techniques of narrow-line laser cooling [9, 10, 11] successfully applied for ^{40}Ca atoms, the recent the recent progress on cooling 88Sr on narrow line in dipole trap was also reported in [12], but, to our knowledge, still do not show significant progress for ^{24}Mg atoms.

Recently, laser-driven Sisyphus-cooling scheme was proposed for cooling atoms in optical dipole trap [13]. This scheme utilize the difference in trap-induced ac Stark shift for ground and exited levels of atom coupled by resonant laser light. The laser cooling scheme has clear semiclassical interpretation: been excited by resonant laser light on the bottom of shallow optical potential related to the ground state an atom moves further in steepest potential related to excited state. Spontaneous emission returns it back from the steepest potential in the excited state to the shallow potential in the ground state. The loosing a portion of energy in each act of these processes leads to atom cooling after several cycles due to "Sisyphus effect" [13]. This semiclassical model was applied for description of laser cooling of Yb and Sr in optical dipole trap.

In the following paper we study application of this cooling scheme to ^{24}Mg atom on narrow $(3s3s)\,^1S_0 \to (3s3p)\,^3P_1$ ($\lambda_1 = 457\,\text{nm}$, $\gamma_1 = 196\,\text{s}^{-1}$) optical transition for the atoms trapped in optical lattice at $\lambda_L = 1064$ nm. Additional light field resonant to $(3s3p)\,^3P_1 \to (3s4s)\,^1S_0$ optical transition ($\lambda_2 = 462$ nm, $\gamma_{21} = 109$

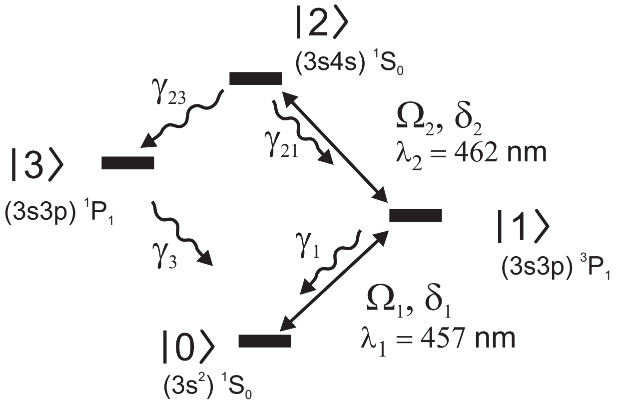

Figure 1. *Relevant energy levels for optical quenching and cooling of* ^{24}Mg.

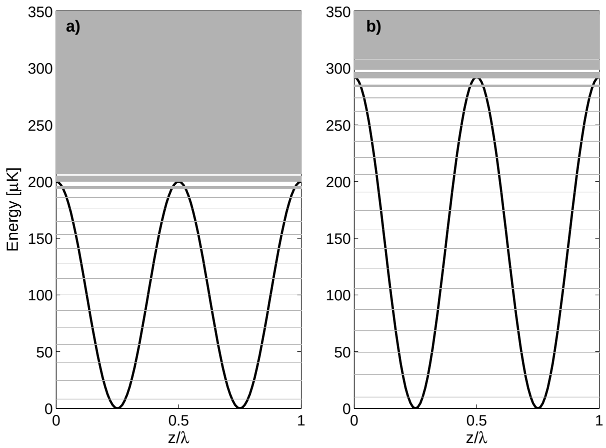

Figure 2. *Ac Stark shift and vibration energy levels for ground* $^1S_0$ *(a) and excited* $^3P_1$ *(b) states of* ^{24}Mg *atoms in optical lattice potential with* $\lambda_L = 1064nm$.

s^{-1} and $\gamma_{23} = 2.1 \cdot 10^7\ \mathrm{s}^{-1}$) is applied for optical quenching (see Fig.1), i.e. increasing the effective linewidth of optical transition [11]. We find the semiclassical description of laser cooling of Mg atom with narrow optical transition can't be used here. The simulation of force on atom shows it is strongly varied on a scale of velocity $\Delta v \ll \hbar k/M$, i.e. on a range that corresponds recoil momentum obtained by atom in the processes of absorption and emission of light fields photons. For description of laser cooling we use quantum approaches that allow to take into account optical pumping and photon recoil effects in laser cooling process. In the paper we point our attention to minimum laser cooling temperature for described scheme and cooling time as well.

