Deep laser cooling of strontium atoms on $^1S_0 \rightarrow {}^3P_0$ transition

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Abstract. Momentum distributions of strontium atoms are characterized by means of bimodal functional dependences, which properties depend on the laser field parameters. It is shown that ultracold fraction of atoms ($T \leq \hbar\gamma/k_B$) can reach 60 %. The calculations are based on the quantum treatment of the problem with taking into account the recoil effect in full. The results can be used for ultradeep laser cooling of strontium atoms.

1. Introduction

Invention such precise and powerful tool as a laser has opened before scientists a wide range of capabilities for atom manipulation: acceleration, deceleration, localization, deflection, and focusing. So laser cooling has become an integral part of both fundamental science and many practical applications (high-precision frequency and time standards, nanolithography, quantum information etc.)

The theoretical description of the kinetics of neutral atoms in the polarized light fields with all the atomic levels, the coherence, the recoil effect is both important and challenging problem. The first step toward understanding mechanisms of interaction between atoms and light was called quasi-classical approach [1, 2]. It lies in the fact that the equations for the density matrix can be reduced to the Fokker-Planck equation for the Wigner function in the phase space. Simplicity of this approach has allowed to understand many of cooling mechanisms in the usual and ordinary terms of force and diffusion. However, this approach can only be applied in certain cases. First, the small recoil frequency parameter compared to the rate of spontaneous decay, and secondly, the momentum of a light field photon should be much smaller than the width of the momentum distribution of the atoms. Later quantum methods were developed [3, 4], for example, the secular approach which describes cooling and localization of atoms in the optical potential. In this approximation distance between the energy bands in the optical potential is greater than their broadening caused by optical pumping. At a fixed depth of the optical potential this approximation is valid in the limit of large detuning, and thus, for a given configuration is disrupted in a deep optical potential. Moreover, even when this condition, the secular approximation is valid only for the lower vibrational levels, and fails for the higher, where the distance between the levels becomes smaller due to the effects of anharmonicity. The more secular approximation is not applicable to atoms undergo above-barrier motion.

Therefore, to describe the laser cooling on forbidden transitions, such as intercombination transitions of Yb, Mg, Sr, used in experiments for ultradeep laser cooling [5–8] it is necessary to use methods of quantum effects into account the effect of the impact and spatial localization of atoms.

2. Laser cooling of strontium atoms

The system of equations on density matrix elements in two-point representation describing the interaction of two-level atom with a field of a standing light wave with taking into account of the effect of recoil and spatial localization:

$$\begin{cases} \left(-\frac{i\hbar}{m}+\frac{\gamma}{2}-i\delta\right)\rho_{21}(1,2) = -\frac{i}{\hbar}\left(V(1)\rho_{11}(1,2)-\rho_{22}(1,2)V(2)\right) \\ \left(-\frac{i\hbar}{m}+\frac{\gamma}{2}+i\delta\right)\rho_{12}(1,2) = -\frac{i}{\hbar}\left(V^*(1)\rho_{22}(1,2)-\rho_{11}(1,2)V^*(2)\right) \\ \left(-\frac{i\hbar}{m}+\frac{\gamma}{2}-i\delta\right)\rho_{22}(1,2) = -\frac{i}{\hbar}\left(V(1)\rho_{12}(1,2)-\rho_{21}(1,2)V^*(2)\right) \\ \left(-\frac{i\hbar}{m}+\frac{\gamma}{2}-i\delta\right)\rho_{11}(1,2)-\gamma f(q)\rho_{22}(1,2) = \\ = -\frac{i}{\hbar}\left(V^*(1)\rho_{11}(1,2)-\rho_{22}(1,2)V(2)\right), \end{cases} \tag{1}$$

there m – atomic mass, $\delta = \omega - \omega_0$ – detuning of light field of atomic transition frequency, γ – frequency of spontaneous radiative decay, $x = (x_1 + x_2)/2$, $q = x_1 - x_2$ – spatial coordinates, ρ_{11}, ρ_{22} – the population of the excited and ground states, ρ_{12}, ρ_{12} – optical coherence between levels, $f(q)$ - function which characterizes the recoil effect in the spontaneous emission:

$$f(q) = \frac{3}{2}\left(\frac{\cos(q)}{q^2} - \frac{\sin(q)}{q^3} + \frac{\sin(q)}{q}\right), \tag{2}$$

and $\hat{V}$ – interaction operator with field of a standing light wave

$$\hat{V} = -2dE_0\cos(kx)\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \tag{3}$$

There d is the matrix element of atomic dipole moment, E_0 is the electric field amplitude.

We have developed an own quantum method [9] to obtaining the stationary distribution of two-level atoms in a standing wave of arbitrary intensity, allowing full account the recoil effect. The method used is to decompose the density matrix elements in the Fourier series for the spatial harmonics, which is possible due to periodicity of the light wave. Thus we obtain a system recursively coupled equations, where each harmonic is expressed through the previous one, and starting from free selected one (in our calculations, usually twenty or more) all the harmonics are equal to zero. Using this method kinetics of atoms in light fields of varying intensity was investigated. The new and most important result was mode which we called the anomalous localization. In strong standing wave (Rabi frequency greater than the constant spontaneous relaxation) was detected a anomalous behavior of atoms, namely, the concentration at the peaks of the optical potential [10].

