Selection of particles by a gradient force in the near field of laser light

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The spatially nonuniform intensity distribution of laser light diffracted by an aperture small in comparison with the wavelength leads to a resonant selection of atoms by virtue of a dipole gradient force acting on an atom. As a result, the effective cross section for the transmission of an atom through the aperture either increases or decreases from the geometric cross section. The direction of the change depends on the detuning of the frequency of the laser field from the frequency of the atomic transition. The effect is sensitive to both the species of the atom and its velocity.

The construction of lasers and development of several methods for acting on atoms and molecules selectively with laser light has opened up some new possibilities for the selection of atoms and molecules, in particular, isotopes.[1] However, the most effective of the laser methods which have been proposed are destructive, since they are based on a photoionization of atoms or a photodissociation of molecules. There is fundamental interest in seeking other selection methods, even without regard to possible practical applications.

The essence of the effect discussed in this letter is illustrated by Fig. 1. The solid curves here are contour curves of the energy density of the laser light diffracted by an aperture of small diameter $2a$ ($a \leqslant \lambda$). The gradient of the energy density of the laser light determines the magnitude of the gradient force acting on an atom.[2] The magnitude of this force depends on not only the intensity gradient but also the magnitude and sign of the detuning of the frequency of the laser field, ω, from the resonance with the atomic transition,[3] ω_0.

If the laser frequency ω has a negative detuning ($\Omega = \omega - \omega_0 < 0$), the gradient force pulls the selected atoms into a region of stronger field, while the other atoms either do not feel the near field (in the case of a large detuning) or are repelled by the gradient force ($\Omega > 0$) into a region of lower energy densities. In the case $\Omega < 0$ the trajectories of the selected atoms curve toward the aperture (these are the curves with arrows), so the flux of particles passing through the aperture per unit time becomes higher than in the case without the near field of the laser light. It is possible to derive an approximate analytic solution of this problem.

The flux increase is conveniently described by introducing an effective cross sec-

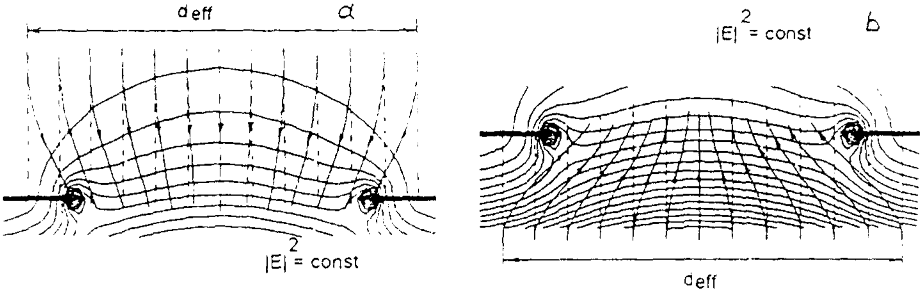

FIG. 1. Geometry of the problem in the case of an attractive gradient force for counterpropagating (a) and copropagating (b) motion of the atoms with respect to the incident light wave. Dashed curves—Trajectories of atoms without the laser field; solid curves with arrows—trajectories of atoms in the presence of the laser field; solid curves without arrows—contour curves of the potential of the gradient force.

tion for capture of particles by the aperture with the field, S_{eff}; the increase in the flux is then described by the ratio $S_{\text{eff}}/S_0 = r_{\text{eff}}^2/a^2$.

Strictly speaking, there are two possible cases of the interaction of the atoms with the near field: 1) Motion of atoms in the direction opposite the field. In this case an atom begins to interact with the field while the atom is in its ground state (the "dressed" state), and it remains in this state over the brief interaction time (Fig. 1a). 2) Motion of atoms from the side of the incident field. In this case the atom begins to interact with the diffracted field while the atom is in a mixed state (Fig. 1b). In the first case the potential of the gradient force is described by the expression[4]

$$U = \frac{\hbar\Omega}{2}\left[\left(1 + 2\frac{\mu^2|E^2|}{\hbar^2|\gamma|^2}\right)^{1/2} - 1\right], \tag{1a}$$

while in the second case it is described by[5]

$$U = \frac{\hbar\Omega}{2}\ln\left(1 + \frac{u^2|E^2|}{\hbar^2|\gamma|^2}\right), \tag{1b}$$

where μ is the dipole moment of the resonant transition, $\Omega = \omega - \omega_0$, $\gamma = (\Gamma/2) - i\Omega$, and Γ is the intrinsic width of the transition. In the case of a large detuning $[\Omega \gg (\mu E/\hbar) \gg \Gamma/2]$, these two expressions have the same potential:

$$U = \frac{\hbar}{2\Omega}\left(\frac{\mu}{\hbar}\right)^2 |E|^2. \tag{2}$$

The average squared electric field $|E^2|$ in the near zone can be found for analytic calculations by approximating the expressions given in Ref. 6:

$$|E^2| \simeq \left(\frac{2kaE_{\text{ap}}}{3\pi}\right)^2 \frac{a^4(R^2+z^2)}{R^6}, \tag{3}$$

