A new type of sub-Doppler cooling of three-level atoms in the field of two standing waves

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We study the laser cooling of three-level Λ atoms in the field of standing waves when the frequency detunings is much higher than the natural width of the excited state of the system and the Rabi frequencies of the light waves. We show that when the difference between the frequency detunings is small compared to the Rabi frequencies in the three-level Λ system, deep (sub-Doppler) cooling of atoms can set in. We give the relationship between light pressure and the atomic velocity and the dependence of the temperature of the cold atoms in the zero-velocity region on the various parameters of the excitation waves. © *1996 American Institute of Physics.* [S1063-7761(96)00604-X]

It has now been established that there are two mechanisms of sub-Doppler laser cooling for three-level atoms in a double-frequency field. One manifests itself in two-photon resonance between the waves and the transitions in the Λ atom and is caused by coherent population trapping in the three-level Λ system.[1,2] This mechanism of sub-Doppler cooling can manifest itself in the excitation of the Λ system by both traveling and standing waves. The other type of deep cooling of three-level atoms is realized in the interaction with the field of standing waves that have a nonzero spatial shift.[3–6] In this case the sub-Doppler cooling of the atoms is ensured when inhomogeneous optical pumping is combined with coherent population transfer between the lower levels of the Λ system.

In this paper we report on the results of studies of a new mechanism of sub-Doppler cooling of three-level atoms in the field of two standing light waves with a zero spatial shift,

$$\mathbf{E}(z,t)=\mathbf{e}E\cos kz(\cos\omega_1 t+\cos\omega_2 t), \tag{1}$$

where $\mathbf{e}$ is the unit polarization vector, ω_m are the frequencies, E is the amplitude, and $k=\omega_m/c$ is the wave vector (the same for both light waves).

Let is examine the excitation of a three-level Λ system by the field of two standing waves whose detunings $\Omega_m=\omega_m-\omega_{3m}$ are much higher than the natural linewidth γ of the atomic transition and the Rabi frequencies $g_m=E_m d/\hbar$ of the excitation channels. In this case the three-level Λ atom is considered an essentially two-level atom with states $|1\rangle$ and $|2\rangle$ (Fig. 1). Indeed, since the detunings are high, the upper level remain practically unpopulated, which means we can assume that the levels $|1\rangle$ and $|2\rangle$ are directly related through the light fields, without involving the state $|3\rangle$. Here the behavior of such an essentially two-level system in the light field strongly depends on the relationship between the frequency-detuning difference $\Omega_0=\Omega_1-\Omega_2$ and the Rabi frequencies g_m. Note that for such a two-level system the detuning is the difference Ω_0 of the frequency detunings of the standing light waves acting on the real three-level atom (see Fig. 1). At the same time, the relaxation of the coherence between the $|1\rangle$ and $|2\rangle$ levels has the meaning of the transition width for the essentially two-level system. However, this system differs from a true two-level system in that the given quantity determines only the relaxation of coherence between the levels rather than of population. As we will shortly see, this fact determines some features in the behavior of the light-pressure force acting on such an essentially two-level atom in the zero-velocity region (in comparison to the real two-level approximation). We also note that physically the relaxation of the coherence between the lower levels in a three-level system (see Fig. 1) is mainly related to the frequency instability of the laser fields acting on the $|m\rangle-|3\rangle$ transitions ($m=1,2$) of the three-level atom.

As is well known,[7] for a two-level atom in the field of a standing light wave there are certain conditions that determine the nature of the atom–field interaction:

$$\left(\frac{\Omega_0^2}{\gamma^2}+1\right)^{1/2}\gg\frac{2g^2}{\gamma^2}, \tag{2a}$$

$$\left(\frac{\Omega_0^2}{\gamma^2}+1\right)^{1/2}\ll\frac{2g^2}{\gamma^2}. \tag{2b}$$

Here Ω_0 is the detuning and g is the standing-wave Rabi frequency. It is usually assumed that condition (2a) specifies the case of low light-wave intensities, when the light-pressure force does not exhibit a complex multiresonance structure related to the multiphoton processes of stimulated absorption and emission of photons in the standing-wave field. Condition (2b), on the other hand, specifies the case of high light-wave intensities, when multiresonance processes[7] cannot be ignored. Clearly, conditions of type (2) determine the behavior of an essentially two-level atom in the combined field (1). In this case, however, Ω_0 must be interpreted, as noted earlier, as the difference $\Omega_1-\Omega_2$ of the frequency detunings of the standing waves.