2. Description of the models

We consider motion of ^{24}Mg atom in the potential of optical lattice with $\lambda_L = 1064\,nm$ that provide higher polarizability of atom in the excited state $(3s3p)\,^3P_1$ than in the ground state $(3s3s)\,^1S_0$. In the following paper we restrict our consideration by two-level model assuming the quench field results to increasing effective linewidth of optical transition to γ_{eff} [11]:

$$\gamma_{eff} = \gamma_1 + \gamma_2 \frac{\Omega_2^2}{\gamma_2^2 + 4\,\delta_2^2}\,, \tag{1}$$

where Ω_2 is Rabi and δ_2 is detuning of quench field. Thus, for example, to get $\gamma_{eff} = 100\gamma_1$ at $\delta_2 = 0$ one have to apply the quench field intensity $I_q \approx 1.6\, W/cm^2$. The simulated polarizability difference for the considered wavelength λ_L is about $\alpha_e/\alpha_g = 1.46$. Here (fig.2) the quantum nature of atomic motion becomes essential. For considered optical lattice potential depth of the ground state $U_g = 200\,\mu K$ with vibration energy separation of the lowest states are $\hbar\omega_g \approx 16.6\,\mu K$. The excited state optical lattice potential depth $U_e = 292\,\mu K$ and the lowest states separation are $\hbar\omega_e \approx 20.1\,\mu K$. The large energy levels separation require quantum model for description of laser cooling dynamics of atoms in the potential of optical lattice. Really, the semiclassical models can't be applied here because of the simulation of force on atom shows it is strongly varied on a velocity range of $\Delta v \ll \hbar k/M$. As well the semiclassical parameter $\varepsilon_R = \hbar k^2/(2M\gamma) \gg 1$ is not small, that also contradicts requirements for semiclassical approach [1, 14, 15].

For description of laser cooling of Mg in the potential of optical lattice we consider two quantum approaches. The first one is based on decomposition of atom density matrix on optical potential vibration level states. Restricting by limited number of lowest vibration states we simulate the stationary distribution over the vibration levels in the optical lattice potential, as well as the laser cooling dynamics to steady state distribution. This approach is similar to method was described in [16]. However, in our model we also take into account the optical coherence of different vibration states.

The second method we consider is based on direct numerical solution of quantum equation for atom density matrix that allows to take into account not only the fixed number of the lowest vibration level states but density matrix of atoms entirely, which also include tunneling effects and above barrier motion. However, in this method, due to the high complicity of the problem we omit the recoil effects from the pumping field resonant to $(3s3s)\,^1S_0 \to (3s3p)\,^3P_1$ optical transition that is equivalent to orthogonal orientation of wave vectors of pumping and optical lattice light waves in one dimensional model.

2.1. Two-level model: exact numerical solution of quantum density matrix equation

We consider the motion of Mg atom in the potential of optical lattice is a standing light wave propagating along z direction with linear polarization along x. The cooling light field also linear polarized along x with wavevector along z or y. The quantum equation for atom density matrix describes evolution of internal and external states of atoms

$$\frac{\partial}{\partial t}\hat\rho = -\frac{i}{\hbar}\left[\hat H_0 + \hat V_{ed}, \hat\rho\right] + \hat\Gamma\left\{\hat\rho\right\} \tag{2}$$

with $\hat H_0$ is Hamiltonian, $\hat V_{ed}$ describes interaction with cooling field and $\hat\Gamma\{\hat\rho\}$ describes relaxation of density matrix due to spontaneous decay.

As was mentioned above, we restrict our consideration by effective two-level model with $(3s3s)\,^1S_0$ is the ground (g) and $(3s3p)\,^3P_1$ is excited state (e), assuming the influence of the quench field Ω_2 results to adjustable linewidth by modification of decay rate from γ_1 to γ_{eff} only, as described in [11]. Further in the paper we omit parameters indexes Ω_1, δ_1 and γ_1 by writing Ω, δ and γ instead. The Hamiltonian of atom in the potential of optical lattice has the form:

$$\hat H_0 = \frac{\hat p^2}{2M} + \hbar\omega_g(z)|g\rangle\langle g| + \hbar[\omega_e(z) + \omega_0]|e\rangle\langle e| \tag{3}$$

