CAPTURE OF ATOMS AND SMALL PARTICLES IN AN OPTICAL TRAP FORMED BY SEQUENCES OF COUNTER-PROPAGATING LIGHT PULSES WITH A LARGE AREA

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A new trap for atoms and small particles based on the interaction between an atom and the field of counter-propagating light pulses that are partially superposed in time has been proposed. A substantial difference from the known analogs consists in that the atom–field interaction is close to the adiabatic one, which allows a considerably higher momentum to be transferred to the atom within the same time interval and makes the trap smaller in size. It has been shown that, owing to the dependence of the light pressure force on the atom velocity, the atomic ensemble is cooled at its interaction with the field.

1. Introduction

Governing the atomic motions by applying light fields has already gone beyond the scope of speculations, being nowadays an ordinary means in physical experiments [1–4]. At the same time, new approaches in this domain are proposed. For instance, it was shown [5–7] that the variation of the momentum of an atom at its interaction with counter-propagating light pulses, which are partially superposed in time, can considerably exceed the double momentum of a photon, which is a fundamental limit of momentum transfer in the case where the atom interacts with counter-propagating pulses one-by-one [9, 10].

As a rule, an atom in an optical trap permanently interacts with the field. This can comprise an appreciable obstacle in physical experiments, in particular, in laser spectroscopy. A possible way out from this situation is to organize the interaction between the atom and the field in such a manner that the atom would undergone the action of laser radiation only within a short time interval, i.e. to construct light traps on the basis of counter-propagating light pulses [11–14]. It is important that, in the cited works, the carrier frequencies of counter-propagating pulses are identical, and, as a result, the force acting on the atom does not exceed $2\hbar k/T$, where T is the pulse-repetition period, and $\hbar k$ is the photon momentum.

We suggest to combine the advantages suggested by a small perturbation of an atom in the pulse trap with a capability to substantially increase the light pressure force in the trap owing to the multiphoton interaction. This combination forms a basis for the propositions of how the momentum transferred to an atom can be made well above $2\hbar k$ [5–8]. With this goal in view, the interaction between the atom and the field must be adiabatic, i.e. the area of light pulses must considerably exceed π. The difference between two schemes of the interaction between a two-level atom and a field of counter-propagating pulses, which are examined in works [5, 7, 8], consists in the following: in works [5, 8], the atom interacts with the field of counter-propagating pulses characterized by different carrier frequencies, whereas, in work [7], the current carrier frequencies change linearly in time. As a result, the directions of the momentum transferred to the atom during its interaction with the field turn out different. In the former case, the direction of a variation of the atom momentum is "counter-intuitive", i.e. the momentum changes in the direction of the momentum of the light pulse, which is the second that interacts with the atom. In the latter case, it coincides with the direction of propagation of the pulse, which is the first that interacts with the atom. In Section 3, it is demonstrated that, owing to this difference, the light pulses form a potential barrier for atoms in the

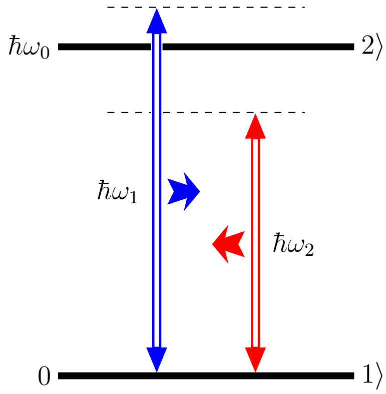

Fig. 1. Diagram of the interaction between an atom and light pulses with the carrier frequencies ω_1 and ω_2. The energy difference between the ground and excited states equals $\hbar\omega_0$

former case and a potential well in the latter one. In Section 4, in order to determine whether those barrier and well can be used to form an optical trap, we analyze the dependence of the force that acts on the atom in the field of a pulse sequence on the atom velocity and show that the force in the potential well acts oppositely to the atom velocity and decelerates the atom in the trap. However, in the case of light barrier, the direction of the force acting on the atom depends on the sign of the difference between the frequencies of the first and second light pulses. As a result, the trap can be constructed in the bichromatic field of pulses as well, provided that the barriers are spatially located not far from each other.

The proposed optical trap can also be applied to hold small particles containing atoms with narrow spectral lines associated with the transition from the ground into the excited state. The parameters of such a trap are evaluated in Section 5. Short conclusions are made in Section 6.

