THE LIGHT PRESSURE ON ATOMS IN THE FIELD OF COUNTER-PROPAGATING TRAINS OF SHORT LIGHT PULSES

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We present a theoretical study of the force of light on a two-level atom in the field of counter-propagating trains of short light pulses with constant and stochastic phases. By the example of a beam of He* atoms that crosses the light beam with the Gaussian distribution of intensity, it is shown that, in the counter-propagating trains of light pulses, a variation of the atom velocity along the laser beam may considerably exceed the maximal variation of the velocity that could be obtained under interaction of the atom with the field of a travelling wave with the same interaction time.

Introduction

The possibility of overcoming the limit of maximal light pressure in the field of a travelling wave $F_{\rm sp} = \frac{1}{2}\hbar k\gamma$ (k is the wave vector, $\gamma = 1/\tau_{\rm sp}$ is the reciprocal lifetime of an excited atom) was mentioned for the first time in [1, 2]. The main idea of those proposals is to arrange the processes of absorption and stimulated radiation of the light by atoms. At this, the atom absorbs a photon of one of the counter-propagating waves and emits it into another one. In the first case, those are two subsequences of counter-propagating π-pulses and, in the second case, they are the pulses with the area much larger than π. The frequency of the last pulses passes through the resonance during the time of interaction of the atom with each pulse adiabatically fast. As the result of interaction of the atom with a pair of counter-propagating pulses, the atom momentum changes by $2\hbar k$. The average force of the light pressure acting on the atom equals $2\hbar k/T$ (T is the period of pulses). Apparently, this force could be considerably larger than $F_{\rm sp}$ if $T \ll 1/\gamma$.

After publishing papers [1, 2], there were proposed another schemes of interaction of atoms with light waves propagating in counter directions. The process of alternative absorption of photons of one of the counter-propagating waves by the atom and the stimulated radiation into the second wave results in a considerable increase of the light pressure force on the atom. The very promising is the scheme of interaction of the atom with the bichromatic field of two standing waves that could be considered as two counter-propagating waves with the amplitude modulation. In particular, it may be the short π-pulses of light. Such a scheme was proposed in [3, 4] and experimentally realized for the first time in [5]. It permits to stop the cesium atom beam at a distance of 10 cm [6] and possesses the velocity dependence that is acceptable for the atom retardation and cooling [4,6–8]. In the another scheme, whose particular case is the fast adiabatic passing through a resonance [2], the atom interacts with two counter-propagating frequency-modulated waves [9, 10]. In this case, the light pressure force may be considerably larger than $F_{\rm sp}$ in a wide range of velocities essentially larger than γ/k. Apparently, the dependence of light pressure on the atom on its velocity plays the key role in a possible implementation of one or another scheme of the interaction of light with atoms or molecules for the governing of their motion.

In spite of the fact that the pressure on molecules in the field of trains of counter-propagating pulses was registered experimentally [11], the possibility of controlling the atom or molecule motion by the trains of pulses is not enough studied yet. Keeping in mind the technical complexity of the π-pulses generation, in [12], it was embarked the theoretical study of the light pressure sensitivity on the deviation of the area of pulses from π for the two-level atoms. It was shown that, for the small velocities of atom $v \ll \gamma/k$, the sensitivity weakly depends on the pulse area. A dependence of the light pressure force on velocities of atom for the pulses with area different from π was not studied yet. Our paper is devoted to elucidation of this problem.

We consider the interaction of two-level atoms with the counter-propagating trains of pulses of the same area within the framework of the quasiclassic theory of interaction of atoms with the electromagnetic field. It is shown that the velocity dependence of the light pressure force has the resonance character with maxima at $kv = 2\pi m/(nT)$, where m and n are integer numbers. This dependence gets smoother for the phase of light pulses distributed randomly. In this case, the interaction time with the field, which is needed to change the atom momentum by a required value, decreases. As an illustration, we calculated the velocity variation of a helium atom that crosses the laser beam with the radial rectangular or Gaussian distribution of intensity.

