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Trapping of atoms by the counter-propagating stochastic light waves

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ABSTRACT

We calculate the temperature of the atoms in the field of counter-propagating stochastic light waves (the chaotic-field model). We show that the temperature of the atomic ensemble depends on the autocorrelation time of the waves, their intensity and the detuning of the carrier frequency of the waves from the atomic transition frequency. The field can form a one-dimensional trap for atoms, as is readily seen from our previous investigation of light-pressure force on an atom in counter-propagating stochastic light waves [V. I. Romanenko, B. W. Shore, L. P. Yatsenko, Opt. Commun. 268 (2006) 121–132]. We carry out numerical simulation of the atomic ensemble using parameters appropriate for sodium atoms. Analyzing the known investigation of the light-pressure force on atoms and their motion in the counter-propagating polychromatic waves, we suggest an hypothesis that any polychromatic counter-propagating waves that have a discrete spectrum, or waves described by a stationary stochastic process, one of which repeats the other, can form a trap for atoms.

1. Introduction

Optical traps for atoms in which, in addition to the confinement, the atoms are cooled, are widely used in experiments with cold atoms. For example, confinement and simultaneous cooling of atoms is realized in a widely used magneto-optical trap [1], wherein the atoms are subjected to laser radiation and a magnetic field. Recently, after a series of articles discussing the formation of a trap for atoms by the trains of counter-propagating light pulses, one of which repeats the other [2–6], it was shown that such a trap can also cool atoms, provided that the pulse parameters are properly chosen [7–9]. Another trap that simultaneously confines and cools atoms, but which is based on two collinear standing waves that can be treated as counter-propagating bichromatic light waves, was proposed in [10] and investigated by the authors in the recent paper [11]. The centers of both types of trap, the trap based on the counter-propagating light pulses and the trap based on the counter-propagating bichromatic waves, are situated at the point where the optical paths of the counter-propagating waves, produced by the same laser, are equal.

The idea of a trap formed by the counter-propagating trains of light pulses can be simply explained for the case of π-pulses [2]. Let's consider a two-level atom A at a point where the pulses do not overlap (Fig. 1). The atom interacts with a π-pulse L travelling leftward toward the point O where the pulses “collide”. After a time delay shorter then the spontaneous emission time τ_{sp} it interacts with the π-pulse R propagating in the opposite direction. The first pulse excites the atom and pushes it toward the point O due to the absorption of a photon. The interaction with the second pulse leads to stimulated emission of the photon in the direction of its propagation, pushing the atom again toward point O. If the pulse repetition period is large ($T \gg \tau_{sp}$), the atom always occupies the ground state before the interaction with a counter-propagating pair of pulses and a trapping force is provided. More detailed consideration shows that the trap can be formed even by pulses with an area much smaller than π and the condition $T \gg \tau_{sp}$ is not obligatory [9]. It should be noted that the light-pressure force on the atoms in the field of counterpropagating bichromatic waves (“bichromatic force” [12]) can be qualitatively interpreted as an interaction with counter-propagating light pulses [10,12]. Both the bichromatic force and the force in the field of the counter-propagating laser pulses is equal to zero at the point where the optical paths of the counter-propagating waves, produced by the same laser, are equal (the center of the trap). Near this point the light-pressure force depends almost linearly on the coordinate, thereby providing the restoring force for any deviation of an atom from the center of the trap. The force arises because the field strengths of the counter-propagating waves are correlated (in the opposite case the averaged force would be zero, as was shown in [13] for stochastic counter-propagating waves with time delay between waves more than the autocorrelation time). Therefore, we can expect the existence of the restoring force even in the case of the stochastic field, provided the autocorrelation time of the waves is much longer than the time of light propagation from the position of the atom to the center of the trap. This consideration is in good agreement with the calculation of the light-pressure force acting on an atom in counter-propagating stochastic waves [13].

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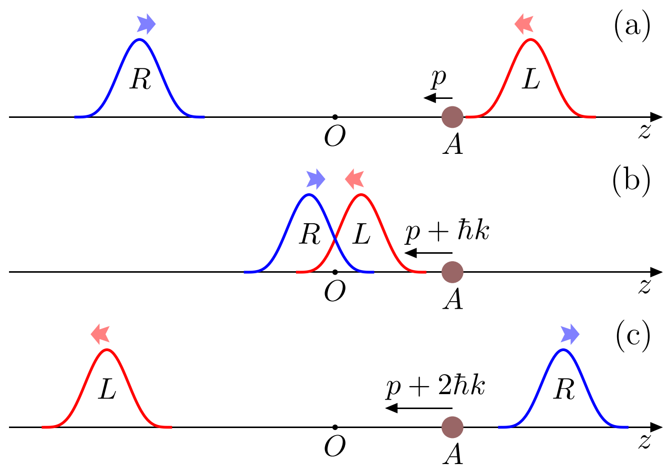

Fig. 1. Interaction of a two-level atom (A) with counter-propagating π-pulses. (a) Initially the atom occupies the ground state and its momentum is p. (b) The pulse L, propagating in the negative z direction, excites the atom and its momentum becomes $p + \hbar k$, where $\hbar k$ is the momentum of the photon. (c) Interaction with the counter-propagating pulse R leads to the stimulated emission of a photon in the direction of z axis and additional change of the atomic momentum by $\hbar k$. As a result, the atomic momentum is changed by $2\hbar k$ after interaction with each pair of counter-propagating pulses. The momentum change is directed toward the point O where the pulses "collide".