2. Basic Equations

Consider a two-level atom with ground state $|1\rangle$, excited state $|2\rangle$, and the frequency of the transition between them ω_0. The atom interacts with the field

$$\mathbf{E}(t) = E_1(t)\mathbf{e}\cos[\omega_1 t - k_1 z + \varphi_1(t)]+$$

$$+E_2(t)\mathbf{e}\cos[\omega_2 t - k_2 z + \varphi_2(t)] \qquad (1)$$

created by a sequence of counter-propagating pulses (see Fig. 1). Here, $\omega_{1,2}$ are the carrier frequencies of pulses; $\varphi_{1,2}(t)$ the corresponding phases, which are, generally speaking, dependent on time; $E_{1,2}(t)$ the pulse envelopes; and $\mathbf{e}$ the unit vector of the pulse electric field polarization. To make the notation simpler, the argument will not be indicated below for the fields and the phases, as well as for the density matrix elements.

The interaction between the atom and the filed is described in the dipole approximation. The Hamiltonian of this interaction looks like

$$H = \hbar\omega_0|2\rangle\langle 2| - \mathbf{d}_{12}|1\rangle\langle 2|\mathbf{E}(t) - \mathbf{d}_{21}|2\rangle\langle 1|\mathbf{E}(t), \qquad (2)$$

where $\mathbf{d}_{12}$ and $\mathbf{d}_{21}$ are the matrix elements of the atomic dipole moment $\mathbf{d}$. Without any loss of generality [15], we may assume that $\mathbf{d}_{12}\mathbf{e} = \mathbf{d}_{21}\mathbf{e}$.

The equations for the occupation inversion $w = \varrho_{22} - \varrho_{11}$ and for the coherence ϱ_{12}, where ϱ_{nm} is the density matrix of the atom, look as follows in the rotating-wave approximation [15]:

$$\dot{w} = 2\,\mathrm{Im}\,\varrho_{12}\left(\Omega_1 e^{ikz - i\varphi_1 - \frac{1}{2}i\delta t} +\right.$$

$$\left. + \,\Omega_2 e^{-ikz - i\varphi_2 + \frac{1}{2}i\delta t}\right) - \gamma\,(1+w)\,,$$

$$\dot{\varrho}_{12} = -\frac{i}{2}\left(\Omega_1 e^{-ikz + i\varphi_1 + \frac{1}{2}i\delta t} +\right.$$

$$\left. + \,\Omega_2 e^{ikz + i\varphi_2 - \frac{1}{2}i\delta t}\right) w + \left(i\Delta - \frac{1}{2}\gamma\right)\varrho_{12}, \qquad (3)$$

where γ is the inverse lifetime of the atom in the excited state, $\Omega_1 = -d_{12}E_1/\hbar$, $\Omega_2 = -d_{12}E_2/\hbar$,

$$\delta = \omega_1 - \omega_2, \quad \Delta = \omega_0 - \frac{1}{2}(\omega_1 + \omega_2)\,. \qquad (4)$$

Here, we selected the normalizing condition in the form $\varrho_{11} + \varrho_{22} = 1$ and assume $k_1 = k_2 = k = \omega_0/c$.

We consider the interaction between an atom and a field created by two sequences of counter-propagating light pulses with the repetition period T. One of the sequences repeats the other with a definite time delay t_d at the atom location point:

$$\Omega_{1,2} = \Omega_0 f(\eta_{1,2}), \qquad (5)$$

where the function $f(\eta)$ describes the shape of a pulse envelope and has the maximum value $f(0) = 1$,

$$\eta_{1,2} = (2t \mp t_d)/2\tau, \qquad (6)$$

t_d is the difference between the arrival times of the maxima of pulses propagating in the negative and positive directions along the z-axis at the point, where the atom is located, and τ is the pulse duration.

While simulating the atom-field interaction, pulses of the Gaussian-like shape are used, as a rule [17, 18]. It is known [8, 19] that the function $\cos^n(\pi t/\tau)$ with the growing even power exponent n tends to $\exp(-t^2/\tau_g^2)$, where $\tau_g = \tau\sqrt{2}/(\pi\sqrt{n})$, within the interval $|t| < \tau/2$. For the numerical simulation, we selected the function $f(\eta)$ in the form

$$f(\eta) = \begin{cases} \cos^4(\pi\eta), & |\eta| < 1/2 \\ 0, & |\eta| > 1/2 \end{cases}. \tag{7}$$

In a vicinity of every pulse, this function is close to the Gaussian one

$$f_G(\eta) = \exp\left(-2\pi^2\eta^2\right) \tag{8}$$

in the interval, where its value is not small (see Fig. 2). In comparison with the Gaussian function (8), function (7) selected by us for the pulse simulation is, on the one hand, more convenient for numerical calculations, because the Gaussian function has to be artificially cut off at certain limits, and, on the other hand, it corresponds to real pulse envelopes confined in time.