1. Main Equations

We consider the two-level atom with a difference $\hbar\omega_0$ between the excited $|2\rangle$ and ground state $|1\rangle$ that interacts with two periodic trains of light pulses propagating along the z-axis in opposite directions. The pulses of these trains and propagation periods T are being the same. Let the atom under the spontaneous radiation from the excited state could transit only into the ground state. Then, in the dipole approximation, the equation for the density matrix of the atom in an electric field $\boldsymbol{E}$ takes the form

$$\frac{\partial}{\partial t}\rho_{11} = \frac{i\boldsymbol{E}}{\hbar}(\boldsymbol{d}_{12}\,\rho_{21} - \boldsymbol{d}_{21}\,\rho_{12}) + \gamma\rho_{22}\,,$$

$$\frac{\partial}{\partial t}\rho_{12} = \frac{i\boldsymbol{E}}{\hbar}(\boldsymbol{d}_{12}\,\rho_{22} - \boldsymbol{d}_{12}\,\rho_{11}) + i\omega_0\rho_{12} - \frac{\gamma}{2}\rho_{12}\,,$$

$$\rho_{11} + \rho_{22} = 1\,, \qquad \rho_{21} = (\rho_{12})^*\,. \tag{1}$$

Here, $\boldsymbol{d}_{12} = (\boldsymbol{d}_{21})^*$ are the matrix elements of the atom dipole moment that may be considered as real without the loss in generality. We set further $\boldsymbol{d}_{12} = \boldsymbol{d}_{21} = \boldsymbol{d}$. To simplify the denotations, we do not indicate a dependence of the electric field $\boldsymbol{E}$ and density matrix on coordinates and time.

The system of equations (1) is written in the coordinate system connected with the atom. We consider the case where the carrying frequencies of pulses are equal in the laboratory coordinate system and exceed ω_0 by Δ. For the moving atoms $\omega_1 = \omega_0 + \Delta - kv$, $\omega_2 = \omega_0 + \Delta + kv$, where v is the projection of atom velocity on the $0z$ axis. We present the electric field strength in the form

$$\boldsymbol{E} = \boldsymbol{e}_1 E_1(t)\cos\left(\omega_1 t - kz + \varphi_1(t)\right) +$$

$$+\boldsymbol{e}_2 E_2(t)\cos\left(\omega_2 t + kz + \varphi_2(t)\right)\,, \tag{2}$$

neglecting a difference between the wave vectors of counter-propagating waves in the atom coordinate system. Here, the units vectors $\boldsymbol{e}_1$ and $\boldsymbol{e}_2$ describe the polarization of counter-propagating waves

$$E_1(t) = \frac{\hbar\theta_1}{\boldsymbol{d}\boldsymbol{e}_1}\sum_{n=-\infty}^{\infty}\delta(t - nT)\,,$$

$$E_2(t) = \frac{\hbar\theta_2}{\boldsymbol{d}\boldsymbol{e}_2}\sum_{n=-\infty}^{\infty}\delta(t - nT - \tau)\,, \tag{3}$$

where n is an integer, θ_1 and θ_2 are the area of pulses, the phases $\varphi_1(t)$ and $\varphi_2(t)$ describe the possible variation of phases of the counter waves in the pulse repetition time.

Solving equations (1) in the rotating wave approximation, we find a connection between the Bloch variables $w(t)$, $u(t)$, $s(t)$

$$w(t) = \rho_{22} - \rho_{11}\,,$$

$$u(t) = \rho_{12}e^{-i\omega_0 t} + \rho_{21}e^{i\omega_0 t}\,,$$

$$s(t) = i\left(\rho_{21}e^{i\omega_0 t} - \rho_{12}e^{-i\omega_0 t}\right) \tag{4}$$

at the moments of time before the beginning of the n-th pulse of wave 1, $t_a = nT - 0$, after its end, $t_b = nT + 0$, before the beginning of the n-th pulse of wave 2, $t_c = nT + \tau - 0$, after its end, $t_d = nT + \tau + 0$, and before the beginning of the $n+1$-th pulse of wave 1, $t_e = nT + T - 0$; τ is the time shift between the trains of pulses of waves 1 and 2. This chain of equations takes the form

$$w(t_b) = w(t_a)\cos\theta_1 - [s(t_a)\cos\Phi_1 - u(t_a)\sin\Phi_1]\sin\theta_1\,,$$

