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Laser acceleration of atoms by nonlinear mechanism

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A nonlinear threshold phenomenon at the interaction of the atoms with the two counter propagating light beams of the different frequencies is presented. The existence of a critical intensity of the interference field is shown, which is the threshold of nonlinear resonance, achieving in the field. This phenomenon leads to the atom acceleration or deceleration, depended on its initial velocity. Such acceleration/deceleration of the shock character, because of the impact with the potential barrier, occurs on ultrashort distances in the order of laser wavelengths and depends neither on the field magnitude nor on the interaction length.

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The problem of acceleration of atoms has been considered since the period of appearance of laser sources [1 – 5]. In the last decades the inverse problem of atoms deceleration became more important connected with the intensive experimental researches regarding the laser manipulation of atoms [6 – 9]. The latter is of great interest and involves large class of atomic and laser spectroscopic issues, especially at very low temperatures (it is worthy to note the unique experiments with the trapping of separate atom or Bose condensation of supercooling atomic gas in optical-dipole or magnetic traps [10 – 15]). We shall not attempt to review the extensive literature regarding the laser manipulation of atoms by the counterpropagating light beams, apart from mentioning the works [16, 17], which consider the acceleration of atoms in a moving periodic potentials-traps. The latter relies on the "conveyor belt" provided by a frequency-chirped optical lattice formed by two counterpropagating laser beams.

In this paper we present a nonlinear mechanism of atom acceleration by two counterpropagating light beams of the different frequencies, which differs from the mentioned schemes of trapped atom acceleration. It is a collision process of the atom with the moving potential barrier. Thus, it is appeared that in the field of two counterpropagating light beams of the different frequencies a critical intensity of the net field exists, above which the atom "reflection" from the slowed interference wave takes place. Such a wave field becomes a potential barrier with respect to the atom, resulting the atom acceleration or deceleration depended on the initial conditions.

We will study the dynamics of interaction of a two-level atom with the two quasi-monochromatic counterpropagating plane waves of different frequencies in the approximation of a given field (the magnitudes of the wave fields will be assumed so strong that the radiation/absorption processes can not change its given values). As will be shown below for the actual cases of strong laser pulses the approximation of a given field in this process is satisfied with great accuracy.

The Hamiltonian of a two-level atom in the field of two quasi-monochromatic counterpropagating plane waves in the rotating wave approximation is given by the expression

$$H(\mathbf{p},\mathbf{r},t)=\frac{\mathbf{p}^2}{2m}+\frac{\hbar\omega_0}{2}\sigma_z+i\hbar\Omega_1 S_1(t)e^{i\omega_1 t-i\mathbf{k}_1\mathbf{r}}\sigma_- + \\ + i\hbar\Omega_2 S_2(t)e^{i\omega_2 t-i\mathbf{k}_2\mathbf{r}}\sigma_- + \text{c.c.}, \qquad (1)$$

where $\mathbf{r}$ and $\mathbf{p}$ are the classical position and momentum of an atom center-of-mass (m), obeying the Hamilton canonical equations of motion

$$\dot{\mathbf{r}}=\partial H/\partial\mathbf{p}, \qquad \dot{\mathbf{p}}=-\partial H/\partial\mathbf{r}. \qquad (2)$$

Here ω_0 is the frequency of the atomic transition, being driven by the linearly polarized counterpropagating waves with the carrier frequencies ω_1, ω_2 (let $\omega_1>\omega_2$), wavenumbers $\mathbf{k}_1,\mathbf{k}_2$, and amplitudes E_1,E_2. Then $\Omega_{1,2}$ are the Rabi frequencies: $\Omega_{1,2}=E_{1,2}d_{1,2}/\hbar$, where $d_{1,2}$ is the projection of the atomic transition dipole moment along the waves polarization directions, $\hbar$ is the Plank constant, $S_{1,2}(t)$ are the slowly varying envelopes of quasi-monochromatic waves ($S_{1,2\,\max}=1$). The variables σ_- and σ_z are the expectation values of the Pauli pseudo-spin operators describing atomic internal state. They obey the optical Bloch equations