with optical potentials in the ground $\hbar\omega_g(z) = U_g\cos^2(kz)$ and $\hbar\omega_e(z) = U_e\cos^2(kz)$ in excited states ($\hbar\omega_0 = E_e - E_g$ is energy difference of unperturbed ground and excited states). The wavevector $k = 2\pi/\lambda_L$ is defined by the optical lattice field. Applying rotating wave approximation the equation for atom density matrix components in coordinate representation $\hat\rho(z_1, z_2)$ takes the followign form:

$$\begin{aligned}
\left(\frac{\partial}{\partial t} - \frac{i\hbar}{M}\frac{\partial}{\partial q}\frac{\partial}{\partial z}\right)\rho^{ee} \;&=\; -\gamma_{eff}\,\rho^{ee} + i\frac{U_e}{\hbar}\sin(2kz)\sin(kq)\rho^{ee} - \frac{i}{\hbar}\left[\hat V\rho^{ge} - \rho^{eg}\hat V^\dagger\right] \\
\left(\frac{\partial}{\partial t} - \frac{i\hbar}{M}\frac{\partial}{\partial q}\frac{\partial}{\partial z}\right)\rho^{gg} \;&=\; \hat\gamma\{\rho^{ee}\} + i\frac{U_g}{\hbar}\sin(2kz)\sin(kq)\rho^{gg} - \frac{i}{\hbar}\left[\hat V^\dagger\rho^{eg} - \rho^{ge}\hat V\right] \\
\left(\frac{\partial}{\partial t} - \frac{i\hbar}{M}\frac{\partial}{\partial q}\frac{\partial}{\partial z}\right)\rho^{eg} \;&+\; \left(\frac{\gamma_{eff}}{2} - i\tilde\delta(z,q)\right)\rho^{eg} = -\frac{i}{\hbar}\left[\hat V\rho^{gg} - \rho^{ee}\hat V\right] \\
\left(\frac{\partial}{\partial t} - \frac{i\hbar}{M}\frac{\partial}{\partial q}\frac{\partial}{\partial z}\right)\rho^{ee} \;&+\; \left(\frac{\gamma_{eff}}{2} + i\tilde\delta(z,-q)\right)\rho^{ge} = -\frac{i}{\hbar}\left[\hat V^\dagger\rho^{ee} - \rho^{gg}\hat V^\dagger\right],
\end{aligned} \tag{4}$$

with $z = (z_1 + z_2)/2$, $q = z_1 - z_2$, and the function $\tilde\delta(z,q)$:

$$\tilde\delta(z,q) = \delta - (U_e - U_g)\frac{1 + \cos(2kz)\cos(kq)}{2\hbar} + (U_e + U_g)\frac{\sin(2kz)\sin(kq)}{2\hbar}.$$

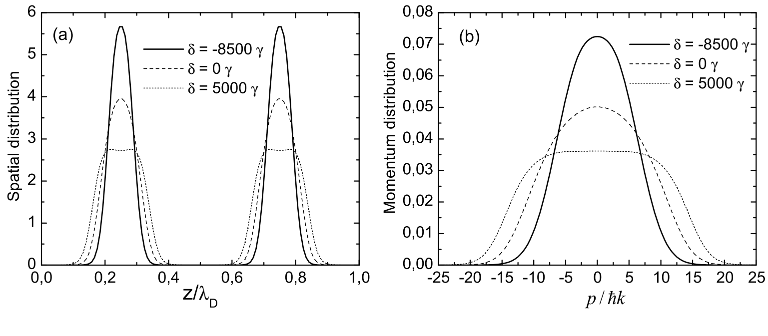

Figure 3. *Spatial (a) and momentum (b) distribution of* ^{24}Mg *atoms in optical lattice* ($U_g = 200\,\mu K$, $U_e = 292\,\mu K$) *for orthogonal orientation of cooling wave and optical lattice trap* ($\theta = \pi/2$) *and cooling field intensity* $I \simeq 34\ W/cm^2$ ($\Omega/\gamma = 20000$) *and different detunings.*