The area of a pulse, the envelope of which is described by function (7), equals $\frac{3}{8}\Omega_0\tau$, amounting to approximately 0.94 times the area of the Gaussian pulse close to it.

The pulse phases $\varphi_{1,2}$ depend quadratically on the time,

$$\varphi_{1,2} = \frac{\beta}{2}\eta_{1,2}^2, \tag{9}$$

so that the current frequency of each pulse changes linearly in time,

$$\varpi_{1,2} = \omega_{1,2} + \dot{\varphi}_{1,2} = \frac{\beta}{\tau^2}\left(t \mp \frac{1}{2}t_d\right). \tag{10}$$

The expression for the light pressure force acting on the atom [16],

$$\mathcal{F} = 2\frac{\partial \mathbf{E}}{\partial z}\operatorname{Re}\varrho_{12}\mathbf{d}_{21}\exp\left(i\left(\omega_0 - \Delta\right)t\right), \tag{11}$$

after its averaging over the period of oscillations with the frequency ω for field (1) takes the form

$$\bar{\mathcal{F}} = \hbar k \operatorname{Im}\varrho_{12}\Big(\Omega_1 e^{ikz - \frac{1}{2}i\delta t - i\varphi_1(t)} - \\ - \Omega_2 e^{-ikz + \frac{1}{2}i\delta t - i\varphi_2(t)}\Big). \tag{12}$$

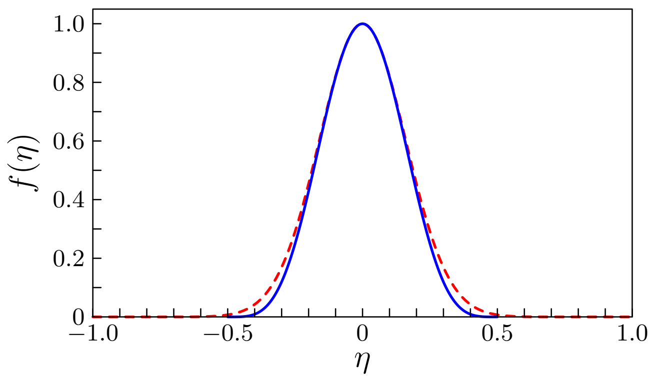

Fig. 2. Comparison between the function $f(x)$ describing the envelope of light pulses (solid curve) and the most approximating Gaussian function (dashed curve)

When the atom moves along the z-axis with the velocity v, its coordinate changes together with the force acting on the atom. Within the wavelength interval, the atom velocity is almost constant. Therefore, in order to calculate the variation of the atom momentum in time, we use the light pressure force averaged over the wavelength $\lambda = 2\pi c/\omega_0$, as it was done when calculating the light pressure on atoms in a bichromatic field,

$$F = \frac{1}{\lambda}\int\limits_{z}^{z+\lambda}\bar{\mathcal{F}}(z')dz'. \tag{13}$$

3. "Heavy" Atom. Light Pressure Force and Potential Energy

For an atom moving along the z-axis with the velocity v, the detuning δ of carrier frequencies of light pulses in time in the atom reference frame changes according to the law

$$\delta = \delta_0 - 2k\int\limits_0^t v(t')dt', \tag{14}$$

where δ_0 is the initial detuning.

Let us consider firstly the force of the light pressure on an atom in the "heavy"-atom approximation, when the variation of the detuning of light pulse carrier frequencies from the transition frequency ω_0 during the atom motion weakly affects the magnitude of light pressure force that acts on the atom. It is true, for instance, when the second term in formula (14) is small in comparison with the first one. However, if we consider the pulses with current frequencies $\varpi_{1,2}$ that vary in time, the role of δ_0

