Trapping of atoms in the near field of laser light

V. V. Klimov
P. N. Lebedev Physics Institute, Russian Academy of Sciences, 117924 Moscow, Russia

V. S. Letokhov
Institute of Spectroscopy, Russian Academy of Sciences, 142092 Troitsk, Moscow Region, Russia

(Submitted 16 November 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **61**, No. 1, 15–19 (10 January 1995)

Atomic-trap configurations of a new type which arise in the near field of laser light are discussed. If there is a negative detuning of the frequency Ω, and the atoms are pulled into a region of str onger field, a trap arises at the axis of the system in front of an aperture. The depth of the well is on the order of $\hbar\Omega/2$. © *1995 American Institute of Physics.*

Controlling the motion of neutral atoms by means of laser light (the cooling and then confinement of atoms, atomic optics, etc.) is one of the most interesting fields in atomic physics (see some reviews,[1–4] some topical issues of journals,[5,6] a monograph,[7] and some proceedings of schools[8]). Despite more than a quarter-century of research in this field, begun in Ref. 9, this field is far from being mined out. There are a multitude of promising directions. One which is particularly promising is the confinement of ultracold atoms.[10]

There are several ways to confine fairly cool atoms, involving various configurations of laser light (Refs. 11–14, for example).

In this letter we are proposing a new type of atomic trap. This new trap may have certain advantages over existing traps. It also allows one to confine atoms at given spatial points, and the distances between the trapped atoms can be arbitrary, even smaller than the wavelength. As the primary force which holds the atom in the trap we suggest using the gradient force which arises in the near field of laser light near a small aperture or a system of apertures in a thin, ideally conducting screen. We restrict the discussion here to the case in which the laser light is incident normally on the aperture. The geometry of the problem is shown in Fig. 1.

This proposed atomic confinement method is based entirely on the nature of the spatial distribution of the electric field. In Ref. 15 we derived an analytic expression for the distribution of the time-average square of the electric field which arises upon diffraction of a circularly polarized wave incident on an aperture small in comparison with the wavelength.

Figure 2 shows the spatial distribution of the field in the case $\mathbf{k}\cdot\mathbf{a}=2$ ($\mathbf{k}$ is the wave vector of the light, and $\mathbf{a}$ the radius of the aperture) according to the exact equations.[15] We see that a definitely 3D extremum arises near the aperture, on the symmetry axis, near an antinode of the standing wave formed by the incident and reflected waves. Below we report a study of the characteristics of this potential well.

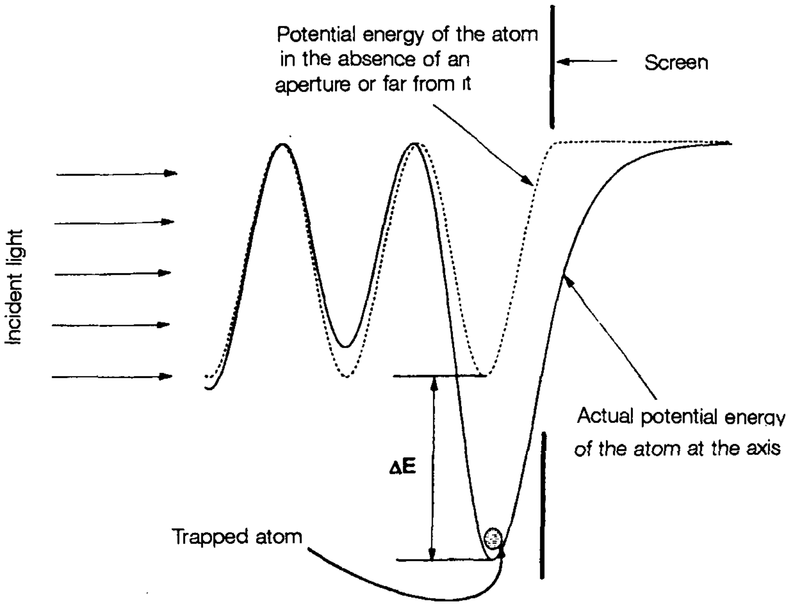

FIG. 1. Geometry of the problem.

