NEW ELECTROMAGNETIC METHODS OF SLOWDOWN AND TRAPPING OF PARTICLES

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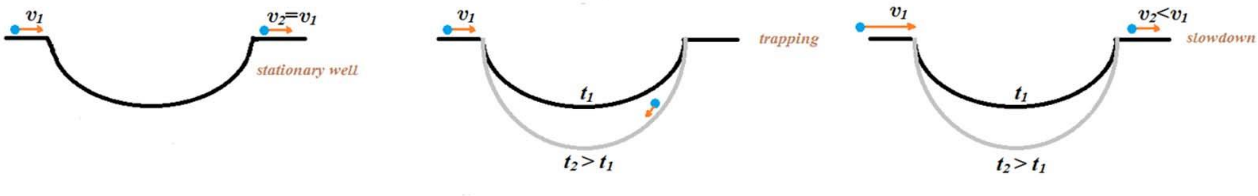
Electromagnetic "cooling" and localization of microparticles (in particular, atoms and molecules) under conditions of the high vacuum are very important for a number of directions of physics and technologies including quantum information, ultra-high-resolution spectroscopy, and optomechanics of such particles.

I have proposed sufficiently simple methods for the slowdown and trapping of various microparticles (including atoms and molecules) by means of external electromagnetic fields which induce (for such particles) potential wells having fixed spatial distributions but deepening over time up to some limit. It is assumed that considered particles are under conditions of the high vacuum and forces acting on these particles are not dissipative, that is they move without friction. Depending on whether the particles have electric (magnetic) moment, it is possible to use the controllable electric (magnetic) field or far-off-resonance laser radiation for inducing of corresponding potential wells for given particles.

In the present work, I theoretically demonstrate possible applications of proposed methods for "cooling" and localization of particles for a number of nonstationary electromagnetic potential wells with different fixed spatial configurations. In particular, optomechanics of levitated particles by various far-off-resonance laser beams, amplifying over time (up to some limit), is analyzed. New schemes of traps and decelerators of polarizable particles, based on corresponding nonstationary gradient forces, are considered.

Proposed "cooling" and trapping methods may be applied in definite cases also for atoms and molecules in the ground quantum state. Realization of such methods for atoms and molecules is important for applications in ultra-high-resolution spectroscopy, precision frequency standards and in quantum computing processes.



Motion of classical particles without friction in a potential well deepening over time

BASIC RELATIONSHIPS

We will consider problems which may be solved on the basis of classical mechanics and electrodynamics. Let us assume that a point particle with the mass m freely moving in a three-dimensional space before its entering to the region V of the potential well $U(R,t)$, which explicitly depends not only on the coordinate R but also on time t. The total energy of such a particle with the non-relativistic velocity v is described by the known formula:

$$E(R,v,t) = 0.5mv^2 + U(R,t) \quad (1)$$

Further we will consider the potential energy $U(R,t)$ of the following type:

$$U(R,t) = s(R) * \varphi(t) \quad (2)$$

where the coordinate function $s(R) \leq 0$ in the region V, and $\varphi(t) \geq 0$ is nondecreasing function of time t.

Such a potential (2) may be created for particles having electric or magnetic moment by a controllable electromagnetic field with the growing strength (up to a certain time moment) but with a fixed spatial distribution. We have the following motion equation of the particle in case of the potential energy (2):

$$m\frac{d^2R}{dt^2} = -\varphi(t)\frac{ds(R)}{dR} \quad (3)$$

From relations (1)-(3) we directly receive the formula for the time derivative of the total energy $E(R,v,t)$ of the particle:

$$\frac{dE}{dt} = s(R)\frac{d\varphi(t)}{dt} \leq 0. \quad (4)$$

According to inequality (4), increase of the function $\varphi(t)$ with time t leads to decrease of the total energy $E(R,v,t)$ (1) of the particle in the region V of the potential well, where the coordinate function $s(R) \leq 0$.

We see from formula (1) that the particle cannot go beyond the potential well and reach the region with $U(R,t) = 0$, when its total energy E will be negative. It is important to note, that under such a condition $E < 0$, the considered classical particle will be localized in the region V of the potential well even after output of the nondecreasing time function $\varphi(t)$ on a constant value.

At the same time, a sufficiently fast particle overcomes such potential wells in spite of their deepening over time. However, according to formulas (1) and (4), kinetic energy of this particle decreases at transits of such wells between space regions where the particle potential energy $U(r,t) = 0$.