The next important step was to study the quantum modes for different parameters of the problem. It is known that the quasi-classical approach gives Gaussian shape momentum distributions of and is completely inapplicable to the quantum regimes ($w_r \approx \gamma$, with $w_r = \hbar k^2/2m$ the recoil frequency and k the wave vector). Laser cooling of strontium atoms at the transition $^1S_0 \rightarrow {}^3P_0$ is a vivid example of such a regime. It is studied in this paper. The results of quantum calculation are shown in figure 1. There is a bimodal distribution: a narrow central peak and a broad substrate (background). Such a clearly expressed bimodal structure with high accuracy can be approximated by two Gaussian functions corresponding to the two-speed groups of atoms. Atoms are essentially non-equilibrium momentum distribution, which is a good approximation can be described by two Gaussian functions. For these parameters "cold" fraction of atoms has temperature $T_1 = 0.67\hbar\gamma$, and "hot" fraction of atoms $T_2 = 26.2\hbar\gamma$.

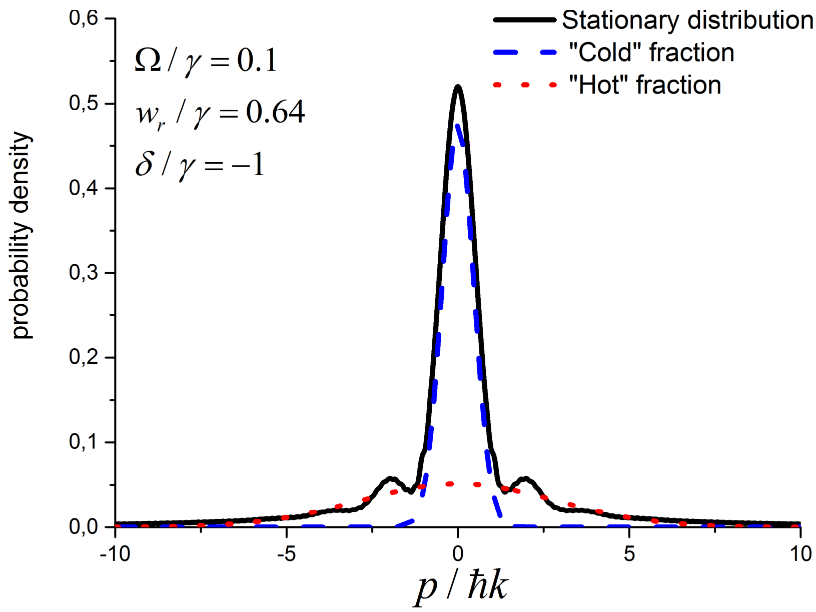

Figure 1. Bimodal momentum distribution of cold strontium atoms. The distribution has narrow structure of cold atoms and wide wings. Parameters of the calculation are written on the figure.

The proportions of “hot” and “cold” fractions of atoms figure 2b, as well as their temperatures figure 2a depend on the parameters of light fields (the Rabi frequency $\Omega = dE_0/\hbar$). Temperature of “cold” fraction is significantly lower than the average temperature defined as $<p^2>/m$ (with $<p^2>$ the average square of atomic momentum) and reaches the limit values $< \hbar\gamma$. The main trend is the general heating. It increases as the temperature of cold fraction and fractions hot temperature. The temperature of the hot fraction has two behaviors violate the monotony of growth. They both can be attributed to distortions of the form of pulse distributions of atoms. The number of atoms in the “cold” fraction maximizing in a weak field, and reaches 60 %. In strong fields the contribution of both factions aligned and it is about 50 %.

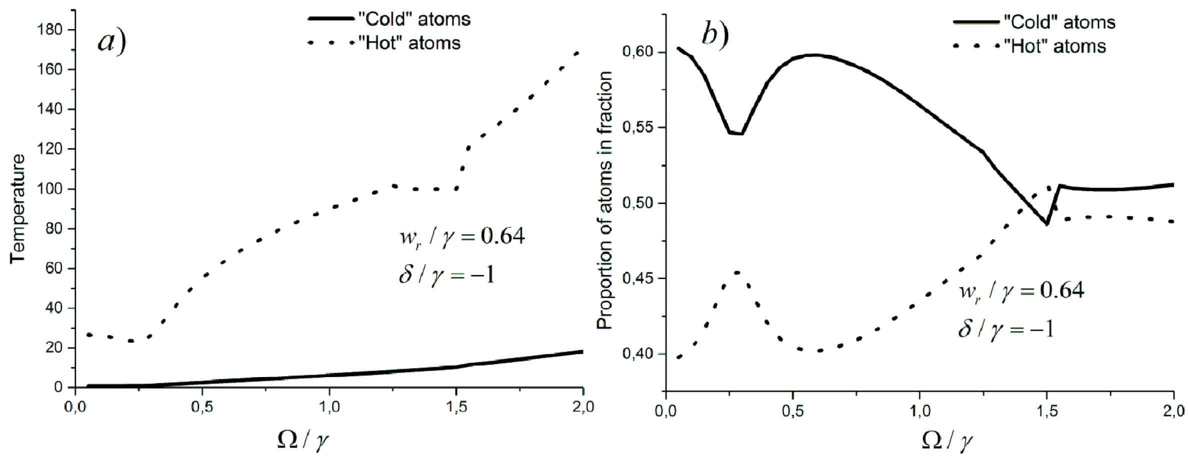

Figure 2. Dependences of temperature (a) and proportion (b) of atoms for “cold” and “hot” fractions of atoms of Rabi frequency. Parameters of the calculation are shown on the plots.

3. Conclusion

Investigation of the possibility of cooling of strontium atoms on the weak transition has been carried out. It has been shown that the atoms can exhibit the essentially non-equilibrium momentum distribution, which can be well approximated by two Gaussian functions. The possibility of obtaining the temperature of cold fraction below $\hbar\gamma$ has been demonstrated. The proportion of cold atoms fraction can be sufficiently high and reach 60 %. If we put atoms with bimodal distribution into the shallow dipole trap, it will lead to cutting off the hot atoms and we get the final momentum distribution of deeply cooled atoms, maintaining a significant number of cold atoms.

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