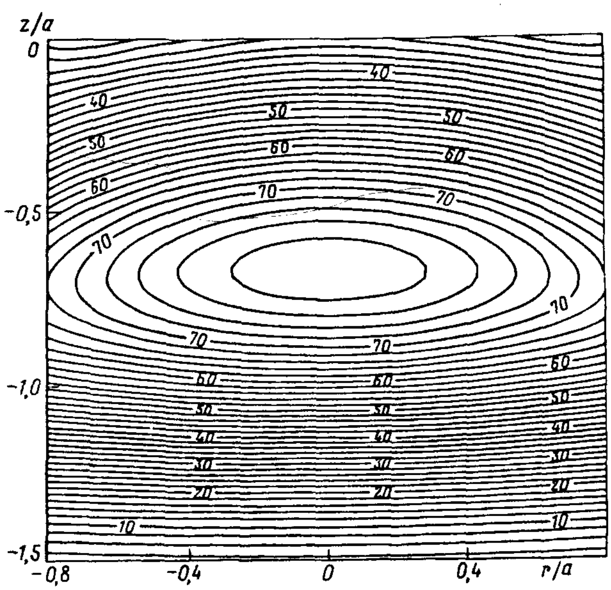

FIG. 2. Contour map (spatial distribution) of the mean square value of the electric field of a circularly polarized wave with amplitude E_0 incident normally on the aperture ($ka=2$, $E_0=3\pi/2$; cgs units).

The only force acting on the atom here is the gradient force. The potential of this force is given in the case at hand by the known expression[16]

$$U_g=\frac{\hbar\Omega}{2}\ln\left(1+\frac{\mu^2E^2}{\hbar^2\gamma^2}\right). \tag{1}$$

Here $\Omega=\omega-\omega_0$ is the detuning, Γ is the total width of the line, μ is the transition dipole moment, and $\gamma^2=\Omega^2+(\Gamma/2)^2$. It can be seen from this expression that an atomic trap forms near a local maximum of the square of the electric field in front of the screen when the frequency detuning Ω is negative. To determine the basic characteristics of this trap, i.e., the position of its minimum and its depth, we need only work from the values of (1) on the symmetry axis of the problem, since it is clear from Fig. 2 that a radial restoring force exists at $r<a$ in all cases.

On the symmetry axis, the expression for the potential of the gradient force simplifies; it can be written as follows, where we are using equations from Ref. 15:

$$U_g=\frac{\hbar\Omega}{2}\ln\left\{1+S\left[\sin(ka\tilde{z})-\frac{ka}{3\pi}A_0(\tilde{z})\right]^2\right\},\quad \tilde{z}<0, \tag{2}$$

$$U_g=\frac{\hbar\Omega}{2}\ln\left(1+S\left(\frac{ka}{3\pi}\right)^2A_0(\tilde{z})^2\right),\quad \tilde{z}>0,$$

$$A_0=3[1-\tilde{z}\arctan(1/\tilde{z})]+\frac{1}{1+\tilde{z}^2}, \tag{3}$$

where

$$\tilde{z}=z/a,\quad S=4G/(1+\Delta^2),\quad G=I/I_g,\quad \Delta=2\Omega/\Gamma.$$

We easily find from this expression that the position of the bottom of the well, $\tilde{z}^*(ka)$, is given implicitly by the equation

$$\frac{d}{d\tilde{z}}A_0(\tilde{z}^*)=3\pi\cos(ka\tilde{z}^*). \tag{4}$$

For small values of ka, a solution of this equation can be found in power-series form:

$$\tilde{z}^*=-\frac{\pi}{2ka}+\frac{32}{3\pi}\left(\frac{ka}{\pi}\right)^3+\dots\,. \tag{5}$$

Figure 3 shows the position of the bottom of the well according to the exact solution in (4). We see that, over a fairly wide range of aperture dimensions (for a given wavelength of the light), the well is in the immediate vicinity of the aperture, near an antinode of the standing wave formed by the incident and reflected waves.

To find the depth of the potential well that forms, we first note that, as the energy of the atom in the trap increases, there is initially a delocalization in the radial direction (along the antinode of the standing wave closest to the aperture). Only at far higher energies does a delocalization occur along the z axis (Fig. 1). The depth of the potential

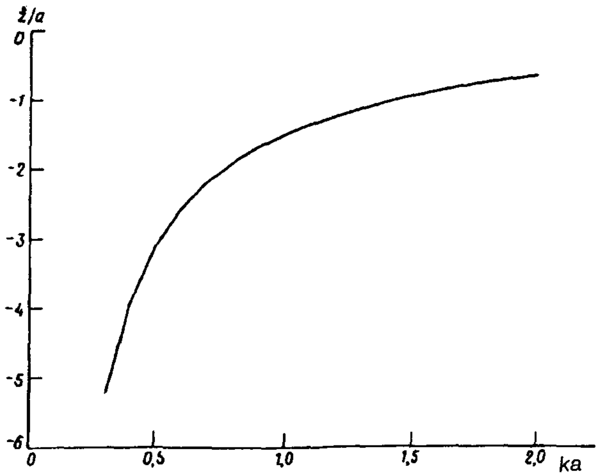

FIG. 3. Position of the bottom of the 3D potential well as a function of the parameter ka.

well is thus governed by the difference between the potential of the gradient force at the antinode of the standing wave and the potential of the gradient force at the bottom of the well:

$$\Delta E = \frac{\hbar\Omega}{2} \ln\left(\frac{1+S}{1+Sg(ka)}\right), \tag{6}$$

where the function

$$g(ka) = \left[\sin(ka\tilde{z}^*) - \frac{ka}{3\pi} A_0(z^*)\right]^2 \tag{7}$$

is shown in Fig. 4.