The spontaneous income part to the ground state $\hat{\gamma}$ in coordinate representation for two-level model has simple form :

$$\begin{aligned} \hat{\gamma}\{\rho^{ee}\} &= \tilde{\gamma}(q)\rho^{ee} \\ \tilde{\gamma}(q) &= 3\,\gamma_{eff}\left(\frac{\sin(k_1q)}{(k_1q)^3} - \frac{\cos(k_1q)}{(k_1q)^2}\right) \end{aligned} \tag{5}$$

with $k_1 = 2\pi/\lambda$ is wavevector of emitted photon ($\lambda = 457$ nm). The cooling field induces transitions between the ground and excited states. This part is described in (4) by operator

$$\hat{V} = \Omega/2\ \exp(ik_1 z \cos(\theta)) \tag{6}$$

with Ω is Rabi frequency of cooling field and θ is angle between the axis z and cooling wave propagation direction. For the case of orthogonal orientation of the cooling wave propagation to the optical lattice trap $\theta = \pi/2$ the equation for density matrix (4) can be solved numerically by the method suggested in [17, 18]. It should be noted the considered method allows to get steady state solution for density matrix with taking into account quantum recoil effects as for atoms in the optical lattice trap as for nontrapped atoms.

The figure 3 shows spatial and momentum distribution of Mg atoms in the optical lattice for orthogonal orientation of cooling wave ($\theta = \pi/2$), for field intensity $I \simeq 34\ W/cm^2$ ($\Omega/\gamma = 20000$) and different detunings.

The obtained numerical solution for steady state density matrix $\hat{\rho}(z_1, z_2)$ contains whole information on internal and translational states of atoms in the potential of optical lattice. In particular one can extract the population of vibration levels in the ground and excited states that in coordinate representation for atom density matrix takes a form:

$$\begin{aligned} \rho_n^{ee} &= \int \psi_n^{*(e)}(z_1)\rho^{ee}(z_1, z_2)\psi_n^{(e)}(z_2)dz_1dz_2\,, \\ \rho_n^{gg} &= \int \psi_n^{*(g)}(z_1)\rho^{gg}(z_1, z_2)\psi_n^{(g)}(z_2)dz_1dz_2 \end{aligned} \tag{7}$$

where $\psi_n^{(e,g)}(z)$ are n-th vibration level eigenfunctions.

The energy of cooled atoms can be found by different way. First of all one can use the relation for the temperature of cooled atoms in the well known form

$$k_BT = < p^2 > /M\,, \tag{8}$$

with $< p^2 >= Tr\{\hat{p}^2\,\hat{\rho}\}$. This relation neglects the atom localization effects in the optical potential. The most accurate relation for energy is expressed by the following averaging:

$$E = Tr\left\{\left(\frac{\hat{p}^2}{2M} + \hbar\omega_e(z)\right)\hat{\rho}^{(ee)}\right\} + Tr\left\{\left(\frac{\hat{p}^2}{2M} + \hbar\omega_g(z)\right)\hat{\rho}^{(gg)}\right\}\,. \tag{9}$$

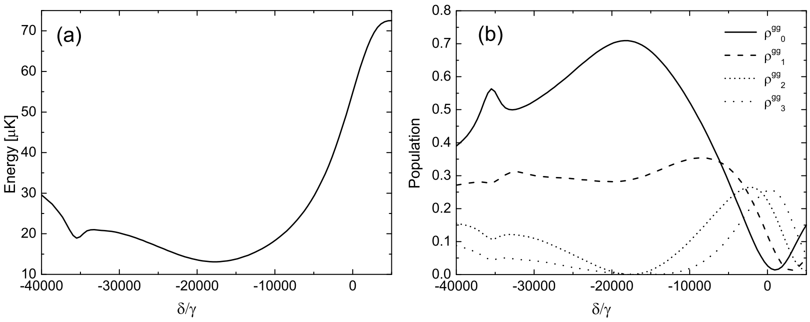

Figure 4. *The energy (a) of cooled ^{24}Mg atoms in the optical lattice and population of the lowest vibration levels (b) as function of cooling field detuning for $I \simeq 0.34$ W/cm^2 $(\Omega/\gamma = 2000)$ obtained by direct numerical solution of eq.(4). $(\theta = \pi/2)$*

As an alternative way one can find the average energy over the vibration states

$$E = \sum_n E_n^{(e)}\,\rho_n^{(ee)} + E_n^{(g)}\,\rho_n^{(gg)}. \tag{10}$$

For considered parameters all above definitions give very close values that denotes the main contribution to energy are given by atoms on the lowest vibration energy levels in the region where the optical potential has close to parabola shape. The energy of Mg atoms for different detuning is shown on figure 4. The total population of excited vibration level states here do not exceed 2% and are not shown on figure 4(b). In the region of detuning $\delta > -6000\gamma$ we find inversion of the lowest vibration levels population resulting to energy growth. For the higher intensity of cooling field this effect is also exists and moves to larger detuning area.