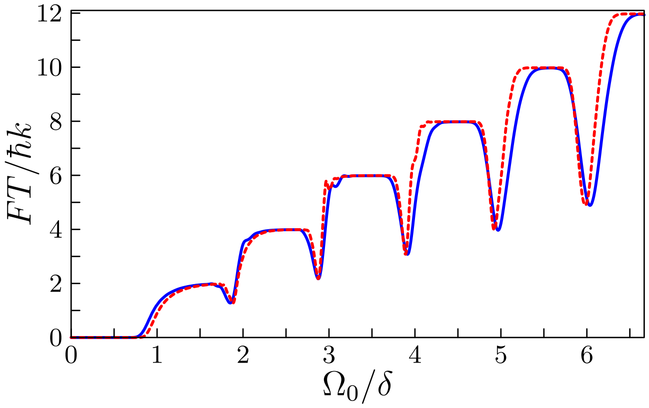

Fig. 3. Dependences of the light pressure force acting on the atom in the field of counter-propagating pulses on the Rabi frequency reckoned in δ-units obtained by numerically solving Eqs. (3) together with Eqs. (12) and (13). The calculation parameters are $T = 100\tau$, $\beta = 0$, $\Delta = 0$, $t_d = 0.25\tau$, $\gamma T = 0.5$, and $\delta\tau = 300$ (solid curve) and 600 (dashed curve). The force was averaged after the transient processes had terminated ($t > 10T$)

is played by the difference $\varpi_1 - \varpi_2$, and this quantity must substantially exceed kv during the most part of the interaction time between the atom and the field.

In Fig. 3, an example of the dependence of the light pressure force acting on the atom on the Rabi frequency of light pulses is shown for the case of chirp-free light pulses ($\beta = 0$). In contrast to what was done in works [5, 8], we calculate the force acting on an atom during a long ($t \gg 1/\gamma$) time of the interaction between the atom and the field, rather than the average transferred momentum. Moreover, while calculating the force acting on the atom, we used equations for the density matrix, which allowed us, unlike the case with the Schrödinger equation, to analyze the closed scheme of the interaction between the atom and the field, when the atom, owing to the spontaneous radiation emission, transits from the excited state in the ground one.

As is seen from Fig. 3, the dependence of the light pressure force acting on the atom on the Rabi frequency in the bichromatic field of counter-propagating light pulses resembles stairs, with the latter being observed more pronounced on the (dotted) curve that corresponds to a larger area of light pulses. The altitude of every stair is close to an even number in terms of $\hbar k/T$-units. Note that the quantity $2\hbar k/T$ is the maximum force of the light pressure on the atom, which can be obtained in the field of light pulses, which alternatively interact with the atom. Really, when the atom absorbs a photon from a light pulse, its momentum can change to that of the photon, $\hbar k$, and when it interacts with the counter-propagating light pulse, its momentum can change again by $\hbar k$ in the same direction.

The behavior of the dependence shown in Fig. 3 originates from the adiabaticity of the interaction between the atom and the bichromatic field [5, 8]. In such a field, the atom is characterized by a spectrum of quasi-energies [22] with the period $\hbar\delta$, which corresponds to the momentum change by $2\hbar k$. When the atom adiabatically interacts with the field, it occupies one of its characteristic states, and the Landau–Zener transitions into other states with close quasi-energy values become probable. As a result, the momentum of the atom during its interaction with a pair of pulses changes by a value multiple of $2\hbar k$. The coefficient of multiplicity is close to Ω_0/δ (for more details, see works [5, 8]).

If the atom moves along the z-axis, the delay t_d between pulses changes in the reference frame connected with the atom. For instance, if the atom is located at a point, at which light pulses arrive simultaneously (let it be selected for the coordinate origin), $t_d = 0$. It is easy to see that, for the atom with the coordinate z, the time delay t_d at this point between the arrivals of pulses that propagate in the positive and negative directions of the z-axis is equal to $2z/c$.

Figure 4,*a* illustrates an example of the dependence of the force that acts on the atom on the atom coordinate obtained for the case of a field with constant current frequencies ($\beta = 0$). One can see that the light pressure force vanishes in the region, where light pulses alternatively interact with the atom. This circumstance is associated with the fact that, owing to a large area of pulses and a large detuning of light pulse carrier frequencies from the resonance one, i.e. $|\omega_1 - \omega_0| = |\omega_2 - \omega_0| = \delta/2 \gg 1/\tau$, the atom is permanently in one of its adiabatic states. As a result, the coherent population return takes place [23]; the atom states at the beginning and the end of the interaction of the atom with the field coincide; therefore, the atom momentum does not change, if the atom interacts with a *single* light pulse, so that the light pressure force equals zero.