At sufficiently high light intensities ($S \gg 1$), the expression for the depth of the well simplifies:

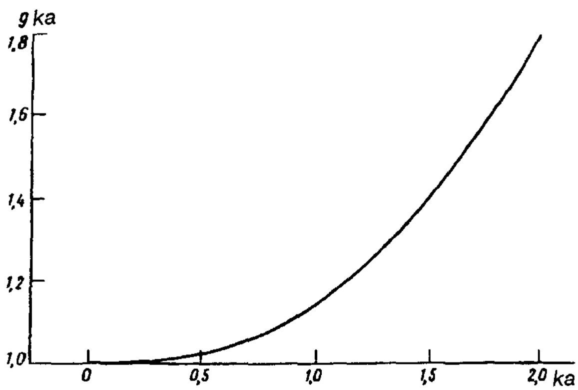

FIG. 4. Plot of the function $g(ka)$, which appears in expression (8) for the depth of the 3D trap.

$$\Delta E = -\frac{\hbar\Omega}{2}\ln[g(ka)], \tag{8}$$

and we easily see from Fig. 4 that this trap has a depth on the order of $\hbar\Omega/2$.

Although it would seem from these expressions that we could increase the depth of the well even further by increasing the aperture diameter, in fact the results found here are valid only under the condition $ka<2$. At larger values of ka, the aperture is no longer small, and we need to work in terms of the exact theory of diffraction by a circular aperture (Ref. 17, for example). It may turn out, of course, that the depth of the well undergoes certain changes.

The method proposed here for trapping atoms looks quite interesting for research on emission from atomic systems under unconventional conditions. By exciting an atom in a trap—i.e., in a strictly determined position with respect to an aperture in a screen—into a Rydberg state, one could experimentally study the effect of the screen with the aperture on the decay rate of the excited state. In addition, with a system of apertures in a screen, with a period smaller than the wavelength, one could set up a given distribution of atoms in a volume small in comparison with the wavelength. It would then become possible to study the cooperative interaction of these atoms in spontaneous emission, i.e., the Dicke effect,[18] in its pure form. Furthermore, one cannot rule out the possibility that 3D systems of traps of this type may prove useful in the mass production of electronic and other devices of atomic scale.

[1] S. Stenholm, Rev. Mod. Phys. **528**, 699 (1986).
[2] W. Phillips *et al.*, Science **239**, 878 (1991).
[3] S. Chu, Science **253**, 861 (1991).
[4] C. Cohen-Tannoudji, Phys. Rep. **219**, 153 (1992).
[5] S. Chu and C. Wieman (editors), J. Opt. Soc. Am. B **6**, 2109 (1990).
[6] V. Balykin *et al.*, Appl. Phys. B **54**, No. 5 (1992).
[7] V. G. Minogin and V. S. Letokhov, *Pressure Exerted by Laser Light on Atoms* [in Russian] (Nauka, Moscow, 1986).
[8] Proc. of Enrico Fermi Intern. School of Physics, Course CXVIII, "Laser manipulation of atoms and ions" (North-Holland, Amsterdam, 1992).
[9] V. S. Letokhov, JETP Lett. **7**, 272 (1968).
[10] D. E. Pritchard *et al.*, in: *Atomic Physics 11*, ed. by S. Haroche, J. G. Gay, and G. Grynberg (World Scientific, Singapore, 1989), p. 179.
[11] S. Chu *et al.*, Phys. Rev. Lett. **57**, 314 (1986).
[12] E. L. Raab *et al.*, Phys. Rev. Lett. **59**, 2631 (1987).
[13] C. G. Aminoff *et al.*, Phys. Rev. Lett. **71**, 3083 (1993).
[14] O. Emile *et al.*, Europhys. Lett. **20**, 687 (1992).
[15] V. V. Klimov and V. S. Letokhov, Opt. Commun. **106**, 151 (1994).
[16] J. P. Gordon and A. Ashkin, Phys. Rev. A **21**, 1606 (1980).
[17] Y. Nomura and S. Katsura, J. Phys. Soc. Jpn. **10**, 285 (1955).
[18] R. H. Dicke, Phys. Rev. A **93**, 99 (1954).

Translated by D. Parsons