2.2. The model based on vibration states decomposition

As we see from the simulations above based on numerical solution of basic equation for atomic density matrix (4) for the considered parameters Mg atoms can be cooled and well localized in the potential of optical lattice. Thus for description of laser cooling and laser cooling time we can also apply an alternative approach based on decomposition of atom density matrix over vibration level states.

$$\begin{array}{ll} \rho_{nm}^{ee} = \langle e,n|\rho^{ee}|e,m\rangle & \rho_{nm}^{eg} = \langle e,n|\rho^{eg}|g,m\rangle \\ \rho_{nm}^{ge} = \langle g,n|\rho^{ge}|e,m\rangle & \rho_{nm}^{gg} = \langle g,n|\rho^{gg}|g,m\rangle \end{array} \tag{11}$$

with elements

$$\rho_{nm}^{ab} = \langle a,n|\rho^{ab}|b,m\rangle = \int \psi_n^{*(a)}(z)\rho^{ab}(z_1,z_2)\psi_m^{(b)}(z)dz_1dz_2\,. \tag{12}$$

and indexes (a), (b) are corresponds to indexes of exited and ground states (e) and (g). The equation for these components has similar to (2) form:

$$\begin{array}{r} \frac{\partial}{\partial t}\rho_{nm}^{ee} = -\gamma_{eff}\,\rho_{nm}^{ee} - i\left(\omega_n^{(e)} - \omega_m^{(e)}\right)\rho_{nm}^{ee} - i\sum_k\left(\Omega_{nk}\rho_{km}^{ge} - \rho_{nk}^{eg}\Omega_{km}^{\dagger}\right) \\ \frac{\partial}{\partial t}\rho_{nm}^{eg} + \left[\frac{\gamma_{eff}}{2} - i\delta\right]\rho_{nm}^{eg} = -i\left(\omega_n^{(e)} - \omega_m^{(g)}\right)\rho_{nm}^{eg} - i\sum_k\left(\Omega_{nk}\rho_{km}^{gg} - \rho_{nk}^{ee}\Omega_{km}\right) \\ \frac{\partial}{\partial t}\rho_{nm}^{ge} + \left[\frac{\gamma_{eff}}{2} + i\delta\right]\rho_{nm}^{ge} = -i\left(\omega_n^{(g)} - \omega_m^{(e)}\right)\rho_{nm}^{ge} - i\sum_k\left(\Omega_{nk}^{\dagger}\rho_{km}^{gg} - \rho_{nk}^{ee}\Omega_{km}^{\dagger}\right) \\ \frac{\partial}{\partial t}\rho_{nm}^{gg} = \hat{\gamma}\left\{\rho^{ee}\right\}_{nm} - i\left(\omega_n^{(g)} - \omega_m^{(g)}\right)\rho_{nm}^{ee} - i\sum_k\left(\Omega_{nk}^{\dagger}\rho_{km}^{eg} - \rho_{nk}^{ge}\Omega_{km}\right) \end{array} \tag{13}$$

where $\hbar\omega_n^{(e)}$ and $\hbar\omega_n^{(g)}$ are the vibration levels energy of the excited and the ground states. Matrix elements Ω_{nm} define coupling of the ground and excited vibration states:

$$\Omega_{nm} = \langle e,n|\hat{V}|g,m\rangle = \int \psi_n^{*(e)}(z)\hat{V}(z)\psi_m^{(g)}(z)dz\,. \tag{14}$$

with $\hat{V}$ is defined in (6). The relaxation term $\hat{\gamma}\{\rho^{ee}\}_{nm}$ describes income to ground vibration states due to emission of spontaneous photons:

