J. Phys. B: At. Mol. Opt. Phys. 24 (1991) 3173-3178. Printed in the UK

An atomic trap based on evanescent light waves

Yu B Ovchinnikov, S V Shul'ga and V I Balykin

Institute of Spectroscopy, USSR Academy of Sciences, 142092 Troitsk, Moscow Region, USSR

Received 18 March 1991

Abstract. A new type of gradient light trap is suggested for neutral atoms, based on the evanescent fields of two laser beams experiencing total internal reflection at a dielectric-vacuum interface. A distinctive feature of the trap is that its bottom is close to the interface: at a distance of the order of the wavelength of light.

1. Introduction

Atomic physicists have recently been actively engaged with investigations into the action of laser light on the mechanical motion of atoms. One of the attractive applications in this field is the development of light traps for neutral atoms. All the known light traps can be subdivided into the following two types: traps using the spontaneous light pressure force and those based on the gradient force. Each type possesses merits of its own. For example, traps of the first type are characterized by a long holding time ($\simeq 1$ min), provided they use an additional magnetic field, and a large volume ($\simeq 1\ \mathrm{cm}^3$), and require moderate laser field intensities (*J. Opt. Soc. Am.* 1989). The traps based on the use of the gradient force (hereafter referred to as gradient traps) are attractive because of their simplicity and the possibility of localizing atoms in regions of about the wavelength of light in size. There are not very many types of gradient traps known to date, all of them using the most simple stable laser field (mode) configurations: a sharply focused Gaussian beam (Ashkin 1984, Chu *et al* 1986a, b) and the TEM_{01}^{*} mode (Yang *et al* 1986). The first of these traps has recently been realized for Na atoms (Chu *et al* 1986). Balykin *et al* (1988a, b) have suggested another gradient trap scheme using the reflection of atoms from laser fields finding their way into a vacuum after undergoing total internal reflection at a dielectric-vacuum interface (Cook and Hill 1982, Balykin *et al* 1987).

In this paper, we propose a new type of gradient atomic trap based on the localization of atoms in the evanescent fields of two laser beams. Such a trap has a number of remarkable features that will be discussed at the end of the paper.

2. Basic idea of the trap

When a plane electromagnetic wave is reflected at a dielectric-vacuum interface, the field that finds its way into the vacuum is an evanescent wave, i.e. one whose amplitude falls exponentially as one moves away from the interface (figure 1). Suppose that the incident field is polarized along the z axis, so that the field amplitude in the vacuum has the form

$$E_{\mathrm{v}}^{(z)} = 2E_{\mathrm{d}}^{(z)} \cos\theta(1-n^{-2})^{-1/2} \exp(-\alpha y) \tag{1}$$

where θ is the angle between the wavevector and the normal to the interface and $E_{\mathrm{d}}^{(z)}$ is the field amplitude in the incident wave. The quantity α is the inverse of the depth of the field penetration into the vacuum, given by

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

where $k = 2\pi n/\lambda$ is the wavevector in the dielectric and λ the radiation wavelength in the vacuum. The characteristic depth $d = \alpha^{-1}$ of the field penetration into the vacuum is of the same order of magnitude as the radiation wavelength. Thus, total internal reflection gives rise to gigantic light field gradients near the dielectric surface. If the frequency of the laser field is close to that of some transition of a two-level atom located in the field, the atom will be acted upon by the gradient force (Cook and Hill 1982)

$$F_{\mathrm{g}}^{(y)} = -\alpha\hbar\Delta G(y)[1+G(y)+\Delta^2/\gamma^2]^{-1} \tag{3}$$

where $\Delta = \omega - \omega_0$ is the detuning of the laser field frequency ω relative to the atomic transition frequency ω_0, $G(y) = I(y)/I_{\mathrm{s}}$ is the saturation parameter, $I(y)$ is the local field intensity, I_{s} is the saturation intensity, and 2γ is the natural atomic transition width. A characteristic feature of the gradient force is that its direction is determined by the sense of the frequency detuning. With the detuning being blue ($\Delta > 0$), the atom is expelled from the evanescent wave, whereas in the case of red detuning ($\Delta < 0$), it is drawn into the wave. This feature of the gradient force was used to implement the quantum-state-selective reflection of Na atoms from an evanescent wave (Balykin *et al* 1988a, b).

We suggest here using this feature of the gradient force to create an atomic trap. The trap is formed by two evanescent waves differing in the sense of frequency detuning and the depth of penetration into the vacuum. The main idea here is to produce a short-range repulsive force and a long-range attractive force, similar to the repulsive and attractive forces acting between two atoms in a molecule.