In Fig. 4,*b*, the coordinate dependence of the atomic potential energy U determined by the equation

$$F = -\frac{dU}{dz} \tag{15}$$

is depicted. The reference mark for the potential energy was so selected that it equals zero beyond the pulse superposition region. As one can see, the counter-

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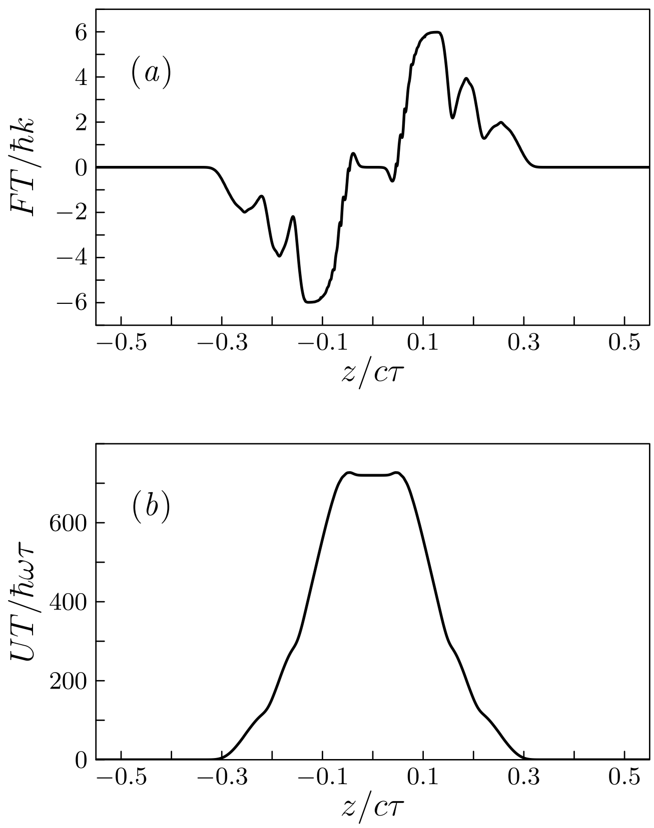

Fig. 4. Dependences of the light pressure force acting on the atom in the field of counter-propagating pulses (a) and the atom potential energy on the atom coordinate (b) determined by numerically solving Eqs. (3) together with Eqs. (12) and (13). The calculation parameters are $T = 100\tau$, $\beta = 0$, $\Delta = 0$, $\gamma T = 0.5$, $\delta\tau = 300$, and $\Omega_0\tau = 1000$. The force was averaged after the transient processes had terminated ($t > 10T$)

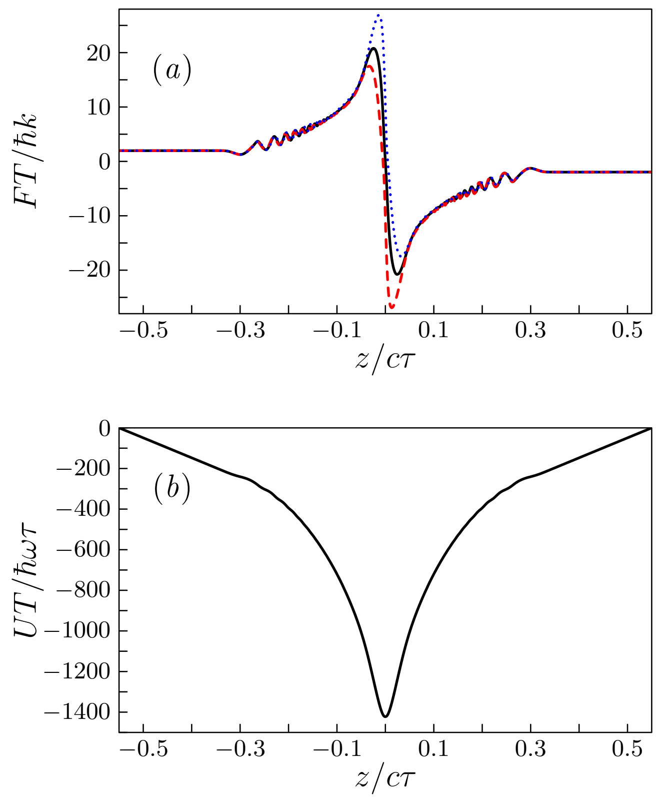

Fig. 5. Dependences of the light pressure force acting on the atom in the field of counter-propagating pulses (a) and the atom potential energy on the atom coordinate (b) determined by numerically solving Eqs. (3) together with Eqs. (12) and (13). The calculation parameters are $T = 100\tau$, $\beta = 200$, $\Delta = 0$, $\gamma T = 0.5$, $\Omega_0\tau = 1000$, and $\delta\tau = 0$ (solid curve), -2 (dashed curve), and 2 (dotted curve). The force was averaged after the transient processes had terminated ($t > 10T$)

propagating light pulses form a potential barrier for atoms.

