AN ELECTROMAGNETIC MIRROR FOR NEUTRAL ATOMS

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When light is totally reflected internally at a vacuum–dielectric interface, an atom in the thin transmitted evanescent wave experiences a radiation force. For light tuned above the transition frequency of a two-level atom, this force tends to repel the atom from the dielectric surface; and hence the internally illuminated surface acts as a mirror for slow neutral atoms. This paper presents the first analysis of this atomic reflection process and suggests that the effect can be used to trap slow atoms or to focus a slow atomic beam.

In recent years, a number of techniques have been proposed for controlling the motion of atoms or molecules by means of the radiation force of laser light propagating freely in vacuum [1]. This paper describes a new scheme for controlling atomic motion which makes use of the radiation force exerted by the thin evanescent wave that is generated on the surface of a dielectric medium when laser light is totally reflected internally at that surface. Specifically, we show that, when the light is tuned above an atomic resonant frequency, a slow atom is reflected by the evanescent wave without making contact with the material surface.

If a plane electromagnetic wave of frequency ω propagates in a medium of refractive index n and is totally reflected internally as depicted in fig. 1, then the electric field of the transmitted evanescent wave takes the form [2]

$$E(x,t) = \hat{\boldsymbol{\varepsilon}}\ \mathcal{E}\ \exp(-\alpha y)\cos(\omega t - kx)\ , \tag{1}$$

where $\hat{\boldsymbol{\varepsilon}}$ is a unit polarization vector,

$$\alpha = \omega(n^2 \sin^2\theta - 1)^{1/2}/c\ , \tag{2}$$

$$k = \omega n \sin\theta/c\ , \tag{3}$$

θ is the angle of incidence of the wave, and $\mathcal{E}$ is the wave amplitude at $y = 0$. The condition for total internal reflection is $\theta > \theta_c = \sin^{-1}(1/n)$. The evanescent wave propagates parallel to the dielectric surface and is substantial only within a few wavelengths of the surface, except for $\theta \approx \theta_c$.

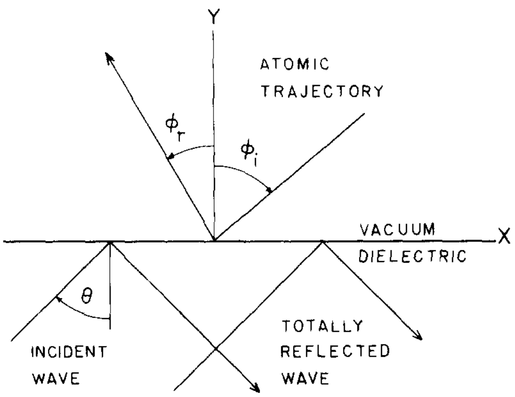

Fig. 1. A plane electromagnetic wave is totally reflected internally at the vacuum-dielectric interface. A reflected atomic trajectory, with angle of incidence ϕ_i and angle of reflection ϕ_r, is also shown.

Now an atom in the evanescent wave experiences a radiation force due to momentum transfer from the wave. For a two-level atom with transition frequency ω_0 and a near-resonant field ($\omega \approx \omega_0$), the radiation force has a component [3]

$$F_y = \frac{2\alpha\hbar(\Delta - kv_x)\Omega^2(y)}{4(\Delta - kv_x)^2 + A^2 + 2\Omega^2(y)} \tag{4}$$

normal to the dielectric surface associated with the gradient of the field amplitude (the dipole force), and a component

$$F_x = \frac{\hbar k A \Omega^2(y)}{4(\Delta - kv_x)^2 + A^2 + 2\Omega^2(y)} \tag{5}$$

parallel to the surface (the spontaneous force), where $\Delta = \omega - \omega_0$ is the detuning frequency, v_x is the x-component of atomic velocity, $A = 4\mu^2\omega_0^3/3\hbar c^3$ is the Einstein spontaneous emission coefficient, and $\Omega(y) = \mu\,\mathcal{E}\exp(-\alpha y)/\hbar$ is the on-resonance Rabi frequency of the two-level atom (μ is the dipole transition moment). Eqs. (4) and (5) are valid when the Rabi frequency $\Omega(y)$ and the Doppler shift kv_x are slowly varying functions of time on the scale of the atomic relaxation time $\tau = 1/A$ [3]. For simplicity, the following discussion is limited to the case in which the detuning Δ is positive ($\omega > \omega_0$) and is large compared to the Doppler shift kv_x. Then, to a good approximation, eqs. (4) and (5) reduce to

$$F_y = \frac{2\alpha\hbar\Delta\Omega^2(y)}{4\Delta^2 + A^2 + 2\Omega^2(y)}, \tag{6}$$

$$F_x = \frac{\hbar k\Delta\Omega^2(y)}{4\Delta^2 + A^2 + 2\Omega^2(y)}. \tag{7}$$

Because $\Delta > 0$, F_y tends to repel the atom from the dielectric surface. The normal force F_y, taken alone, is derivable from the potential energy

$$V(y) = (1/2)\hbar\Delta\ln[1 + 2\Omega^2(y)/(4\Delta^2 + A^2)]\,. \tag{8}$$

Therefore, an atom of mass M initially moving toward the surface with velocity v_y is reflected by the thin evanescent wave if $(1/2)Mv_y^2 < V(0)$, i.e., the maximum reflected velocity is

$$v_y^{\max} = \left[\frac{\hbar\Delta}{M}\ln\left(1 + \frac{2\mu^2\mathcal{E}^2}{\hbar^2(4\Delta^2 + A^2)}\right)\right]^{1/2}. \tag{9}$$