The trap is shown schematically in figure 1. The attracting evanescent wave is formed by a red-detuned laser beam incident upon the dielectric-vacuum interface at an angle only slightly greater than the critical value. According to formula (2), the depth of field penetration into the vacuum may in this case be as great as a few wavelengths of light. The repulsing evanescent wave is produced by a blue-detuned laser beam incident upon the interface at a very small angle. The penetration depth for such a wave may be extremely shallow: of the order of one tenth of the wavelength of light. If an atom is placed close enough to the dielectric surface, the first wave will tend to push the atom away from the surface, while the second will tend to pull it toward the surface, the equilibrium position being at about a wavelength of light distant from the surface.

If the trap is formed by two laser beams with a Gaussian transverse intensity distribution (TEM$_{00}$ mode), the atomic motion in the $x0z$ plane can also be restricted. To do this, it is sufficient to make the cross section of the laser beam forming the attractive wave much smaller than that of the beam forming the repulsive wave. In that case, the resultant gradient force of the two laser beams in the $x0z$ plane will be

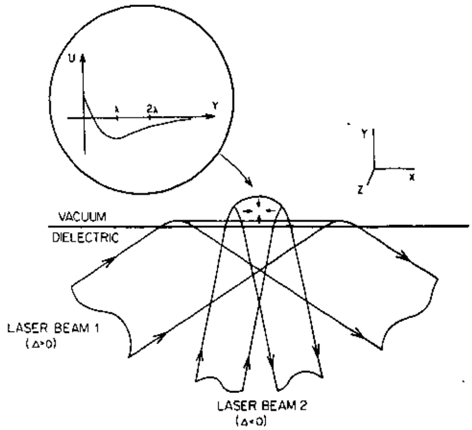

Figure 1. Schematic diagram of the evanescent light trap formed by the evanescent waves of two laser beams undergoing total internal reflection at a dielectric–vacuum interface. The curve in the circle shows the atomic potential energy in the trap as a function of the y coordinate.

directed toward the centre of the trap. This force is of the same order of magnitude as the gradient force in the Gaussian beam forming the attractive evanescent wave.

3. Evaluation of the main parameters of the trap

We will henceforth be interested in the case of weak atomic transition saturation,

$$G \ll (1+\Delta^2/\gamma^2) \tag{4}$$

because this condition provides for the longest possible time of atomic localization in the trap (Gordon and Ashkin 1980). If condition (4) is satisfied, the resultant force on the atom in the trap may be represented as a sum of the forces acting on the atom in each of the two evanescent waves. If the condition $\Delta \gg \gamma$ is satisfied in addition to condition (4), the potential of our trap may be represented in the form (Gordon and Ashkin 1980)

$$U = \hbar\gamma(\gamma G_1/2\Delta_1 + \gamma G_2/2\Delta_2) \tag{5}$$

where Δ_1 and Δ_2 are the frequency detunings of the two evanescent waves and G_1 and G_2 their local saturation parameters, respectively.

In the case of a one-dimensional trap relying on the total internal reflection of two plane waves, the saturation parameters of their respective evanescent waves have the form $G_1 = G_{01}\exp(-2\alpha_1 y)$ and $G_2 = G_{02}\exp(-2\alpha_2 y)$, where G_{01} and G_{02} stand for the saturation parameters at the interface. The corresponding potentials for $G_{01} = G_{02} = 4\times10^7$, $\Delta_1 = 5\times10^5\gamma$, $\Delta_2 = -10^6\gamma$, $\theta_1 = 47°$, and $\theta_2 = 45.7°$ ($n = 1.4$) are shown in figure 2(a). The dotted curve corresponds to the resultant potential. It can be seen from the figure that the potential minimum is at a distance of $x_{\min} = \lambda$ from the dielectric surface and the depth of the well is $\Delta U \simeq 7\hbar\gamma$, its width at the $\Delta U/2$ level being also of the same order of magnitude as the wavelength of light.

The lifetime of atoms in such a trap is determined mainly by their heating as a result of momentum diffusion in the light field forming the trap. If condition (4) is