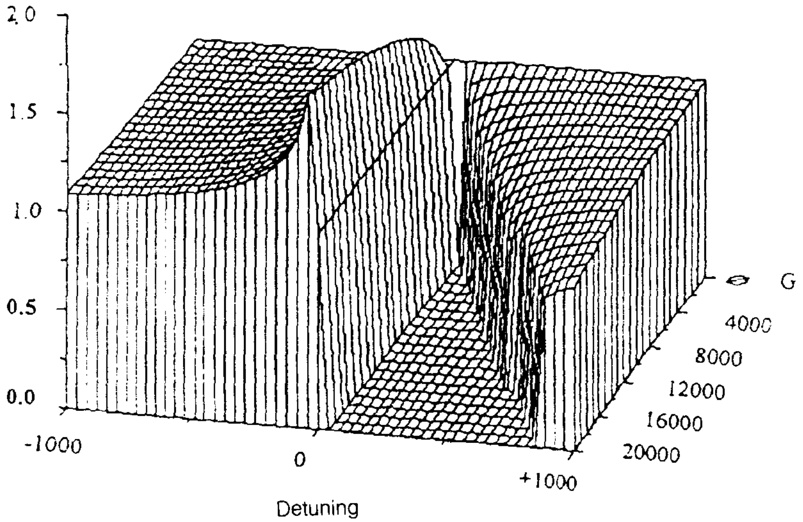

FIG. 2. Relative effective cross section for the capture of atoms versus the detuning of the field frequency, in units of $\Gamma/2$, and value of the saturation parameter $G=I/I_{\text{sat}}$ for the case $\eta=\hbar\Gamma/Mv_0^2=0.01$. This is an approximate analytic solution. The atoms are moving opposite the laser field.

where R is the magnitude of the radius vector, z is the coordinate along the symmetry axis, and E_{ap} is the amplitude of the circularly polarized light wave which is incident normally on the aperture.

We restrict the discussion to the motion of a particle which is incident normally on the screen with the aperture, at an impact parameter r_0. The motion of an atom in potential (1) with field (3) can be described by the system of equations

$$\begin{aligned} &M\dot{x}=p, \quad \dot{p}=-\partial U/\partial x, \\ &M\dot{z}=q, \quad \dot{q}=-\partial U/\partial z, \end{aligned} \tag{4}$$

where M is the mass of the particle. An approximate analytic solution of these equations can be derived (it will be published separately). Examining the particles incident at the edge of the aperture on the basis of this solution, we find the effective capture radius in the case in which the atoms are moving opposite the incident light wave:

$$r_{\text{eff}}=a\left(\frac{\sqrt{1-\alpha}+1}{2}\right)^{1/4}, \tag{5}$$

where

$$\alpha=4\eta\left(\frac{ka}{3\pi}\right)^2\frac{G_\kappa}{1+\kappa^2}\left[1+\left(\frac{15\pi}{16}\right)^2\right], \tag{6}$$

$\kappa=2\Omega/\Gamma$ is the relative frequency detuning, $G=I/I_{\text{sat}}$ is a saturation parameter, and we have introduced the parameter