The existence of the restoring force is a necessary but not sufficient condition for confinement of atoms in a trap. The laser radiation heats the atoms due to momentum diffusion from the scattering of laser photons. In optical traps for atoms the heating is compensated by a "friction force" which originates from the interaction of atoms with monochromatic standing waves that are slightly detuned from the atomic transition [1]. In the case of the counter-propagating stochastic wave we should determine whether the continuous spectrum of radiation with spectral width more then $1/\tau_{sp}$ can cool atoms and how the spectral width affects the temperature of the possible cooling. In this paper we examine the interaction of atoms with counter-propagating stochastic plane waves (a chaotic-field model, where the real and imaginary parts of the complex amplitude of the electrical field fluctuate independently), and show that in this case, as in the case of the counter-propagating laser pulses or bichromatic field, the atoms can be confined and cooled by the same field. The trap under consideration combines the idea of the confinement of atoms by the counter-propagating waves and their cooling by white light [14–16] using the same laser radiation.

This paper is organized as follows. In Section 2 we present the trap model considered in this paper. In Section 3 the equations that describe the evolution of the atom in the stochastic field are written, in Section 4 the light-pressure force on an atom in the weak field is derived and the minimal temperature of the atomic ensemble in the stochastic field is found. In Section 5 we describe the numerical calculation routine used in the investigation. Results of the numerical calculations of the statistic properties of the ensemble of sodium atoms and their discussion are presented in Section 6. The conclusions are given in Section 7. In the Appendix, we explain the origin of the momentum diffusion of atoms in the field of laser radiation.

2. Trap model

According to the results of [13], the light pressure force in the field of the counter-propagating stochastic waves, one of which repeats the other with a certain time delay, is directed to the point where this delay is equal to zero. Thus, it is possible to form an optical trap by the stochastic light field. Whenever the radiation field of a multimode laser is close to stochastic [17,18], it is possible to construct a trap on the basis of such lasers.

A schematic drawing of an one-dimensional trap for atoms, formed by the counter-propagating stochastic waves is depicted in Fig. 2. The waves are produced by the same laser and are directed towards each other by a system of mirrors (not shown in the figure).

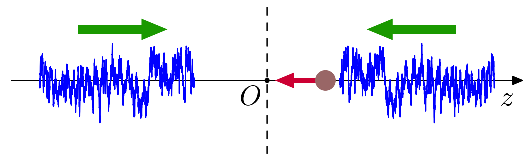

Fig. 2. Schematic view of the trap. The atom (indicated by the circle) near the point O is subjected to the field of the counter-propagating light waves with the stochastic envelope. The waves are produced by the same source and in the point O their amplitudes and phases are equal. Due to the force of light pressure the atom moves near the center O of the trap.

3. Main equations

In the calculations we assume the condition [19,20]

$$\frac{\hbar^2 k^2}{2m} \ll \hbar\gamma, \tag{1}$$

which means that the light-pressure force is formed faster than the change of the atomic velocity will have a significant impact on its value (the heavy atom approximation). Here $k = \omega/c$ is the wave vector, ω is the carrier frequency of the waves, γ is the rate constant of spontaneous emission. Criterion Eq. (1) is the basis for the semi-classical approach in derivation of the Doppler-cooling limit [20].

Let's consider an atom in the field of two counter-propagating waves, one of which repeats the other with some time delay. The origin of the coordinate system is situated at the point O (see Fig. 2), where this delay is equal to zero. The atom with the coordinate z is subjected to the electric field

$$\mathbf{E} = \frac{1}{2}\mathbf{e}[E_0(t - z/c)\exp(i\omega t - ikz) + E_0(t + z/c)\exp(i\omega t + ikz)] + \text{c. c.} \tag{2}$$

Here $\mathbf{e}$ is the unit vector of polarization.

We describe the laser radiation by the chaotic field model [17,18], in which the real and imaginary parts of the complex amplitude of the field fluctuate independently. The ensemble average of the complex amplitude equals to zero and the autocorrelation functions of the real and the imaginary parts are

$$\langle \mathrm{Re}E_0(t)\mathrm{Re}E_0(t')\rangle = \frac{1}{2}|E_0|^2\exp - G|t - t'|), \tag{3}$$

$$\langle \mathrm{Im}E_0(t)\mathrm{Im}E_0(t')\rangle = \frac{1}{2}|E_0|^2\exp(-G|t - t'|), \tag{4}$$

where brackets $\langle\ \rangle$ denote averaging over the ensemble of the possible realizations of the stochastic process, G is the inverse correlation time and $|E_0|^2 = \langle E_0(t)E_0^*(t)\rangle$ does not depend on time.

We use a simple two-level model of the atom-field interaction and assume the absence of polarization gradients. The difference of energies of the ground $|1\rangle$ and the excited $|2\rangle$ states is $\hbar\omega_0$. The light pressure force on the atom is given by the formula [1,19]

$$F = (\varrho_{12}\mathbf{d}_{21} + \varrho_{21}\mathbf{d}_{12})\frac{\partial \mathbf{E}}{\partial z}, \tag{5}$$

where $\mathbf{d}_{12}$ and $\mathbf{d}_{21}$ are the matrix elements of the dipole moment, ϱ_{12} and ϱ_{21} are the non-diagonal elements of the density matrix ϱ.

According to Eq. (5) a force calculation requires we know not only the fields but also the density matrix of the atom. We use two approaches for calculating the density matrix of the atom. In our analytic calculation of the temperature of the atomic ensemble in a weak field we use the density matrix equation. In our numerical calculation of the statistical properties of the atomic ensemble we use the Monte Carlo wave-function method [21]. The results of both