Further we will analyze trapping and slowdown of considered classical particles by a spatially inhomogeneous electromagnetic radiation with intensity increasing over time up to a certain limit. In so doing, it is assumed that the radiation pressure exerted on particles by such a radiation is small compared to the light induced gradient force acting upon them. This is possible for

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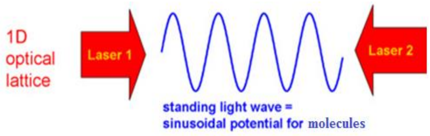
particles that are nearly transparent in the spectral range of their irradiation. We will analyze not too strong radiation, for which the induced electric dipole
moment of the particle is proportional to the electric field strength, while the potential energy of the particle is proportional to the electric field squared.

TRAPPING OF PARTICLES BY LASER FIELDS AMPLIFYING OVER TIME

Let us analyze the possible (for practical realization) case of the amplifying with time standing light wave (along the axis z) whose intensity has the transversal Gaussian distribution. Such a radiation creates the potential well of the type $U(R,t) = s(R) * \varphi(t)$ (2) with the following coordinate function $s(R)$ for particles with light induced dipole moments:

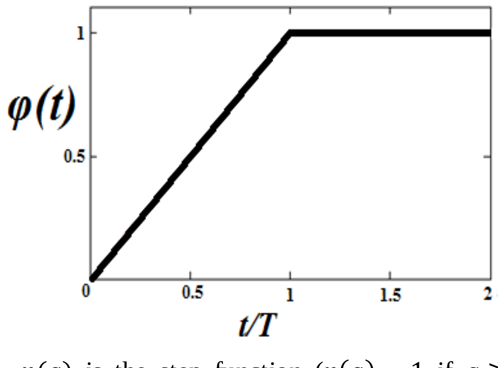
$$s(R) = -J_0 * \exp(-r^2/r_0^2) * \sin^2(kz), \qquad (5)$$

where $r = \sqrt{x^2 + y^2}$ is the distance from the central axis of the light beam (with the characteristic radius r_0), k is the wave number, and $J_0 > 0$ is the value with the dimension of energy, which is determined by a polarizability of a particle.



For example, we will consider the following time dependence $\varphi(t)$ (2) for the radiation intensity:

$$\varphi(t) = (t/T) * \eta(T - t) + \eta(t - T), (t \geq 0), \qquad (6)$$



where $\eta(q)$ is the step function ($\eta(q) = 1$ if $q \geq 0$ и $\eta(q) = 0$ when $q < 0$). The function $\varphi(t)$ (6) linearly increases from 0 to 1 in the interval $0 \leq t \leq T$ and is equal to unit, when $t > T$.

Fig.1, a present numerically calculated (on the basis of the motion equation (3)), temporary dependences of the distance $r(t)$ from the axis of the light beam and longitudinal coordinate $z(t)$ of the particle, which approaches from the outside to the given beam at starting conditions specified in the moment t_0=0. We see, that during increasing of the radiation intensity with time t (6), trapping and three-dimensional localization of the considered particle occurs in the region of the beam which, according to the function $s(R)$ (5), creates the spatially periodic potential along the axis z. In this case the particle carries out vibration transversal motions $r(t)$ in limits determined by the characteristic radius r_0 of the light beam (Fig.1, *a*) and also undergoes comparatively fast nondamped oscillations $z(t)$ in the longitudinal direction in the limit of the half wavelength $\lambda = 2\pi/k \ll r_0$ of the radiation (Fig.2).