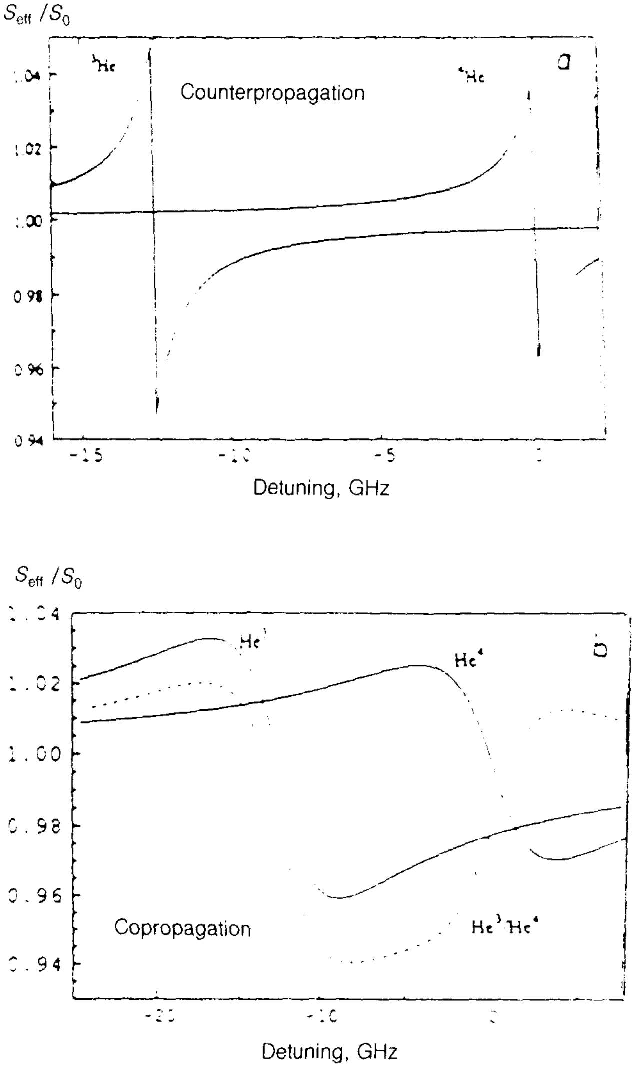

FIG. 3. Effective cross section for the capture of *He^3 and *He^4 atoms (solid curves) in a metastable state versus the frequency detuning of the laser light ($a=\lambda/2\pi$, $\lambda=1.083$ μm, $G=10^7$, $v_0=50$ m/s). These are exact solutions for the cases of copropagating (a) and counterpropagating (b) motion of the atoms.

$$\eta=\hbar\Gamma/Mv_0^2, \tag{7}$$

where v_0 is the velocity of the particle. The parameter η characterizes the relation between optical and mechanical processes. Corresponding expressions hold in the case of motion of the atoms in the direction of the light wave.

Figure 2 shows the relative increase in the effective capture cross section for the case $\eta=0.01$ versus the frequency detuning κ and the saturation parameter G according to (5). We see that in the case $\kappa < 0$ the effective cross section for the transmission of the particles increases, while at $\kappa > 0$, and at sufficiently large values of G, there can be even a complete deflection of particles away from the aperture.

A numerical simulation was carried out to find the transmission of a beam of particles through an illuminated small aperture with the exact interaction potential for various detunings and various saturation parameters. The results confirm the results of the approximate solution.

The resonant nature of the selection of atoms in the near field can be demonstrated in the example of the increase in the effective capture cross section as a function of the frequency of the laser light for an atomic beam of $^*\mathrm{He}^3$ and $^*\mathrm{He}^4$ atoms in the metastable triplet state (Fig. 3). The frequency of the laser light is tuned near the $2_2 P^3 \rightarrow 2_1 S^3$ transition, at the frequency $\nu_0 = 2.8 \times 10^{14}$ Hz or $\lambda_0 = 1.083\ \mu$m. The isotope shift for this transition is $\Delta\nu = 12.7$ GHz, and the intrinsic width is $\Gamma/(2\pi) = 1.64$ MHz.

In summary, it has been shown that illuminating with resonant light an aperture (or system of apertures) which is (are) small in comparison with the wavelength makes possible a nondestructive selection of slow neutral atoms (and molecules). We wish to stress that we are not talking about a practical implementation of isotope separation here (the two species $^*\mathrm{He}^3$ and $^*\mathrm{He}^4$ are convenient examples for calculations and experiments). We are instead talking about the physical effect. This effect might also be utilized to select molecules, e.g., left-hand and right-hand moving molecules in a circularly polarized field.

A quantum-mechanical analysis of the problem incorporating fluctuations of the stimulated transitions (absorption and stimulated reemission in another direction) leads to an increase in the entropy of the laser light. In this approximation, the system becomes nonconservative and can be thought of as a possible realization of Maxwell's demon, which would sort particles by velocity and species.[7] The results of this analysis will be the subject of a detailed publication.

[1] V. S. Letokhov, *Nonlinear Selective Photoprocesses in Atoms and Molecules* [in Russian] (Nauka, Moscow, 1983).

[2] G. A. Askar'yan, Usp. Fiz. Nauk **110**, 115 (1973) [Sov. Phys. Usp. **16**, 414 (1973)].

[3] V. G. Minogin and V. S. Letokhov, *Pressure Exerted by Laser Radiation on Atoms* [in Russian] (Nauka, Moscow, 1986).

[4] J. Dalibard and C. Cohen-Tannoudji, J. Opt. Soc. Am. B **2**, 1707 (1985).

[5] J. P. Gordon and A. Ashkin, Phys. Rev. A **21**, 1606 (1980).

[6] V. V. Klimov and V. S. Letokhov, Opt. Commun. **106**, 151 (1994).

[7] *Maxwell's Demon: Entropy, Information and Computing*, ed. by H. S. Leff and A. F. Rex (Adam Hilger, Bristol, 1990).

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