$$s(t_b) = w(t_a)\sin\theta_1\cos\Phi_1 + \frac{1-\cos\theta_1}{2}u(t_a)\sin 2\Phi_1 +$$

$$+\frac{1+\cos\theta_1}{2}s(t_a)-\frac{1-\cos\theta_1}{2}s(t_a)\cos 2\Phi_1\,,$$

$$u(t_b)=-w(t_a)\sin\theta_1\sin\Phi_1+\frac{1-\cos\theta_1}{2}u(t_a)\cos 2\Phi_1+$$

$$+\frac{1+\cos\theta_1}{2}u(t_a)+\frac{1-\cos\theta_1}{2}s(t_a)\sin 2\Phi_1\,,$$

$$w(t_c)=[1+w(t_b)]\,e^{-\gamma\tau}-1\,,$$

$$s(t_c)=s(t_b)e^{-\frac{1}{2}\gamma\tau}\,,$$

$$u(t_c)=u(t_b)e^{-\frac{1}{2}\gamma\tau}\,,$$

$$w(t_d)=w(t_c)\cos\theta_2-[s(t_c)\cos\Phi_2-u(t_c)\sin\Phi_2]\sin\theta_2\,,$$

$$s(t_d)=w(t_c)\sin\theta_2\cos\Phi_2+\frac{1-\cos\theta_2}{2}u(t_c)\sin 2\Phi_2+$$

$$+\frac{1+\cos\theta_2}{2}s(t_c)-\frac{1-\cos\theta_2}{2}s(t_c)\cos 2\Phi_2\,,$$

$$u(t_d)=-w(t_c)\sin\theta_2\sin\Phi_2+\frac{1-\cos\theta_2}{2}u(t_c)\cos 2\Phi_2+$$

$$+\frac{1+\cos\theta_2}{2}u(t_c)+\frac{1-\cos\theta_2}{2}s(t_c)\sin 2\Phi_2\,,$$

$$w(t_e)=[1+w(t_d)]\,e^{-\gamma(T-\tau)}-1\,,$$

$$s(t_e)=s(t_d)e^{-\frac{1}{2}\gamma(T-\tau)}\,,$$

$$u(t_e)=u(t_d)e^{-\frac{1}{2}\gamma(T-\tau)}\,, \tag{5}$$

where

$$\Phi_1=nT\Delta-k\int_0^{nT}v\,dt+\varphi_1(nT)+kz\,,$$

$$\Phi_2=(nT+\tau)\Delta+k\int_0^{nT+\tau}v\,dt+\varphi_2(nT+\tau)+kz\,. \tag{6}$$

For the sake of definiteness, we assume that the atom begins to interact with the field at a moment of time $t=0$.

The force acting on the atom is defined by the expression [13, 14]

$$F=\boldsymbol{d}\,(\rho_{12}+\rho_{21})\,\frac{\partial\boldsymbol{E}}{\partial z}. \tag{7}$$

Passing to the variables $w(t)$, $u(t)$, $s(t)$ and using (5), we easily obtain

$$F=\frac{\hbar k}{2T}\left[w(t_b)-w(t_a)+w(t_c)-w(t_d)\right]. \tag{8}$$

This formula has a clear physical meaning. According to the definition of $w(t)$, a combination $\frac{1}{2}w(t_b)-\frac{1}{2}w(t_a)$ equals the average number of photons absorbed by the atom (or emitted by the atom in the process of spontaneous radiation if this combination is negative) during the interaction with a pulse of wave 1. The expression $\frac{1}{2}w(t_d)-\frac{1}{2}w(t_c)$ describes the average number of photons that were absorbed by the atom during the interaction with a pulse of wave 2. Taking into account that absorption or radiation of one photon results in a variation of the atom momentum by $\hbar k$ and that waves 1 and 2 propagate in the opposite directions, we obtain expression (8).

2. Pressure of Light on Atoms in the Field of One Set of Pulses with Chaotic Phases

In the case of one set of pulses ($\theta_1=\theta$, $\theta_2=0$) and $\varphi_1(nT)$ = const, the quasi-stationary solution of the system of equations (5) and the light pressure on the atom F have been found in [12]:

$$F=\frac{\hbar k}{2T}\,\frac{\left(1-e^{-\gamma T}\right)(1-\cos\theta)}{1+e^{-\gamma T}-\cos kvT\,(1+\cos\theta)\,e^{-\frac{1}{2}\gamma T}}\,. \tag{9}$$

This force is a periodic function of the atom velocity and the pulse area.