$$\begin{aligned}\hat{\gamma}\{\hat{\rho}\}_{nm} &= \gamma_{eff}\sum_{\nu\mu}\Gamma^{\nu\mu}_{nm}\rho^{ee}_{\nu\mu} \\ \Gamma^{\nu\mu}_{nm} &= \int \psi^{*(g)}_n(z_1)\psi^{(e)}_\nu(z_1)\tilde{\gamma}(z_1-z_2)\psi^{*(e)}_n(z_2)\psi^{(g)}_\nu(z_2)dz_1dz_2\end{aligned} \tag{15}$$

and $\tilde{\gamma}(q)$ is defined in (5). The equation (13) describe evolution of diagonal elements (vibration levels population) and nondiagonal elements as well. To make better insight into these complex equation we consider first low intensity limit for cooling field $S_{nm} \ll 1$

$$S_{nm} = \frac{|\Omega_{nm}|^2}{\gamma^2_{eff}/4 + \left[\delta^2 - (\omega^{(e)-\omega^{(g)}})^2\right]} \tag{16}$$

and consider evolution of the population of the ground and excited states that described by balance equation in this limit:

$$\begin{aligned}\frac{\partial}{\partial t}\rho^{ee}_{nn} &= -\gamma_{eff}\left(1+\sum_{m=1}^{Ng}S_{nm}\right)\rho^{ee}_{nn} + \gamma_{eff}\sum_{m=1}^{Ng}S_{nm}\,\rho^{gg}_{mm} \\ \frac{\partial}{\partial t}\rho^{gg}_{nn} &= \gamma_{eff}\sum_{n=1}^{Ne}\left(\Gamma^{nn}_{mm}+S_{nm}\right)\rho^{ee}_{nn} - \gamma_{eff}\left(\sum_{n=1}^{Ne}S_{nm}\right)\rho^{gg}_{mm}\end{aligned} \tag{17}$$

for fixed number of the excited (Ne) and the ground (Ng) vibration states. The equation (17) can be solved analytically. Restricting by two vibration levels in the ground and excited states we get

$$\begin{aligned}\rho^{gg}_{00} &= \left[1+\frac{\Gamma^{00}_{11}S_{00}+\Gamma^{11}_{11}S_{10}}{(1-\Gamma^{00}_{11})S_{01}+(1-\Gamma^{11}_{11})S_{11}}\right]^{-1} \\ \rho^{gg}_{11} &= \left[1+\frac{(1-\Gamma^{00}_{11})S_{01}+(1-\Gamma^{11}_{11})S_{11}}{\Gamma^{00}_{11}S_{00}+\Gamma^{11}_{11}S_{10}}\right]^{-1}\end{aligned} \tag{18}$$

desribes for ρ^{gg}_{00} smooth curve on detuning with minimums determined by $\omega^{(e)}_0 \to \omega^{(g)}_0$ and $\omega^{(e)}_1 \to \omega^{(g)}_0$ resonances (i.e. for detuning $\delta = \omega^{(e)}_0 - \omega^{(g)}_0$ and $\delta = \omega^{(e)}_1 - \omega^{(g)}_0$) and maximum for detuning close to $\delta = \omega^{(e)}_0 - \omega^{(g)}_1$ and $\delta = \omega^{(e)}_1 - \omega^{(g)}_1$.

3. Results

The fugure 5 shows the energy of cooled Mg atoms in the optical lattice and population of the ground state vibration levels obtained by both described above methods (section 2.1 and 2.2). Both methods demonstrates close results with the differences far from the minimum cooling energy when the populations of the top vibration levels are not negligible and tunneling effects and above barrier motion of atoms can not be neglected. Nevertheless, the simplified model (13) well describe the laser cooling near the minimum of energy and allows to estimate the cooling time.

As well the populations and energy of ^{24}Mg atoms in dipole trap and coplanar geometry of pumping field is shown on figure 6. We see the balance equations (17) well describe atom behavior in the trap for low intensity of pumping field. The modulations of population and total energy on detuning corresponds to resonances $\omega^{(e)}_0 \to \omega^{(g)}_1$, $\omega^{(e)}_0 \to \omega^{(g)}_2$, $\omega^{(e)}_0 \to \omega^{(g)}_3$, and $\omega^{(e)}_0 \to \omega^{(g)}_4$. With increasing the pumping field intensity the balance equation approach (13) violates. Additionally, we see the field shift of the resonances (Fig. 6(b) and 6(d)).