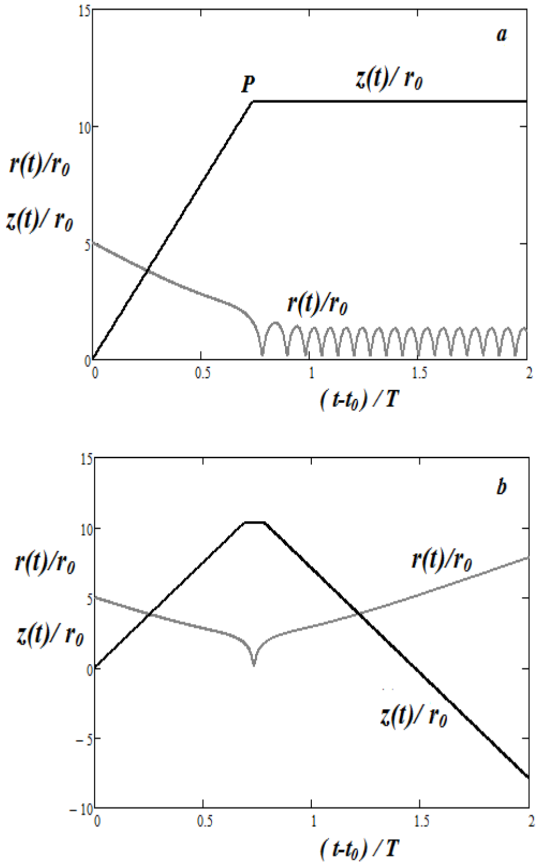


Fig.1. Dependences of particle coordinates $r(t) = \sqrt{x(t)^2 + y(t)^2}$ and $z(t)$ on time $t \geq t_0$ at particle initial coordinates $x(t_0)$=0, $y(t_0) = 5r_0$, $z(t_0)$=0 and its initial velocity components $v_x(t_0) = -2.5(r_0/T)$, $v_y(t_0) = -5(r_0/T)$, $v_z(t_0) = 15(r_0/T)$, given in moments $t_0 = 0$ (*a*) and $t_0 > T$ (*b*), when $J_0 = 5000m(r_0/T)^2$ and kr_0=1000.

The given particle remains localized in such a potential well even if $(t - t_0) > T$ (Fig.1, *a*), that is after the output of the radiation intensity on the constant value according to formula (6). One can see from comparison of Fig.1,*a* and dependence 1 in Fig.3 that trapping of this particle occurs when its total energy $E(t)$ (1) decreases up to negative values because of the inequality (4).

Fig.1, *b* presents dynamics of a particle with the same initial values of velocity and coordinates as in Fig.1, *a* but specified in a moment $t_0 > T$. Then, according to the dependence (6), the given particle flies through the stationary light beam, whose intensity is equal to the maximum value for the considered case of Fig.1,*a*. We see that this particle is not captured by the light beam and moves away from it after the primary rapprochement (Fig.1,*b*). The total energy $E(t)$ (1) of the given particle is constant during the whole its movement (dependence 2 in Fig.3).

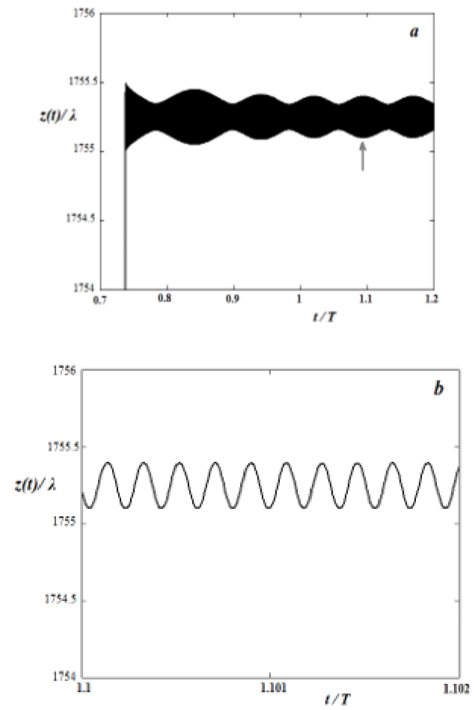


Fig.2. Particle coordinate $z(t)$ (in units of the radiation wavelength $\lambda = 2\pi/k$) versus time t in enlarged scales in the neighborhood of the point P from fig.1,*a*. Fig. 2,*b* presents the dependence $z(t)$ in the narrow region indicated by the arrow in fig. 2,*a*.

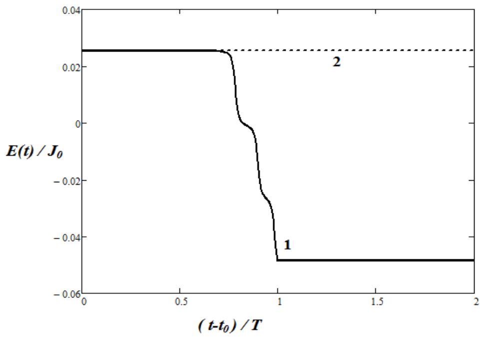
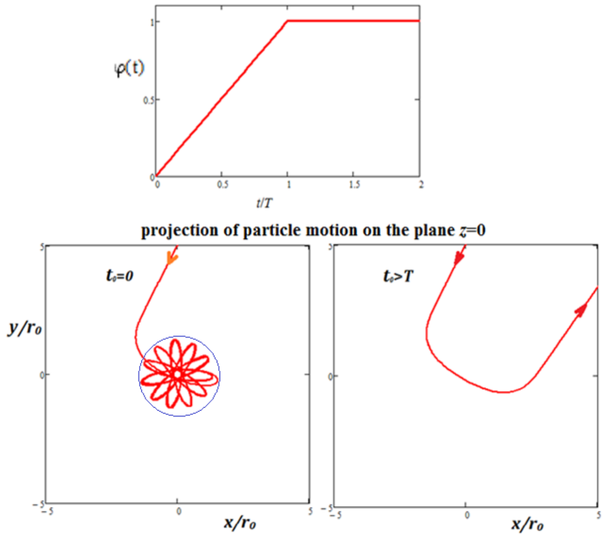