Average (5) for stochastic phases $\varphi_1(nT)$ gives a relation between average values of the Bloch variables at the time moments t_a, t_b, t_c, t_d. Obviously, for a quasi-stationary solution, these averages are periodic with period T. Simple computations give a magnitude of the stochastic force as

$$F_{\rm st}=\frac{\hbar k}{2T}\frac{\left(1-e^{-\gamma T}\right)(1-\cos\theta)}{\left(1-e^{-\gamma T}\cos\theta\right)}. \tag{10}$$

As could be anticipated, the average force acting on the atom in the case of the stochastic phase of pulses does not depend on the velocity. At high frequencies of the pulses $T^{-1} \gg \gamma$ and rather large pulse areas $\theta \gg \sqrt{\gamma T}$, $F_{\rm st}$ approaches $F_{\rm sp}$.

Fig. 1 shows the light pressure force for constant and stochastic phases $\varphi_1(nT)$. It is easy to see that $F_{\rm st}$ considerably exceeds the averaged F with respect to the velocity. Apparently, the minimum in the dependence of F versus velocity at $\theta \neq \pi$ is connected with the preservation of the coherence of the variables $u(t)$, $w(t)$ during the period of pulses. The appearance of the stochastic phase destroys the coherency and approaches F to $F_{\rm sp}$ (for π-pulses, these variables equal zero and the dependence of F on v is leveled).

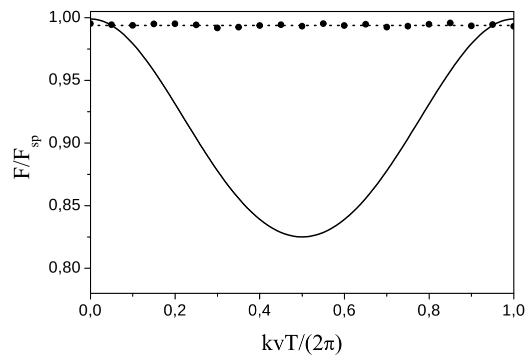

Fig. 1. The light pressure on atoms in the field of one train of pulses. The parameters: $\gamma T = 0.1$, $\tau = 0.1T$, $\theta = 0.8\pi$. The curves are obtained by calculation: the continuous line — formula (9), dashed line — formula (10). The line formed by bold dots presents the average force of light pressure acting on the atom in the case of stochastic phase of pulses (calculated in a time of $100\,T$ after establishing the quasi-stationary solution)

3. Light Pressure on Atoms in the Field of Two Counter-Trains of Pulses

The expression of the averaged force for pulses of an arbitrary area for two counter waves, when the quasi-stationary solution of Eqs. (5) exists, was obtained in [12] in the limit $kv \ll 1/\gamma$. Unfortunately, it does not allow one to analyze the possibility of acceleration or retardation of atoms in the field of counter trains of pulses. The exception is an ideal case of π-pulses, where the light pressure force does not depend on the velocity. Generally speaking, the analytic expression of the light pressure force may be obtained only if $kvT/(2\pi) = n/m$ is a rational number. In this case, the quasi-stationary solution of (5) with the period of mT is realized and the corresponding expression of the light pressure force can be found for every combination of n, m.

Now we consider the criteria of existence of the quasi-stationary solution for the pulses with area close to π. It was already noted that the light pressure force on the atom in the ideal case of π-pulses is maximal and close to $2\hbar k/T$. This allows us to estimate variations of Φ_1 and Φ_2 due to the time dependence of the velocity during the time of establishing the quasi-stationary solution $\tau_{\rm qs}$: $\Delta\Phi \sim k\Delta v\tau_{\rm qs} \sim \hbar k^2\tau_{\rm qs}^2/(mT)$, where m is the atom mass. Assuming $\tau_{\rm qs} \sim 1/\gamma$ and requiring $\Delta\Phi \ll 1$, we obtain the condition of existence of a quasi-stationary solution of Eqs. (5), (6):