$$\dot{\sigma}_{-} = -i\omega_0\sigma_{-} + \\ + \Omega_1 S_1(t) e^{i\mathbf{k}_1\mathbf{r} - i\omega_1 t} + \Omega_2 S_2(t) e^{i\mathbf{k}_2\mathbf{r} - i\omega_2 t}\sigma_z, \\ \dot{\sigma}_z = -2\left[\Omega_1 S_1(t) e^{i\omega_1 t - i\mathbf{k}_1\mathbf{r}} + \right. \\ \left. + \Omega_2 S_2(t) e^{i\omega_2 t - i\mathbf{k}_2\mathbf{r}}\right]\sigma_{-} + \text{c.c.}, \quad (3)$$

which include the center-of-mass motion of the atoms.

For the plane waves propagating along the Z axis from the Eqs. (6)–(3) one can obtain the velocity of the atom in the field

$$v_z = \frac{c}{n}\left[1 \mp \sqrt{\left(1 - n\frac{v_{0z}}{c}\right)^2 - 2\frac{n^2}{mc^2}V_{sw}(z,t)}\right]; \\ v_x = v_{0x}; \quad v_y = v_{0y}, \quad (4)$$

where $v_0 = (v_{0x}, v_{0y}, v_{0z})$ is the initial velocity of the atom. The quantity $n > 1$, which is the "effective refractive index" of slowed interference wave propagating with the phase velocity $v_{ph} = c/n < c$, and the interaction potential $V_{sw}(z,t)$ of the atom with a such wave field are given by the expressions

$$n = (\omega_1 + \omega_2)/(\omega_1 - \omega_2), \quad (5a)$$

$$V_{sw}(z,t) = V_0 S_1(t) S_2(t) \cos\left[(\omega_1 - \omega_2)(t - nz/c)\right], \quad (5b)$$

$$V_0 = 2\hbar\Omega_1\Omega_2\left(\Delta_1^{-1} + \Delta_2^{-2}\right). \quad (5c)$$

As it is seen from Eq. (4), if the maximal value of the interaction potential $V_{sw}(z,t)_{\max} = |V_0|$ (5) is larger than a certain value

$$V_{cr} = \frac{mc^2}{2n^2}\left(1 - n\frac{v_{0z}}{c}\right)^2, \quad (6)$$

which will be called a critical, the expression (4) for the atom velocity may become a complex. This complexity is bypassed in the complex plane by continuously passing from the one Riemann sheet to another, at which the root changes its sign. Hence, the atom velocity remains a real everywhere and the multivalence of the expression (4) vanishes too. Indeed, if $|V_0| < V_{cr}$, one should take the root in the Eq. (4) with the sign $(-)$ if $v_{0z} \le c/n$, and with the sign $(+)$ if $v_{0z} \ge c/n$, to satisfy the initial condition $v_z = v_{0z}$ at the $V_{sw}(z, t = -\infty) = 0$. Then, after the interaction ($V_{sw}(z, t = +\infty) = 0$) the energy of the atom remains unchanged. However, when $|V_0| > V_{cr}$ the value $V_{sw}(z(t_0), t_0) = V_{cr}$ (where $z(t_0)$ is the atom coordinate at the moment $t = t_0$) steps out as a turn point, and for $t > t_0$ one should change the sign of the root, in respect to the moments $t \le t_0$. At that, the slowed interference wave becomes a potential barrier for the atom and the "reflection" of the atom from such moving barrier occurs. To explain the physics of this phenomenon it is necessary to clear up the meaning of the critical field. This is an essentially nonlinear phenomenon of threshold nature, and the critical intensity of the interference wave is the threshold value for this process. Namely, the Eq. (4) shows that the critical value V_{cr} is the value of the potential, at which the longitudinal velocity of the atom in the field $v_z(t)$ becomes equal to the phase velocity of slowed interference wave: $v_z(t) = c/n$, irrespective of the atom initial velocity v_{0z}. The latter is the condition of resonance with the Doppler-shifted waves frequencies, at which the coherent scattering, that is the induced "Compton" scattering of counterpropagating waves on an atom occurs:

$$\omega_1\left(1 - v_z(t)/c\right) = \omega_2\left(1 + v_z(t)/c\right). \quad (7)$$