Fig.3. The total energy $E(t)$ (in units $J_0 = 5000 \cdot m \cdot r_0^2 / T^2$) versus time $t \geq t_0$. Curves 1 and 2 were calculated respectively for parameters of fig.1,*a* and fig.1,*b*.

VISUAL DEMONSTRATION OF DISCUSSED TRAPPING PROCESS



I have carried out numerical calculations also for a number of other potential wells with cylindrical and spherical symmetries described by the general formula $U(R,t) = s(R) * \varphi(t)$. These calculations confirmed following qualitative results (*a*), (*b*) and (*c*) of the present work:

(a) Even a highly shallow but increasing with time potential well may continuously capture sufficiently slow-speed particles flying through it.

(b) Such trapped particles will remain in this potential well even after going out of a nondecreasing strength of the corresponding electromagnetic field on stationary values. However, such a stationary trap already will not capture new particles.

(c) Since considered electromagnetic traps are based on non-dissipative forces, then particles, captured in given traps, carry out non-damped oscillation motions in limits of corresponding potential wells.

SLOWDOWN OF PARTICLES BY LASER FIELDS AMPLIFYING OVER TIME

Now we will analyze the case of a running (along the axis *z*) light beam, the intensity of which increases over time and is characterized by the Gaussian transverse intensity distribution. For particles with induced dipole moment, this radiation creates a potential well of the type $U(R,t) = s(R) * \varphi(t)$ with the coordinate function $s(R)$ of the form:

$$s(R) = -P_0 * exp(-r^2/r_0^2), \tag{7}$$

where $r = \sqrt{x^2 + y^2}$ is the distance from the beam central axis (r_0 is the characteristic beam radius), $P_0 > 0$ is a constant quantity with the dimension of energy that is determined by a particle polarizability.

For example, let us consider the following time dependence $\varphi(t)$ (2) for the beam intensity:

$$\varphi(t) = 1 - exp\left(\frac{-t}{\tau}\right), \ (t \geq 0), \tag{8}$$

where τ is a characteristic time interval? Function $\varphi(t)$ (8) increases with time from 0 to 1 and asymptotically approaches to 1 when $t \gg \tau$.

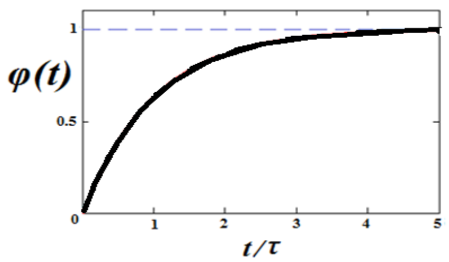


Fig.4a demonstrates numerically calculated, on the basis of motion equations (3), dependence of the modulus of the particle velocity v on time t at initial conditions specified in a moment t_0. The situation is considered, when such particles in this moment t_0 are located outside of the region where the light beam (7) can exert sufficient influence on them. In case $t_0 = 0$, particles with the speed $v_0 = v(t_0)$ transit through the laser beam (7) during increasing of its intensity according to the time dependence $\varphi(t)$ (8). Then, at first the sharp increase of the particle speed takes place because of its getting into the light induced potential well (curve 1 in Fig.4a). However, after the passage of such a deepening over time well, the particle speed goes to the constant final value v_f, which is about 35% lower than its initial value v_0.