$$\gamma T \gg \frac{\hbar k^2}{\gamma m}. \qquad (11)$$

If criterion (11) holds true (for example, for atoms with $m \sim 100$ a.u.m, the wave length of laser radiation $\lambda \sim 1000$ nm, time of propagation of pulses $T \sim 1$ ns, time of spontaneous radiation of atoms in the excited state $\tau_{\rm sp} \sim 10$ ns, the left part of (11) exceeds the right one by 3 orders), then we may speak about a dependence of the light pressure force on the atom velocity. In the opposite case, a variation of the atom momentum per unit time depends not only on its velocity but also on the history of its interaction with the field. It is necessary to note that the criterion holds true for pulses with the area that is rather close to π. In the opposite case, a variation of the atom velocity during time $1/\gamma$ is considerably smaller, and the Bloch equation may have a quasi-stationary solution.

Here, we consider the dependence of the light pressure force on the atom velocity for constant phases $\varphi_1(nT)$ and $\varphi_2(nT+\tau)$ only numerically. The case of random phases will be analyzed analytically.

Like for an atom in the field of a train of pulses with chaotic phases, averaging (5) over phases $\varphi_1(nT)$ and $\varphi_2(nT+\tau)$, using the periodicity of Bloch variables with period T and (8), and assuming $\theta_1 = \theta_2 = \theta$, we obtain the expression for the light pressure force on atoms in the field of two counter trains of light pulses:

$$F_{\rm st} = \frac{\hbar k}{2T}\frac{(1-\cos\theta)^2\left(e^{\gamma(T-\tau)} - e^{\gamma\tau}\right)}{e^{\gamma T} - \cos^2\theta}. \qquad (12)$$

Fig. 2 illustrates the dependence of the light pressure force on the atom velocity along the pulse propagation direction computed according to formulas (5), (6), (8) after establishing the quasi-stationary solution for the constant and stochastic phases $\varphi_1(nT)$ and $\varphi_2(nT+\tau)$, and the sane dependence for stochastic phases computed

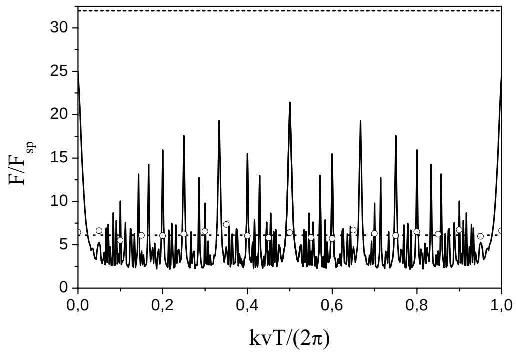

Fig. 2. The light pressure on atoms in the field of two counter-propagating trains of pulses. The parameters: $\gamma T = 0.1$, $\tau = 0.1\,T$. The curves obtained by calculations: the continuous line [$\theta = 0.8\pi$, formulas (5), (8) after establishing the quasi-stationary solution]; the dashed line in the upper part of the graph ($\theta = \pi$, the same formulas and regime); the line formed by circles presents the average force of light pressure acting on the atom in the case of the stochastic phase of pulses [calculated in a time of $100\,T$ after establishing the quasi-stationary solution, $\theta = 0.8\pi$); the dashed line on the graph bottom (the same force calculated according to (12)]

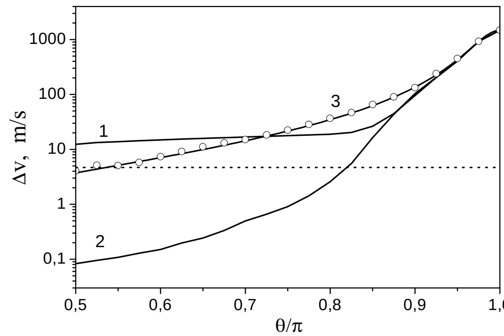

Fig. 3. The velocity variation of a He* atom along a direction of propagation of the laser beam versus the pulse area. Curves *1*, *3* – the atom initial velocity along the laser beam $v = 0$. *2* – $v = 100$ m/s; Curves *1*, *2* – calculation for fixed phases φ_1, φ_2 according to formulas (5), (6), (8); Curve *3* – calculation for stochastic phases φ_1, φ_2 (circles denotes the results of calculation according to formulas (5), (6), (8); the dashed line is the calculation according to formula (12)). The duration of atom – field interaction is 10 microseconds (other parameters are specified in the text)

according to (12). Comparison of the results obtained for stochastic phases with the help of (12) and by the Monte-Carlo method by using (5), (8) for the stochastic phases (uniformly distributed over the interval 0.2π) shows that they are in good agreement.