Additionally the model based on decomposition on vibration state allows to solve dynamical problem and estimate the cooling time. To find the cooling time we assume the atoms populate the highest vibrational energy level of the ground state optical potential at $t = 0$. The time evolution of vibration levels population has a complex dependence. We fit $\rho^{gg}_{00}(t)$ by exponential function of the form $\rho^{gg}_{00}(t) = a - b\exp(-t/\tau)$ with τ describes the cooling time. Additionally we note, the energy of cooled atoms does not depend on parameter γ_{eff} (i.e. on quench field intensity) in the range of our simulations $\gamma < \gamma_{ef} < 100\gamma$, while the cooling time τ is inversely proportional to γ_{eff} in considered model. This allows us to represent the cooling time τ in the more general form through dimensionless value $\tilde{\tau}$ figure 7(b)

$$\tau = \tilde{\tau}/\gamma_{eff}. \tag{19}$$

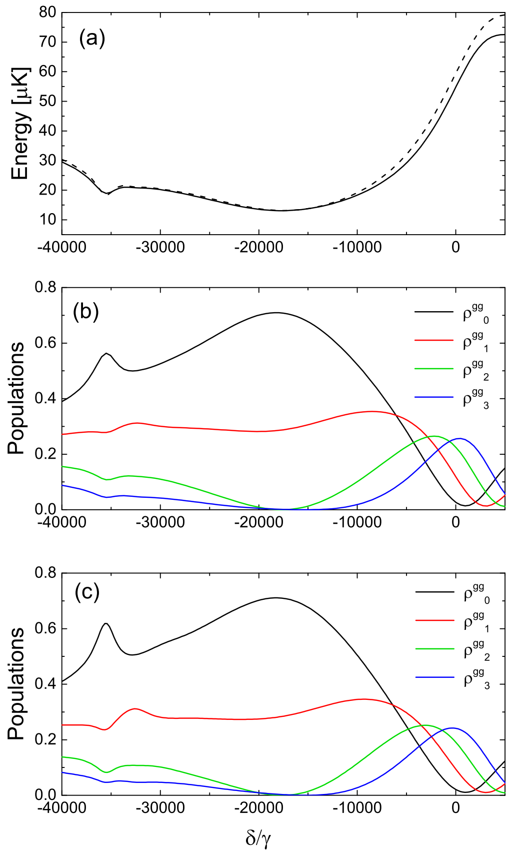

Figure 5. *The energy of cooled ^{24}Mg atoms in the optical lattice (a) as function of cooling filed detuning obtained by exact numerical solution of eq.(2) (solid line) and by decomposition of vibration state method eq.(13) (dashed line). Populations of the ground state vibration levels (g) as function of detuning for exact numerical solution (b) and decomposition on vibration state model (c). Pumping field $\Omega/\gamma = 2000$ ($I = 0.34W/cm^2$), $\gamma_{eff} = 100\gamma$. Orthogonal orientation of pumping field and the trap $\theta = \pi/2$.*

4. Conclusion

We study laser cooling of ^{24}Mg atoms in the optical lattice trap with additional pumping field resonant to narrow $(3s3s)\,^1S_0 \rightarrow (3s3p)\,^3P_1$ ($\lambda = 457$ nm) optical transition and quench field resonant to $(3s3p)\,^3P_1 \rightarrow (3s4s)\,^1S_0$. The effect of quenching we consider in simplified form as widening of optical transition to γ_{eff} only. We have considered two quantum models. The first one is based on the direct numerical solution of quantum kinetic equation for atom density matrix and the second one is simplified model is based on decomposition of atom density matrix over vibration states in the trap of optical lattice. Additionally to vibration state model we consider simplified balance equations that allow clarify modulations on detuning the atom energy and population of vibration levels.

Both considered models describe cooling of atoms on the lowest vibration levels with difference appears for high intensity of pumping field (above $50W/cm^2$, or Rabi above 25000γ) when the populations of the top vibration levels are not negligible and tunneling effects and above barrier motion of atoms can not be neglected. Nevertheless, the vibration state model well describe the laser cooling to minimum of cooling energy (about 10 μK). Additionally this model allows to estimate the cooling time. The parameters of pumping field for cooling to minimum energy do not coincide with conditions for fast cooling. We find parameters that allow cooling the atoms for reasonable cooling time $\tau \approx 10/\gamma_{eff}$ ($\tau \approx 0.5$ ms for $\gamma_{eff} = 100\gamma$) to energy $E \approx 12$ μK.