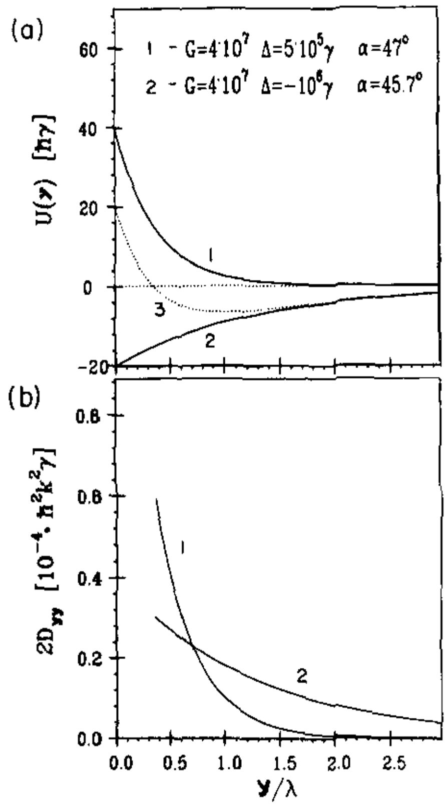

Figure 2. (*a*) Atomic potential energy in evanescent waves with a positive frequency detuning (curve 1) and a negative frequency detuning (curve 2). The dotted curve represents the resultant potential of a one-dimensional evanescent trap; (*b*) momentum diffusion coefficients for the respective waves.

satisfied, the coefficient of the atomic momentum diffusion in the y direction normal to the dielectric-vacuum interface is defined by the expression (Gordon and Ashkin 1980)

$$2D_{yy} = \hbar^2\alpha_1^2\gamma(G_{01}\gamma^2/\Delta_1^2)\exp(-2\alpha_1 y) + \hbar^2\alpha_2^2\gamma(G_{02}\gamma^2/\Delta_2^2)\exp(-2\alpha_2 y). \tag{6}$$

The spatial behaviour of the momentum diffusion coefficients for the laser beams of the above parameters is illustrated in figure 2(*b*). Given the average atomic momentum diffusion coefficient in the trap, one can find the atomic lifetime in it: $\tau = M\Delta U/D$, where M is the atomic mass. If we put $\Delta U = 7\hbar\gamma$ and $D = 10^{-5}\hbar^2k^2\gamma$, we then have $\tau \simeq 3$ s at $\lambda \simeq 600$ nm, $\gamma = 3\times10^7\ \mathrm{s}^{-1}$, $M = 4\times10^{-24}$ g.

When considering the localization of atoms in a three-dimensional evanescent trap formed by the evanescent waves of two Gaussian laser beams, account should also be taken of the spontaneous radiation pressure force. The greatest effect on the stability of the trap is exerted by the x component of this force, given by

$$F_{sp}^{(x)} = \hbar k_x\gamma\{G(x,y)/[1+G(x,y)+\Delta^2/\gamma^2]\} \tag{7}$$

where $k_x = k\sin\theta$. To estimate the corresponding gradient force component, we take that the field intensity distribution in the evanescent wave is the same as the transverse intensity distribution in the laser beam, i.e. $G(x,y) \simeq G(x_0,y)\exp(-2x^2/w^2)$, where

$G(x_0, y)$ is the saturation parameter of the attractive field in the centre of the trap and w is the laser beam radius. In that case, we have

$$F_{gr}^{(x)} = 2\hbar\Delta(x/w^2)\{G(x,y)/[1+G(x,y)+\Delta^2/\gamma^2]\}. \tag{8}$$

Equating expressions (7) and (8), we find that the spontaneous light pressure force moves the atom to a distance of $x=(k_x w\gamma/2\Delta)w$ away from the centre of the trap. The spontaneous radiation pressure force can be disregarded if the atomic displacement is much smaller than the laser beam radius. Considering this fact, the restriction on the diameter of the laser beam forming the attractive evanescent wave may be expressed as follows:

$$2w \ll 4\Delta/k_x\gamma. \tag{9}$$

To calculate the evanescent wave fields exactly we have used the results of Kozaki and Sakurai (1978). We have considered as an example an evanescent trap formed by laser beams having the following parameters. The beam producing the repulsive field has a frequency detuning of $\Delta_1 = 5\times10^5\gamma$, an average beam saturation parameter $\langle G_1\rangle = 2\times10^7$, an angle of incidence of $\theta_1 = 70°$, and a waist diameter of $2w_1 = 20\ \mu$m. The corresponding parameters for the laser beam producing the attractive evanescent wave are as follows: $\Delta_2 = -10^6\gamma$, $\langle G_2\rangle = 5\times10^6$, $\theta_2 = 46.6°$, and $2w_2 = 10\ \mu$m. The depth of such a trap is $\Delta U \simeq 8\hbar\gamma$, its minimum being localized at a distance of around 0.4λ from the dielectric–vacuum interface. For an allowed transition in Na ($\gamma = 3\times10^7\ s^{-1}$, $I_s = 10$ mW cm^{-2}), the radiation powers in the laser beams are $P_1 = 640$ mW and $P_2 =$ 40 mW, respectively. The lifetime of the atoms in the trap, governed by their diffusion heating, is $\tau \simeq 1$ s, which agrees well with the values obtained both theoretically (Gordon and Ashkin 1980) and experimentally (Chu *et al* 1986a, b) for other gradient traps.