We note that the light pressure force for stochastic phases for the parameters specified in Fig. 2 is close to the light pressure force averaged over the velocity at constant phases obtained by integration of the continuous line unlike the case of one train of pulses considered in the previous section. Keeping this in mind and taking into account that the time of increasing the velocity from $v_{\min}$ to $v_{\max}$ is determined mostly by a minimal value of the force in the interval $[v_{\min}, v_{\max}]$ and not by its maxima (narrow "Doppler" resonance conditioned by multiphoton transitions induced by the counter waves), we may expect that, at this interval, the trains of pulses with stochastic phases are more favorable for governing by the motion of atoms and molecules than the trains of pulses with constant phases.

4. A Numeric Simulation of the Light Pressure on He* Atoms

Let us consider the light pressure action in the field of trains of counter pulses on atoms with account of the velocity variation during their interaction with the field. For simulation, we choose the lightest atoms He* in a metastable state that are used in the experiments with light pressure [14]. Let helium atoms come out of a supersonic nozzle and cross the laser beam formed by the counter trains of light pulses with the velocity $v_0 = 1000$ m/s. Let the wavelength of laser radiation be 1083.33 nm that corresponds to the transition frequency $2^3S_1 \rightarrow 2^3P_2$ in ^{4}He (the lifetime of the state 2^3P_2 is $\tau_{\rm sp} = 98.04$ ns). Under the absorption or stimulated radiation of one photon, the atom velocity changes by 9.2 cm/s. Let the pulse repetition frequency be $T = 1$ ns, $\tau = 0.1$ ns, and duration time ~ 1 ps. Thus, we may neglect the relaxation processes during the action of pulses on atoms.

Substitution of these parameters in (11) shows that Eqs. (5) for the pulses with area close to π do not have a quasi-stationary solution. While solving these equations numerically and computing $\int_0^t v\,dt'$ in (6), we take into account that the dependence of the atom velocity on time is of a ladder type; after the interaction with a light pulse, the atom velocity changes instantly by a definite value and stays constant if the light pulses do not act on the atom.

Firstly, we consider the interaction of helium atoms with fields with the rectangular distribution of intensity along the beam radius. This means that He atoms interact with the light pulses of a fixed area θ. Assume that, during the interaction with the field, atoms are at a distance $2r_0 = 1$ cm. A resultant variation of the velocity of atoms as a function of θ is shown in Fig. 3. As seen from the graph, the variation of velocity along the laser beam considerably depends for small θ on its initial velocity at fixed φ_1 and φ_2. Apparently, at the initial velocity that corresponds to one of the maxima in Fig. 2, the atom velocity variation during the short interaction time is much larger than in cases where the initial velocity corresponds to one of the minima. We note a good agreement of the calculation results of the velocity variation for the stochastic phases φ_1 and φ_2 according to (12) and for the averaged force acting on the atom in the case of the stochastic phase according to formulas (5), (6), (8). A minor deviation of these results and the corresponding calculation for fixed phases allow one to use formula (12) for calculation of the atom variation velocity in the fields of train pulses with area close to π.

Now we consider the interaction of helium atoms with the fields with the Gaussian distribution of intensity in the radial direction. Assume that the pulse area equals θ_0 at the beam center and decreases by e times for atoms at a distance $r_0 = 5$ mm from the center. Therefore, the atoms that cross the laser beam through its center interact with the train of counter pulses with area that varies in time as

$$\theta = \theta_0 \exp\left(-\frac{(t-t_0)^2}{T_f^2}\right), \qquad (13)$$

where $T_f = r_0/v_0 = 5$ microseconds, t_0 is the time of the atom flight from the beginning of interaction with the field ($t = 0$) to the laser beam center.