Next we derive the law of reflection for the atomic trajectory. From eqs. (6) and (7) the ratio of the tangential to the normal force is seen to be

$$R = \frac{F_x}{F_y} = \frac{kA}{2\alpha\Delta} = \frac{nA\sin\theta}{2\Delta(n^2\sin^2\theta - 1)^{1/2}}. \tag{10}$$

This ratio is independent of position. Therefore, the increments of velocity, Δv_x and Δv_y, experienced by the atom during the reflection process must have the same ratio ($\Delta v_x = R\Delta v_y$), and since in reflection $\Delta v_y = -2v_y$, where v_y is the initial (negative) normal velocity, we have $\Delta v_x = -2Rv_y$. Suppose now that the atom moves in the xy-plane as illustrated in fig. 1. Then from the geometry of the initial and final velocity vectors, it is easy to show that the atomic trajectory obeys the law of reflection

$$\tan\phi_r = \tan\phi_i - 2R\,, \tag{11}$$

where the angle of incidence ϕ_i and the angle of reflection ϕ_r are algebraic quantities measured in the sense indicated in fig. 1. Note that a positive ϕ_i indicates that v_x is initially opposite to the propagation direction of the evanescent wave. Eq. (11) has the solution $\phi_r = -\phi_i$ for $\phi_i = \tan^{-1}R$. For this angle of incidence, the atom is retroreflected. When R is negligibly small ($R \ll 1$), eq. (11) reduces to the simple reflection law $\phi_r = \phi_i$. According to eq. (10), this occurs when the detuning Δ is much larger than the Einstein A-coefficient, except for $\theta \approx \theta_c = \sin^{-1}(1/n)$. It should be noted that if the atom has a component of velocity in the z-direction, the planes of incidence and reflection of the atomic trajectory are not, in general, the same because of the impulse delivered to the atom in the x-direction. However, as $R \to 0$ these planes become coincident and the simple reflection law $\phi_r = \phi_i$ is again obtained.

To estimate the atomic velocity $v_y^{\max}$ that can be reflected in practice, we suppose that a z-polarized electromagnetic wave of intensity I enters the dielectric normally through a plane surface not shown in fig. 1. By a straightforward application of Fresnel's reflection formulas [2], it is found that the square of the evanescent wave amplitude is $\mathcal{E}^2 = 128\pi n^2\cos^2\theta\, I/(n^2 - 1)(n + 1)^2 c$. Let the intensity and angle of incidence of the wave be $I = 1$ W/cm^2 and $\theta = 60°$, respectively, and let the refractive index of the dielectric be $n = 1.5$. Then for reasonable atomic parameters ($M = 4 \times 10^{-23}$ g, $\omega_0 = 3 \times 10^{15}$ s^{-1}, $A = 10^8$ s^{-1}, and detuning $\Delta = 5 \times 10^8$ s^{-1}, one obtains from eq. (9) the value $v_y^{\max} = 110$ cm/s. In a strong field ($\Omega_0 \equiv \mu\mathcal{E}/\hbar \gg A$), $v_y^{\max}$ assumes its maximum value $v_y^{\max} \approx 0.75\,(\hbar\Omega_0/M)^{1/2}$ for detuning $\Delta \approx 0.56\,\Omega_0$, and since $\Omega_0 \propto I^{1/2}$, this implies that the upper limit on $v_y^{\max}$ is proportional to $I^{1/4}$, which is a rather slowly increasing function of intensity. Therefore, the available tunable CW laser power (~1 W) limits $v_y^{\max}$ to values of order 100–400 cm/s for mirror areas ranging from 1 cm^2 to 1 mm^2. However, values of $v_y^{\max}$ approaching typical thermal velocities (~10^4 cm/s) can be achieved for very short time intervals by use of pulsed laser radiation.

The above considerations suggest a new type of trap for slow neutral atoms. Suppose that laser radiation is totally reflected by each of the six faces of a cubical cavity in a dielectric medium. Then a slow atom inside the cavity will be reflected by the evanescent waves on the cavity walls without making thermal contact with the dielectric itself. In this way a cold atomic vapor ($T \lesssim 5 \times 10^{-4}$ K) might be held in the cavity for a time sufficiently long to perform essentially Doppler-free spectroscopy. An advantage of this type of trap is that the atoms interact with the radiation only during the brief reflection processes, and consequently the quantum fluctuations of the radiation force [4], which tend to heat the atomic vapor, are much less of a problem than in those schemes in which the atoms are continuously illuminated.

Other possible applications of the reflection process immediately come to mind. For example, it is evident that the dielectric surface in fig. 1 can be given a small curvature to produce a concave mirror for neutral atoms. Such a mirror could be used to focus an atomic beam of slow atoms or to image atoms that are scattered by a small object. Moreover, a complete "optics" of atomic beams could be constructed on the basis of such reflecting elements. But in this connection, it is very important to note that gravity will play an important role, since, for the velocities of interest (~100 cm/s), the atomic trajectories are bent significantly by gravity over a distance of a few centimeters.

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