In Fig. 5,a, an example of the coordinate dependence of the force acting on the atom is shown for the case of a field with current frequencies linearly varying in time ($\beta = 200$). In contrast to Fig. 4,a, the light pressure force differs from zero, being close to $2\hbar k/T$, in the region, where light pulses interact, in turn, with the atom. This circumstance is associated with an adiabatically quick passage of the resonance [15], when either of light pulses interacts with the atom, which results in that the atom transits from the ground state into the excited one, which is accompanied by the absorption of a photon and a momentum change by $\hbar k$. When the atom interacts with the counter-propagating pulse, the induced photon emission takes place, and the atom changes its momentum by another $\hbar k$ in the same direction [10].

In Fig. 4,b, the coordinate dependence of the atomic potential energy is depicted for a field with current frequencies that vary linearly in time. In contrast to the interaction between the atom and the field created by counter-propagating pulses with fixed current frequencies, the potential well for the atom is formed in this case.

Hence, the field created by counter-propagating light pulses with fixed frequencies or frequencies that linearly vary in time allows potential barriers or potential wells to be created in the space, which can be used to control the motion of atoms or nanoparticles containing atoms with a narrow absorption line or to localize them in a definite space region. For instance, the potential well can be used directly to hold atoms in a small spatial region. At the same time, two potential barriers, which are simple to be created with the use of two pairs of counter-propagating

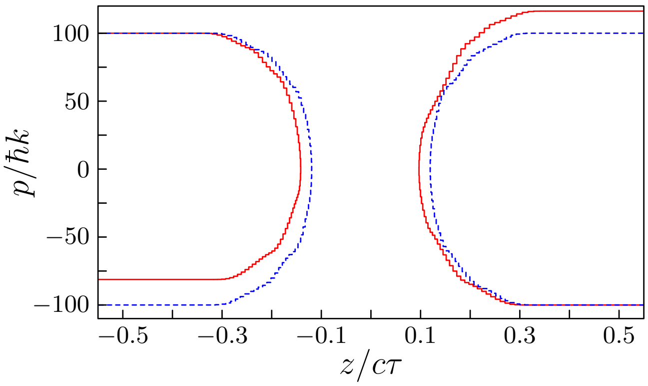

Fig. 6. Phase trajectories of an atom in the field of sequences of counter-propagating pulses. The calculation parameters are $T = 100\tau$, $\beta = 0$, $\Delta = 0$, $\gamma T = 0.5$, $\delta\tau = 300$, $\Omega_0\tau = 1000$, $\alpha = 10^{-6}$, and $\mu = 1$ (solid curves) and 0 (dashed curves). The force was averaged after the transient processes had terminated ($t > 10T$). The left-hand side of the figure corresponds to the initial momentum $p_{\rm ini} = 100\hbar k$ and the right-hand side to $p_{\rm ini} = -100\hbar k$

pulse sequences, can be used to form an optical trap between them.

While creating traps, the important issue is the dependence of the light pressure force on the atom velocity. It can result in a growth of the atom energy followed by a probable escape of the atom beyond the trap boundaries, as well as in its reduction, which corresponds to a stable atom localization in the trap.

4. Optical Trap Formed by Sequences of Counter-Propagating Pulses

In the course of long-term interaction between the atom and the field, the velocity of the former changes. Simultaneously, according to Eq. (14), the difference between the carrier frequencies of light pulses that act on the atom also changes in the atom reference frame. Let us consider firstly light pulses with a fixed carrier frequency ($\beta = 0$). Let $\delta_0 > 0$ and $v > 0$. Then, if v grows, δ decreases, and Ω_0/δ increases. At the same time, one can see from Fig. 2 that, in general, the light pressure force that acts on the atom grows with Ω_0/δ. Hence, if v is positive and grows, the force acting on the atom also grows. However, if $v < 0$ and $|v|$ grows, similar speculations bring us to a conclusion that the light pressure force decreases.