Finally we note the important assumption we used for accounting the quench field (1) might not be enough

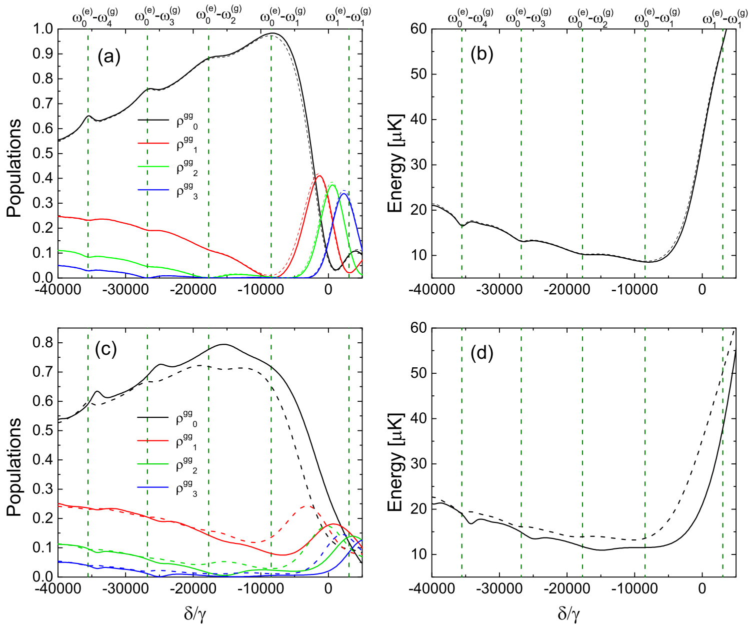

Figure 6. *Populations and energy of cooled* ^{24}Mg *atoms in the optical lattice for different intensity of cooling field ((a) and (b) for* $\Omega/\gamma = 2000$ *and (c) and (d) for* $\Omega/\gamma = 10000$*) as function of pumping filed detuning obtained by exact numerical solution of eq.(13) - solid lines and by balance eq.(17) - dashed lines. Coplanar geometry of pumping field and optical lattice trap* $\theta = 0$*.*

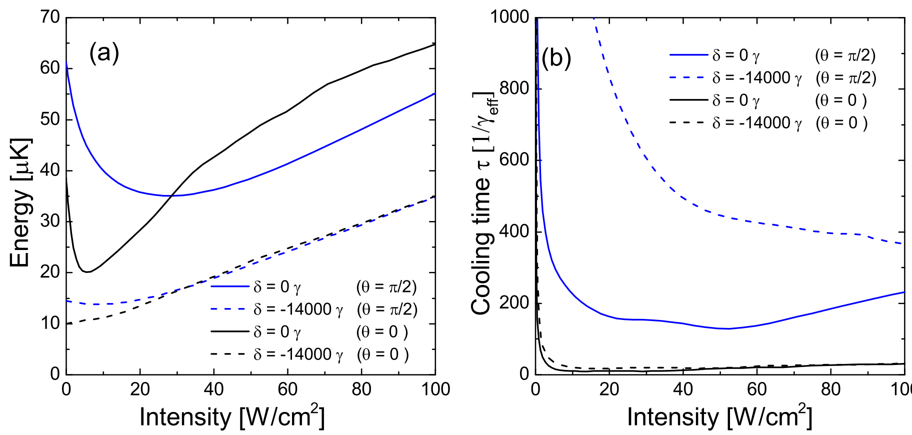

Figure 7. *Energy of cooled* ^{24}Mg *atoms in the optical lattice (a) and cooling time* $\tilde{\tau}$ *(b) for different orientation of cooling wave* θ *and different detunings obtained by solution based on decomposition on vibration state model as function of cooling field intensity.*

adequate the real situation and demands more detailed consideration on a base of three level scheme in dipole trap. We hope to finish this consideration in the near future. The work was supported by Russian Science Foundation (project N16-12-00054). V.I.Yudin acknowledges the support of the Ministry of Education and Science (3.1326.2017/4.6) and RFBR (grant 17-02-00570). The work of R. Ya. Il'enkov was personally supported by Russian Science Foundation (project N17-72-10139).

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