Since the resonant velocity of the atom $v_z(t) = c/n$ is acquired in the field at the value $V_{sw} = V_{cr}$ (due to the waves intensity effect) this is a nonlinear resonance, because of which the "reflection" of the atom from the moving barrier occurs. Note, that actually this is a reflection in the frame of reference moving with the velocity $V = c/n$, which is the rest frame of the slowed interference wave. In this frame atom with the velocity v'_{0z} swoops on the motionless barrier and, as is seen from Eq. (4), an elastic reflection of the atom occurs: $v'_z = -v'_{0z}$.

Thus, if the maximal value of the interaction potential $|V_0| > V_{cr}$, then after the interaction ("reflection") for the atom velocity we have

$$v_{zf} = \frac{c}{n}\left(1 - n\frac{v_{0z}}{c}\right) + \frac{c}{n}. \quad (8)$$

Eq. (8) shows that, if $v_{0z} < c/n$, then $v_{zf} > v_{0z}$ and the atom is accelerated. But if $v_{0z} > c/n$, then $v_{zf} < v_{0z}$ and the deceleration of the atom takes place. The kinetic energy lost by atom at the deceleration is transferred to the waves according to induced "Compton" scattering at which the conservation of the photons number takes place, that is: atom absorbs photons of small frequency ω_2 and emits the same number of photons with large frequency ω_1(and the vice versa- at the acceleration). For the initially resonant velocity of the atom ($v_{0z} = c/n$), $V_{cr} = 0$ and consequently the atom velocity does not change ($v_{zf} = v_{0z}$).

For the kinetic energy change of the atom center-of-mass we have

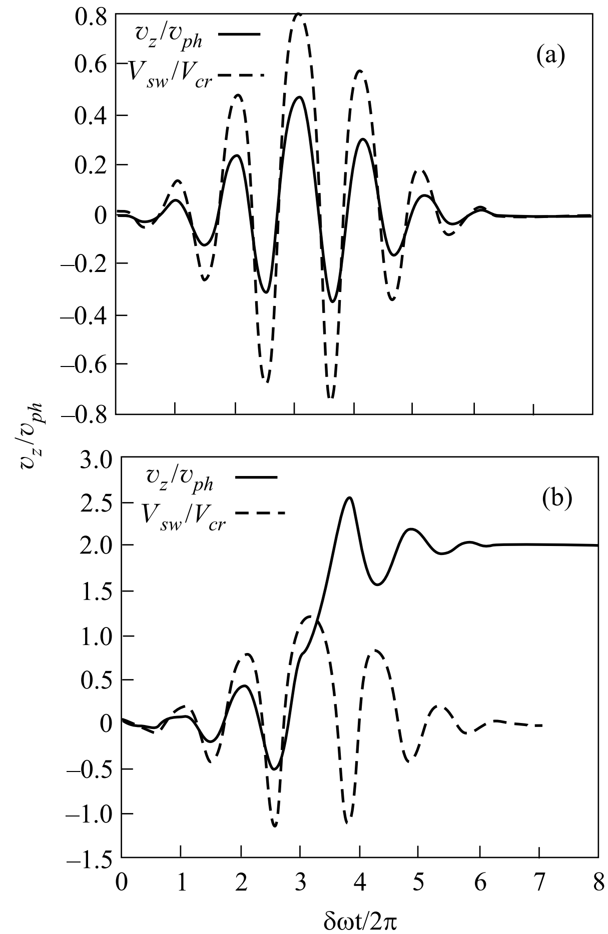
$$\Delta\varepsilon = \frac{2mc^2}{n^2}\left(1 - n\frac{v_{0z}}{c}\right). \quad (9)$$