Let the atom move along the z-axis toward the barrier created by the sequences of counter-propagating pulses. Let a pulse with a higher carrier frequency (i.e. $\delta > 0$) act on it first. When having achieved the barrier, the atom is decelerated by the light pressure force, and its velocity diminishes. After the atom having been reflected from the barrier, the atom velocity grows. However, since it is directed oppositely, the light pressure force, according to the reasoning given above, is less than that when the atom moves toward the barrier. Therefore, the atom, after having been reflected from the barrier located at larger z's, flies away from it with a velocity lower than the initial one, if $\delta > 0$. However, if the atom collides with the barrier when moving to the negative direction along the z-axis, then, according to similar speculations, its velocity after the reflection from the barrier will exceed the initial one. In Fig. 6, the phase trajectories of the atom are shown for both cases of motion, namely, with the initial velocity directed in the positive (the right part of the figure) and negative (the left part of the figure) directions of the z-axis. The trajectories (solid curves) illustrate an increase or a reduction of the atom velocity, when the atom is reflected from the barrier, depending on the direction of its initial velocity. The dotted curve denotes the phase trajectory obtained in the approximation of a very heavy atom, i.e. when $kv \lll \delta_0$.

While calculating the atom momentum change, we neglected the influence of a variation of the atom velocity on the light pressure force in the course of interaction between the atom and the field created by a pair of pulses. The change of the atom momentum was calculated as follows. First we calculated the variation of the atom momentum,

$$\Delta p = \int\limits_{t_{\rm ini}}^{t_{\rm fin}} F\,dt, \tag{16}$$

where $t_{\rm ini}$ and $t_{\rm fin}$ are the initial and final times of the interaction between the atom and the field of a pulse pair. Then, we calculated the variation of the atom velocity,

$$\Delta v = \frac{\Delta p}{M}, \tag{17}$$

where M is the atom mass. The obtained v-value and the corresponding δ-value calculated according to Eq. (14) were used to repeat the calculation procedure for the next pair of pulses. For illustrative calculation, we selected the overestimated values of parameters $\mu = \hbar k^2\tau/M$ and $\alpha = \hbar k/cM$, which govern the dependence of the dimensionless detuning $\delta\tau$ on the atom momentum in $\hbar k$-units,

$$\delta\tau = \delta_0\tau - \mu\left(\frac{p}{\hbar k}\right) \tag{18}$$

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and the dependence of the dimensionless coordinate $\Delta z/c\tau$ on the dimensionless time $\Delta t/\tau$,

$$\frac{\Delta z}{c\tau} = \alpha \left(\frac{p}{\hbar k}\right) \frac{\Delta t}{\tau}, \tag{19}$$

respectively.

By selecting the difference between the frequencies of light pulses in such a way that the velocity of an atom after its interaction with the barrier formed by those pulses would decrease and placing two barriers beside each other, it is possible to obtain a one-dimensional trap for atoms.

Now, let us analyze a possibility of creating a trap on the basis of counter-propagating pulses with varying current frequencies. In Fig. 5,*a*, the dependences of the force on the atom coordinate are plotted for δ's, which are identical by absolute value, but different by sign. The positive (negative) sign of δ at $\delta_0 = 0$ corresponds, according to Eq. (14), to the motion of the atom in the negative (positive) direction of the z-axis. It is easy to see that the light pressure force is less, when the atom moves away from the coordinate origin than when it moves in the opposite direction. Therefore, one may expect a stable holding of the atom by the field of counter-propagating pulses with varying frequencies.

Figure 7 illustrates the motion of an atom in a trap created by counter-propagating sequences of light pulses with frequencies varying in time. One can see that, owing to the Doppler shift of carrier frequencies for light pulses in the atom reference frame, the atom becomes ultimately localized at the trap center. It should be noted that this fact does not mean that all atoms will gather at the center, because the applied model of classical motion of an atom in the light field does not take the momentum diffusion into account [16]. In order to evaluate the localization region, which constitutes a subject of our subsequent researches, the quantum-mechanical description of the motion of atoms should be applied.

Unlike the light trap formed by sequences of counter-propagating π-pulses or pulses with a small area [11–14], the light pressure force in the region, where pulses are spatially superposed, does not diminish, but grows. As a result, the potential well in this region becomes much deeper.