Fig. 4 depicts the dependence of the atom velocity variation along the laser beam propagation direction on an initial velocity of atom in the same direction. In computations, we set $t_0 = 3T_f$ and assume that the atom has been the same time in the laser beam (after passing the beam center). Averaging over the atom initial coordinate was carried out for the counter-propagating trains of pulses rather than for one train of light pulses. In the latter case, the result does not depend on the atom initial coordinate.

We note, first of all, a large, approximately 30 times, variation of the atom velocity under interaction with two counter-propagating trains of light pulses comparing with one train of light pulses. For comparison, we indicate the velocity change of a He atom under action of the same force F_{sp} during the same time, that is 14 m/s.

As seen from Fig. 4, the atom velocity variation practically does not depend on its initial velocity along

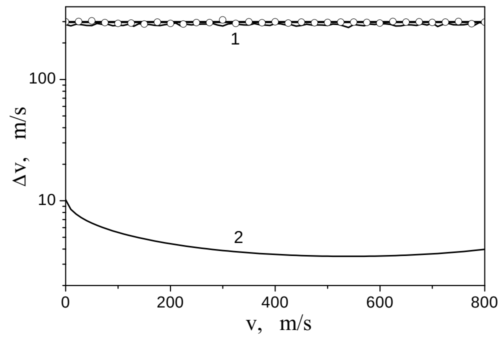

Fig. 4. The velocity variation of He* atom along a direction of the laser beam versus its initial velocity in this direction for $\theta_0 = \pi$ (other parameters are specified in the text). Continuous line *1* is calculated according to formulas (5), (6), (8), (13) for an atom in the field of counter-propagating trains of pulses and fixed φ_1, φ_2; Curve *2* is the same for one train of pulses, circles correspond to calculations according to the same formulas for an atom in the field of counter-propagating trains of pulses with stochastic phases φ_1 and φ_2. The straight line shows the velocity variation of an atom in the case of stochastic phases $\varphi_1$and φ_2 obtained by integration of (12) with the pulse area time dependence given by (13)

the laser beam for counter-propagating pulses and considerably depends on it for one train of pulses. A minimum of the latter dependence coincides with $\pi/(kT)$ in accordance with (9). Concerning the dependence of the atom velocity variation on the initial velocity, we note that the calculations carried out indicate approximate limits of the velocity variation. A sensitivity of the result obtained to the initial conditions is so large that averaging over an initial coordinate cannot be carried out with the accuracy required for construction of a smooth curve. Taking into account a considerable variation of the atom velocity during interaction with the field, we could expect that the relevant result may be obtained assuming that phases φ_1 and φ_2 are stochastic. In fact, as seen from Fig. 4, the velocity variation in the field of counter pulses with chaotic phases is very close to its variation in the field with fixed φ_1 and φ_2.

The case of chaotic phases when θ_0 is close to π provided that $\gamma T \ll 1$ may be studied analytically. Here we consider only the case $\theta_0 = \pi$ when the velocity variation is close to the maximum allowed. Noting that force (12) has a sharp maximum at $\theta = \pi$. Making the variable change $t \to t + t_0$ and expanding $\cos\theta$ in (13) into a series in t, we obtain the light pressure force

$$F = 2\hbar k\gamma \frac{(T-2\tau)}{T}\left(\gamma T + \frac{\pi^2 t^4}{T_f^4}\right)^{-1}. \qquad (14)$$

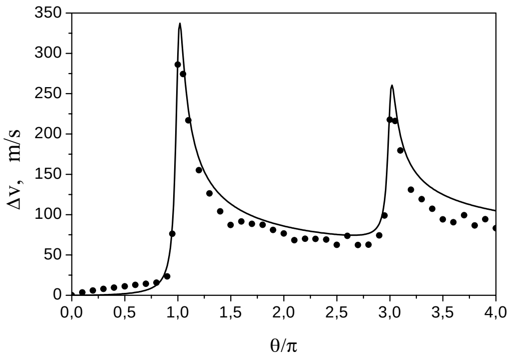

Fig. 5. The velocity variation of a He* atom along the laser beam propagation line versus the pulse maximum area θ_0 for an initial velocity of atom $v = 0$. The continuous line shows the atom velocity variation in the case of stochastic phases φ_1 and φ_2 obtained by integration of (12) with the pulse area time dependence given by (13). Calculations according to formulas (5), (8), (13), (6) for the atom in the field of counter-propagating pulses and fixed φ_1 and φ_2 are shown by bold dots (the parameters are the same as in Fig. 4)