As is seen from this formulae the acceleration of the atom depends neither on the field magnitude (only should be an above threshold field) nor the interaction length. This is an impact acceleration/deceleration on the ultrashort distances (in the order of laser wavelengths), which may serve as a significant tool for the laser manipulation of atoms. The threshold character of such acceleration may be used for the separation of atoms by the velocities.

To illustrate the entire picture of this nonlinear effect we present the graphics of numerical solutions of the equations (6)–(3) for the laser pulses with the Gaussian envelopes. To accentuate this acceleration mechanism due to nonlinear resonance created by the field we especially present the acceleration of an atom in rest – the case, when the atom velocity initially is very far from the resonant one (7).

Figure (a) illustrates the temporal evolution of the atom center-of-mass velocity (solid curve), when $v_0 = 0$ and the intensity is below the critical point: $V_0 < V_{cr}$. By the dotted curve the variation of the scaled potential V_{sw}/V_{cr} along the atom trajectory is shown. As we see, there is no acceleration under the threshold of nonlinear resonance (the net gain is defined by the initial phase). In the Figure (b) the atom dynamics is displayed, when the intensity is above the critical point: $V_0 > V_{cr}$. From these figures it is clearly seen, that at the critical point $V_{sw} = V_{cr}$ the longitudinal velocity of the atom becomes equal to phase velocity of the interference wave: $v_z(t) = v_{ph} = c/n$ and it is a turning point for the solid curves. The latter corresponds to the formulae (4), where the root changes its sign and the further evolution of the velocity proceeds along the second brunch of the root with the inverse sign. In the resonance range the velocity of the atom strictly increases due to genuine nonlinear character of the resonance in the field (see Eq. (7)). Then, after the leaving the resonance range the final velocity of the atom becomes $v_{zf} = 2v_{ph}$ in accordance with the analytical results (see Eqs. (4) and (8)). For the initial condition $v_0 > v_{ph}$ a deceleration of the atom after the "reflection" occures. The maximal deceleration: $v_{zf} = 0$ occures at the initial velocity $v_0 = 2v_{ph}$, for which we have the inverse picture of the Figure (b).

The estimations show that an atom in rest can be accelerated up to the thermal velocities $\sim 10^5$ cm/s by the laser pulses with the electric fields strengths $E \sim \sim 10^6$ V/cm, at the "refractive index" $n \sim 10^5$ (corresponding to temporal coherency $(\omega_1 - \omega_2)/\omega_1 \sim 10^{-5}$ of lasers) with the detunings $\Delta_{1,2}/\omega_0 \sim 10^{-1}$. Note, that the fields necessary for this effect are much more smaller than the atomic ones and a model of supposed two level atom is well enough justified. The energy acquired by the atom at such interaction, i.e. the energy of the wave field transferred to the atom is about ~10^{-2} eV,



Solid curves display the temporal evolution of the atom scaled velocity v_z/v_{ph} (time in units of interference wave period $2\pi/(\omega_1 - \omega_2)$). Pulse duration has been chosen to be $(\omega_1 - \omega_2)\tau = 10$. The dotted curve shows the variation of the scaled interaction potential V_{sw}/V_{cr}, sensed by the atom along the trajectory. The initial conditions are: $v_0 = 0$, $z_0 = 0$. (a) The intensity is below the critical point: $V_0 = 0.8V_{cr}$, (b) intensity is above the critical point: $V_0 = 1.3V_{cr}$

which is negligibly small in respect to even week laser pulses. So, the applied approximation of a given field is satisfied with great accuracy. In the inverse regime of deceleration with the same fields one can stop such a thermal atomic beam on a distance in the order of laser wavelengths.

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