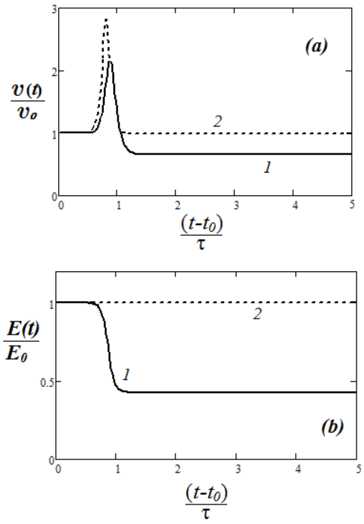


Fig.4. Dependence of the particle velocity modulus v (a) and its total energy E (b) on time t at following initial coordinates of this particle $x(t_0)$=0, $y(t_0) = 5r_0$, $z(t_0)$=0 and its velocity components $v_x(t_0) = 0.5\,(r_0/\tau)$, $v_y(t_0) = -5(r_0/\tau)$ and $v_z(t_0) = 1.5(r_0/\tau)$, specified in the moment $t_0 = 0$ (curves 1) and $t_0 \gg \tau$ (curves 2) for the function $\varphi(t)$ (6), when $P_0 = 100m(r_0/\tau)^2$,$v_0 = v(t_0) = \sqrt{v_x(t_0)^2 + v_y(t_0)^2 + v_z(t_0)^2}$ and $E_0 = E(t_0)$.

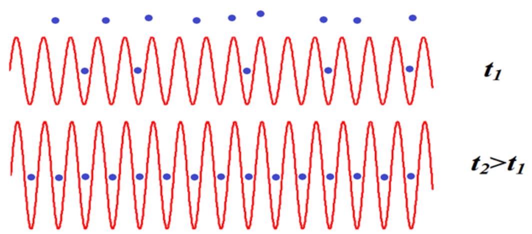
According to the formula (4), this process is accompanied by decrease of the particle total energy (curve 1 in Fig.4b).

Curves 2 in Fig.1 correspond to a particle with the same initial values of velocity and coordinates as for considered above curves 1, but specified in a time moment $t_0 \gg \tau$. Then, according to the time dependence (8), such a particle initially transits through the stationary light beam whose intensity already reaches a maximum value. In this case the final particle speed v_f is equal to its initial value v_0 and the total energy of the particle is constant during all process of particle transit through such a stationary potential well (curves 2 in Figs.4a and 4b).

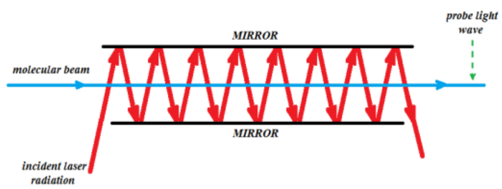
POSSIBLE APPLICATIONS

We have considered structureless classical particles in potential wells of the certain type $U(R,t) = s(R) * \varphi(t)$. In practice it is possible, for example, for a collection of noninteracting (with each other) microparticles, which fly without friction under conditions of the ultrahigh vacuum at action of the controllable electric (magnetic) fields or nonresonance laser radiation with fixed spatial configurations.

For analysis of possible trapping and slowdown of atoms and molecules by electromagnetic potential wells, consideration of their quantum structure is necessary. At the same time, results obtained in this work may be applied also for such atomic objects in definite cases. Thus, for example, it is possible creation of traps for atoms and molecules by a nonhomogeneous laser radiation with frequencies essentially detuned from resonances with atomic (molecular) transitions. Then the gradient force acts on atoms (molecules), which are in the ground quantum state, in the direction to the point of minimum of the light induced potential well. In particular, such wells may be induced also by laser beams considered in the present work. However, as was shown above, even highly slow-speed microparticles, flying from outside through such stationary beams, will not be captured in corresponding potential wells. At the same time, proposed intensification of the laser radiation (during a certain time interval) will lead to large increase of a number of particles captured in given traps.



It is necessary to note, that existing methods for slowdown of atoms by means of resonance laser radiation are inefficient for molecules because of their relatively complex quantum level structure. At the same time, the slowdown mechanism of particles by nonresonance light beams demonstrated in the present work is applicable also for cooling of ensembles of molecules in the ground quantum state. Therefore, in the future, development of corresponding effective decelerators of molecules under conditions of ultra-high vacuum will be important on the basis of search of optimal spatial configurations and amplification dynamics of nonresonance laser radiation.



Scheme of possible molecules decelerator on the basis of nonresonant laser radiation amplifying over time.

This work is the continuation of research carried out by author in following recent papers:

[1] *A.Ch. Izmailov* ”Trapping of classical particles by an electromagnetic potential well deepening over time”, Optics and Spectroscopy, 2015, V. 119, N5, pages 883-886 (see also arXiv:1503.01076, March 2015)

[2] *A.Ch. Izmailov* “On motion control of microparticles by an electromagnetic field amplifying over time for spectroscopy problems”, Optics and Spectroscopy, 2017, V. 122, N2, pages 315-321 (see also arXiv: 1604.07345, April 2016)