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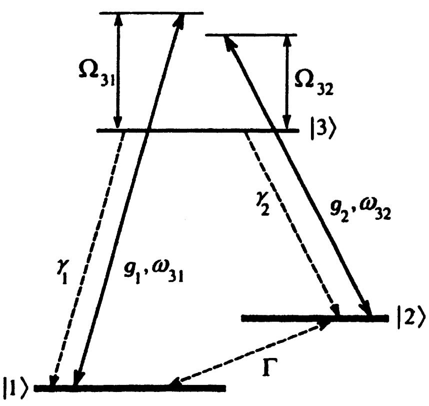

FIG. 1. The energy-level diagram of a Λ atom: $\Omega_m = \omega_m - \omega_{3m}$ is the detuning of light waves with frequencies ω_m from the transition frequencies ω_{3m} ($m=1, 2$), γ_m are the partial probabilities of spontaneous decays in the $|3\rangle \rightarrow |m\rangle$ channels ($m=1, 2$), and Γ is the relaxation rate of the coherence between the levels $|1\rangle$ and $|2\rangle$.

In investigating sub-Doppler cooling of three-level atoms in the field (1) the case of greatest interest is that of considerable saturations for the essentially two-level atom (condition (2b)), i.e., the situation in which the difference in the standing-wave detunings is smaller than the Rabi frequencies. This means that one can expect a considerable slope in the force (and, consequently, intensive cooling) in the region of zero atomic velocities, since it is known[7] that if condition (2b) holds for a two-level atom, the dynamic friction coefficient increases with the light-wave intensity. At the same time, momentum diffusion is low (in comparison to the diffusion calculated for the model of a two-level atom) since it is determined by the population of the upper state $|3\rangle$ of the three-level system, which can be made negligible by choosing large frequency detunings. Such an atom–field interaction scheme creates conditions for deep (sub-Doppler) cooling of atoms.

Now let us discuss in greater detail the light-pressure force acting on an Λ atom in the field (1) for the case of nonresonant relaxation, assuming that the difference in detunings is much smaller than the Rabi frequencies. Figure 2(a) depicts the light-pressure force averaged over the light wavelength as a function of the atomic velocity, obtained by the method of continued matrix fractions,[4,7] for different values of the standing-wave intensities. Clearly visible are the multiphoton absorption and emission resonances for the essentially two-level atom (between states $|1\rangle$ and $|2\rangle$). Similar resonances were observed by Xie *et al.*,[9] who called them Ramanons by analogy with Dopplerons of two-level atom theory.[10]

Figure 2(b) depicts the dependence of the light-pressure force on the atomic velocity as the difference in the standing-wave frequency detunings is increased. Here for equal standing-wave detunings the light-pressure force is seen to vary according to a dispersion law, which corresponds to the case of sub-Doppler cooling of three-level atoms because of coherent populating trapping.[4] Clearly, as the detuning difference Ω_1 increases, the amplitude of the force grows, while the dynamic friction coefficient at zero velocity of the Λ atoms changes little. When the detuning difference Ω_0 becomes greater than the light-wave intensity (i.e., when condition (2a) is met), there is a decrease in the slope of the force in the zero-velocity region, which leads to ordinary (Doppler) cooling.

Figure 3(a) depicts the temperature of cold atoms as a function of the difference in the standing-wave detunings at zero atomic velocities. To find the temperature we calculated the velocity diffusion coefficient at zero Λ atom velocities with allowance for the nonadiabatic corrections determined by the statistics of the re-emitted photons, and then calculated the temperature of cold atoms according to the theory of Brownian motion.[4,7] As Fig. 3(a) shows, an increase in the detuning difference Ω_0 leads to a rapid rise in temperature of the cold atoms. This growth in temperature is caused by the reduction in the dynamic friction coefficient in the region of zero atomic velocities, as Fig. 2(b) clearly shows. We also note that for nonzero values of Ω_0 there exists a local temperature minimum for the chosen intensities of the light waves (Fig. 3(a)).

Figure 3(b) illustrates the dependence of the atomic temperature on the standing-wave intensity. Clearly, sub-Doppler cooling of three-level atoms occurs when the standing-wave intensity is increased. However, at fairly high intensities of the light waves the temperature of the cooled atoms begins to rise despite the increase in dynamic friction (see Fig. 2(a)), which is due to a considerable increase in population of the upper level of the Λ system and the resulting increase in momentum diffusion.