Let us now consider the possible ways to fill the trap with atoms. The stationary cooling of the atoms inside the trap by the spontaneous radiation pressure force is inefficient because of the dynamic Stark shift of the atomic resonance frequency (Gordon and Ashkin 1980). Cold ^{4}He atoms (Kuo-Ho Yang *et al* 1986) are also rather difficult to use for the purpose, the trap being too close to the 'hot' surface of the dielectric. The pulsed switching of one or both laser beams forming the trap on and off (Chu *et al* 1986a, b) is apparently the most suitable method for filling the trap.

Let us now estimate the number of atoms that can be retained in the trap. The trap volume can be estimated as $V \simeq 4w^2\lambda$. For $w = 10\lambda$ and $\lambda = 6\times10^{-5}$ cm, we have $V \simeq 10^{-10}$ cm^3. Considering that the atomic number density attainable in optical molasses is $n = 10^{11}$ atoms/cm^3 (Raab *et al* 1987), the trap with such a volume can hold some 10 atoms. The volume of the trap can be materially increased by extending its size along the dielectric–vacuum interface. If we take $\Delta_1 = 10^5\gamma$, the restriction on the trap diameter will, according to (10), be $2w < 4$ cm, which corresponds to a trap volume of $V_{max} = 10^{-3}$ cm^3, the number of atoms that can in this case be held in the trap amounting to some 10^8 (at an atomic number density of $n = 10^{11}$ atoms/cm^3). It should be noted that the number of trapped atoms can also be increased by varying periodically the depth of penetration of the attractive wave into the vacuum. If at the start of trapping the angle of incidence of the laser beam forming the attractive evanescent wave is made greater than the critical value, the beam will completely leave the dielectric. The volume of the gradient trap formed by this beam is by several orders of magnitude greater than that of the corresponding evanescent trap. The same applies to the number of atoms that can be caught in the gradient trap. If the angle of incidence is reduced after such an entrapment to a value smaller than the critical one, all the trapped atoms will be drawn into the evanescent trap, provided, of course, that the angle variation time is shorter than the characteristic atomic lifetime in the trap.

4. Conclusion

We have proposed here a new type of gradient trap, called the evanescent atomic trap, formed by the evanescent fields of two laser beams undergoing total internal reflection at a dielectric–vacuum interface, and demonstrated that the characteristic atomic lifetime in such a trap can be of the order of 1 s.

A characteristic feature of this trap is that it is located close to the dielectric surface, around a wavelength of light distant from it. What is more, this distance can be reduced, for instance, by lowering the intensity of the repulsive evanescent wave. Such a trap may prove useful in studying the interaction between cold atoms and a surface and analysing its microstructure. When the repulsive potential is switched off, the atoms in the trap can be 'seated' onto the surface. The seating accuracy is governed by the size of the trap and may be around 1 μm.

Another distinctive feature of the trap is its small size (approximately equal to λ) in the direction normal to the dielectric–vacuum interface. This property may prove useful in realizing the Lamb–Dicke radiation–atom interaction conditions and also in developing pulsed schemes for cooling atoms down to 10^{-6} K (Chu *et al* 1986a, b).

Acknowledgments

The authors wish to express their gratitude to Professor V S Letokhov and Dr A I Sidorov for many valuable discussions.

References

Ashkin A 1984 *Opt. Lett.* **9** 454
Balykin V I, Letokhov V S and Minogin V G 1988a *Phys. Scr.* T **22** 119
Balykin V I, Letokhov V S, Ovchinnikov Yu B and Sidorov A I 1987 *Pis'ma Zh. Eksp. Fiz.* **45** 282
—— 1988b *Phys. Rev. Lett.* **60** 2137
Chu S, Bjorkholm J E, Ashkin A and Cable A 1986a *Phys. Rev. Lett.* **57** 314
Chu S, Bjorkholm J E, Ashkin A, Gordon J P and Hollberg L W 1986b *Opt. Lett.* **11** 73
Cook R J and Hill R K 1982 *Opt. Commun.* **43** 258
Gordon J P and Ashkin A 1980 *Phys. Rev.* A **21** 1606; 1989 *J. Opt. Soc. Am.* B **6**
Kozaki S and Sakurai H 1978 *J. Opt. Soc. Am.* **68** 508
Raab E L, Prentiss M, Cable A, Chu S and Pritchard D E 1987 *Phys. Rev. Lett.* **59** 2631
Yang K-H, Stwalley W C, Heughan S P, Bahus J T, Wang K-K and Hess T R 1986 *Phys. Rev.* **34** 2962