Depending on the way used to create a trap, i.e. whether pulses with a fixed frequency or a current frequency that varies in time are applied, the pulse intensity can differ considerably. In work [7], the intensities required to transfer the same momentum to a helium or rubidium atom in the cases where the nanosecond pulses acting on the atom have either a fixed carrier frequency or a current carrier frequency that varies in time, were compared. According to the estimations given in that work, the required intensity amounts to about 1 MW/cm^2 in the former and to a few kW/cm^2 in the latter case.

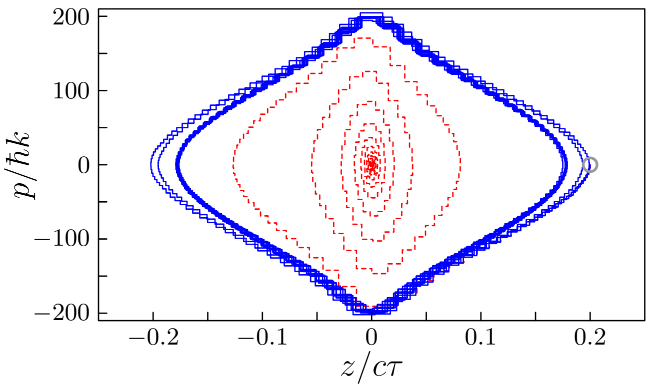

Fig. 7. Phase trajectories of an atom in the field of sequences of counter-propagating pulses. The calculation parameters are $T = 100\tau$, $\beta = 200$, $\Delta = 0$, $\gamma T = 0.5$, $\delta = 300$, $\Omega_0\tau = 1000$, $\alpha = 10^{-6}$, and $\mu = 0.01$ (dashed curve) and 0 (solid curve). The force was averaged after the transient processes had terminated ($t > 10T$). The initial coordinate $z_{\rm ini} = 0.2c\tau$ is denoted by a gray ring on the right

5. Traps for Nanoparticles

The optical trap proposed for atoms can also be used for capturing and holding nanoparticles. For this purpose, the particles must contain “active” atoms with narrow absorption lines, and the concentration of such atoms in the particles must be sufficiently high. Let us evaluate the minimum required concentration of “active” atoms in a nanoparticle. The evident requirement for the holding and manipulation of a nanoparticle to be possible is a substantial predominance of the light pressure force, F, over the gravitation one, Mg. Let us evaluate the light pressure force on an atom. In the region of spatial pulse superposition, it is of the order of $10\hbar k/T$. For the wavelength $\lambda \approx 600$ nm, the pulse repetition frequency $T^{-1} \approx 100$ MHz, and an atom with $M \approx 50$ amu, we obtain $F/mg \approx 10^6$. Hence, even if the concentration of “active” atoms in nanoparticles exceeds 0.001%, the nanoparticles can be held in optical traps formed by counter-propagating light pulses with a large area.

6. Conclusions

We have proposed optical traps, which are based on the adiabatic interaction between atoms, including atoms in nanoparticles, and sequences of counter-propagating light pulses with a large area. In comparison with traps on the basis of π-pulses and pulses with a small area, the new traps are characterized by a larger light pressure force in the region of spatial pulse superposition, which allows atoms and nanoparticles to be localized in a smaller volume. In addition, owing to the dependence of the light pressure force in those traps on the atom velocity, the energy of atoms in the trap decreases. However, the issue concerning the maximum cooling of atoms in the traps remains opened, because the classical description of the motion of an atom in the trap, which was used in this work, is not enough for its study.

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УТРИМАННЯ АТОМІВ І МАЛИХ ЧАСТИНОК ОПТИЧНОЮ ПАСТКОЮ, СФОРМОВАНОЮ ПОСЛІДОВНОСТЯМИ ЗУСТРІЧНИХ СВІТЛОВИХ ІМПУЛЬСІВ ВЕЛИКОЇ ПЛОЩІ

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Р е з ю м е

Запропоновано нову пастку для атомів і малих частинок, в основі якої – взаємодія атома з полем зустрічних імпульсів, що частково накладаються у часі. Суттєвою відмінністю від відомих аналогів є близька до адіабатичної взаємодія атома з полем, що дозволяє протягом того ж часу взаємодії передати атому значно більший імпульс і зменшити розмір пастки. Показано, що завдяки залежності світлового тиску від швидкості під час взаємодії з полем відбувається охолодження ансамблю атомів.