Finally, Fig. 3(c) depicts the variation of the temperature of cold atoms caused by a simultaneous increase of both detunings with the difference Ω_0 kept constant.

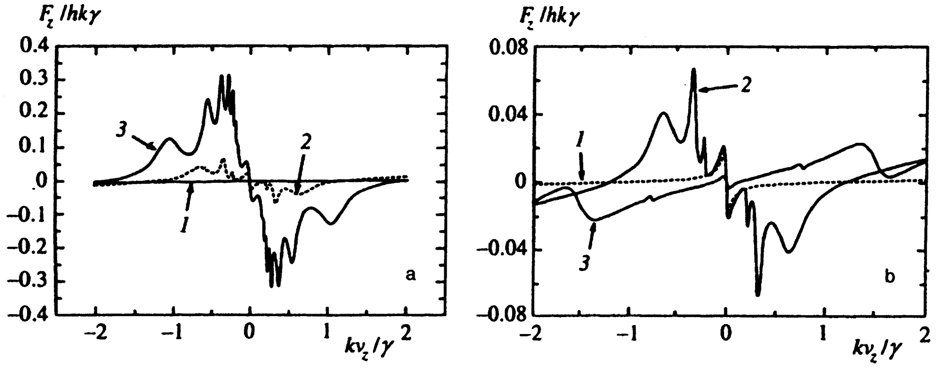

FIG. 2. a) The light-pressure force F_z as a function of the standing-wave intensity. The number at the curves correspond to $g=1$ (*1*), 3 (*2*) and 5 (*3*). The other parameters $\Omega_1=10$, $\Omega_2=11$, $\gamma_1=1$, $\gamma_2=1$, and $\Gamma=0.005$. b) The light-pressure force F_z as a function of the difference in the standing-wave detunings. The numbers at the curves correspond to $\Omega_1=10$ and $\Omega_2=10$ (curve *1*), $\Omega_1=10$ and $\Omega_2=11$ (curve *2*), and $\Omega_1=10$ and $\Omega_2=13$ (curve *3*). The other parameters are $g=3$, $\gamma_1=1$, $\gamma_2=1$, and $\Gamma=0.005$.

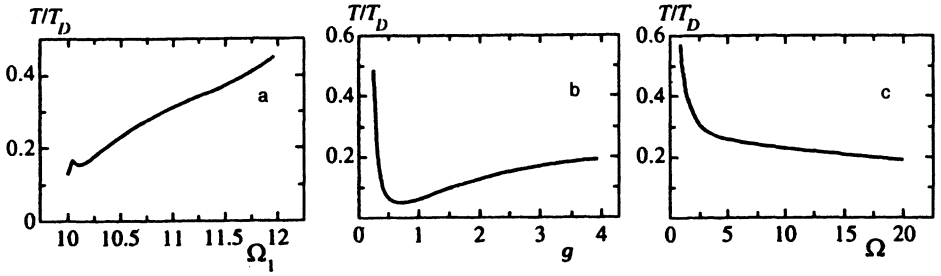

FIG. 3. The temperature of an ensemble of Λ atoms as functions of (a) the detuning Ω_1 (at $\Omega_2=10$, $g=3$, $\gamma_1=1$, $\gamma_2=1$, and $\Gamma=0.005$), (b) the intensity g of the standing waves (at $\Omega_1=10$, $\Omega_2=10.25$, $\gamma_1=1$, $\gamma_2=1$, and $\Gamma=0.005$), and (c) the detunings $\Omega_1=\Omega$ and $\Omega_2=\Omega+\Omega_0$ (at $\Omega_0=0.5$, $g=3$, $\gamma_1=1$, $\gamma_2=1$, and $\Gamma=0.005$).

Two remarks are in order. First, although the general behavior of the light-pressure force (Fig. 2) acting on a three-level atom qualitatively agrees with the model of a two-level atom (in our case this is the essentially two-level atom involving the lower states of a three-level Λ system), there is an important difference; namely, the characteristic velocity scale on which the force is fairly high but still is considerably lower than that in the model of a two-level atom. Moreover, as the intensity grew, we found no marked changes in the light-pressure force in the region of zero atomic velocities,[7] which possibly indicates that the system experiences no real population relaxation between the lower levels of the three-level atom.

Second, we believe that this mechanism of sub-Doppler cooling could be used in systems with double radio-optical resonance.[11]

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