By integration of (14) within the limits $(-\infty, \infty)$, we get the atom momentum variation during the time of passing through the laser beam:

$$\Delta P = \hbar k \frac{(T - 2\tau)\, T_f}{T^2} \sqrt{2\pi}\, \sqrt[4]{\gamma T}. \tag{15}$$

A calculation of the velocity variation $\Delta P/m$ of a helium atom during the time of crossing of the laser beam according to (15) agrees with the results given in Fig. 4 for the stochastic phases with 1% accuracy.

Now we consider a sensitivity of the atom velocity variation to a variation of a maximal pulse area θ_0. The results reported above show that the velocity variation of a He* atom, as a result of its durable interaction with the field of counter pulses, may be satisfactory described with the help of expression (12) for the force acting on an atom in the field of stochastic pulses and expression (13) for the law of variation of the pulse area (what the atom "sees" while crossing the laser beam). Fig. 5 demonstrates a dependence of the velocity variation of a He* atom along the laser beam direction on a maximum pulse area θ_0 calculated in such a way that results correspond to those made with the help of formulas (5), (6), (8), (13) for the atom in the field of counter-propagating trains of pulses and fixed φ_1 and φ_2.

We mark two important conclusions that could be made from Fig. 5. Firstly, a maximum of velocity variation is not realized at $\theta_0 = \pi$ but at a little bit larger θ_0. Apparently, this is a result of a longer interaction time of the atom with pulses whose areas are close to π while crossing the laser beam. Secondly, a sufficiently high "pedestal" between $\theta_0 = \pi$ and $\theta_0 = \pi$ (Fig. 5) is favourable for observation of an action of the light pressure on atoms. Thus, at θ_0, far from optimal choice, the velocity variation of a He atom in the field of two trains of counter-propagating pulses is by one order larger than that in the field of one train (compare with Fig. 4) or under action of the force F_{sp} in one travelling wave. The appearance of this pedestal is conditioned by the fact that, for any $\theta_0 > \pi$, the atom passes through some parts of the laser beam where θ is close to $(2n+1)\pi$ (where n is an integer) that results in a considerable variation of its velocity.

Conclusions

The light pressure force on an atom in the field of counter-propagating short trains of light pulses depends on its velocity resonantly with narrow maxima (their width is much smaller than γ/k) at velocities $2\pi \frac{m}{n}(kT)^{-1}$, where m, n are integers. The light pressure force practically does not depend on the atom velocity for the fluctuating phases of pulses. This may considerably decrease the transferring time of a definite momentum from the field to an atom.

We calculated the velocity variation of excited He* atoms that cross the laser beam with the Gaussian distribution of intensity in the field of counter-propagating trains of light pulses for the parameters typical of possible experiments. It is shown that it may considerably exceed a maximum velocity variation for the same duration of interaction with the travelling wave field and achieve 300 m/s. A requirement that the area of pulses must be close to π (at the laser beam center) is not critical for observation of the light pressure on atoms. Even for the pulse area $\sim 2\pi$ at the center of the laser beam, there is a considerable excess of the light pressure in the field of counter-propagating light pulses over the light pressure in the field of one travelling wave.

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ТИСК СВІТЛА НА АТОМИ У ПОЛІ ЗУСТРІЧНИХ ПОСЛІДОВНОСТЕЙ КОРОТКИХ СВІТЛОВИХ ІМПУЛЬСІВ

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Р е з ю м е

Теоретично досліджено силу світлового тиску на дворівневий атом у полі зустрічних послідовностей коротких світлових імпульсів з постійними та стохастичними фазами. На прикладі пучка атомів He^*, що перетинає лазерний промінь з гауссовим розподілом інтенсивності, показано, що для зустрічних послідовностей світлових імпульсів зміна швидкості атома вздовж напрямку лазерного променя може значно перевищувати максимальну зміну швидкості, яка досягається за такої ж тривалості взаємодії атома з полем біжучої хвилі.