Tight focusing of an atomic beam by the near field of diffracted laser light

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It is shown on the basis of classical dynamics that the near field of laser light, which arises upon the diffraction of a plane light wave by an aperture small in comparison with the wavelength, gives rise, by virtue of a gradient force, to a tight focusing of a normally incident atomic beam if the detuning of the frequency of the laser light from resonance is negative. Explicit expressions are derived for the trajectories of particles and for the caustic surface in the approximation of a weak scattering potential. The defocusing which would result from a velocity spread of the beam atoms is estimated.

Research on the effect of radiation-pressure forces on the motion of free atoms in laser beams has resulted in the emergence of a new type of optics: atomic optics.[1,2] Of primary interest in atomic optics is the possibility of focusing atoms with a spatial resolution[3,4] of 1–10 Å. In this letter we wish to propose the use as a focusing field of the near field resulting from the diffraction of laser light by an aperture which is small in comparison with the wavelength in a thin, ideally conducting screen (Fig. 1). If the deviation of the field frequency ω from the frequency of the atomic transition, ω_0, is negative, then the "sagging" of the field through a small aperture in a screen gives rise to a spatial nonuniformity in the intensity. The gradient force which arises because of this nonuniformity has focusing properties for atoms at resonance with the field.

The intensity distribution in the near field in the case of diffraction by a small aperture can be expressed in terms of elementary functions.[5] Figure 2 shows this distribution at various distances from the screen.

In the paraxial approximation, the exact equations[5] reduce to ($\tilde{z}=z/a$, $\tilde{r}=r/a$)

$$\langle E\rangle^2=\left(\frac{kaE_{0m}}{3\pi}\right)^2\{b(\tilde{z})-d(\tilde{z})\tilde{r}^2\},\tag{1}$$

$$b(\tilde{z})=2\left[3[1-\tilde{z}\arctan(1/\tilde{z})]+\frac{1}{1+\tilde{z}^2}\right]^2,\quad \tilde{z}>0,$$

$$b(\tilde{z})=b(-\tilde{z})+2\left(\frac{3\pi}{ka}\right)^2\sin^2 ka\tilde{z},\quad \tilde{z}<0,\tag{2}$$

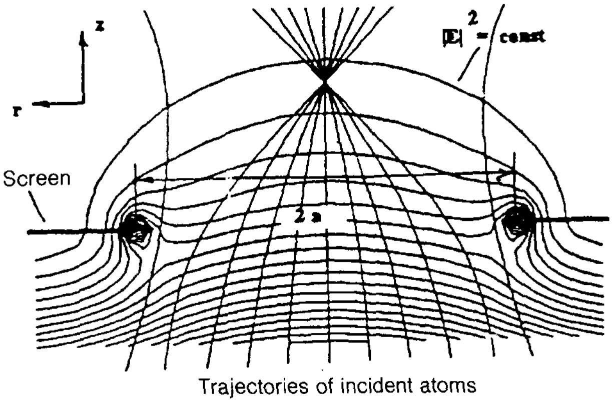

FIG. 1. Schematic diagram of the focusing of an atomic beam by the near field formed upon the diffraction of a plane light wave by an aperture with a diameter $2a \ll \lambda$. The horizontal lines are contour curves of the field intensity; the vertical lines correspond to trajectories of atoms.

$$d(\tilde{z}) = \frac{9\tilde{z}^4 + 14\tilde{z}^2 + 4}{(\tilde{z}^2+1)^4} - \frac{12z(3\tilde{z}^2+1)\arctan(1/\tilde{z})}{(\tilde{z}^2+1)^3}, \quad \tilde{z} > 0,$$

$$d(\tilde{z}) = d(-\tilde{z}) + 4\left(\frac{3\pi}{ka}\right)\sin ka\tilde{z}\left(\frac{1-3\tilde{z}^2}{(\tilde{z}^2+1)^3}\right), \quad \tilde{z} < 0. \tag{3}$$

In the interaction geometry of Fig. 1, the potential of the gradient force is[6]

$$U_h = \frac{\hbar\Omega}{2}\ln\left(1 + \frac{\mu^2 E^2}{\hbar^2|\gamma|^2}\right), \tag{4}$$

where μ is the dipole moment of the working transition, $\Omega = \omega - \omega_0$, and $\gamma = \Gamma/2 - i\Omega$. Figure 1 also shows contour curves of the potential of the gradient force.

A simple qualitative analysis of Eqs. (1) and (4) shows that if the detuning from the frequency of the working transition is positive, there will be a repulsion of atoms, i.e., a defocusing of the atoms, at the periphery of the aperture. If the deviation is instead negative, the potential of the gradient force will be attractive, and we conclude from Figs. 1 and 2 that the particles will concentrate near the axis of the aperture. The focusing properties of the near field can be analyzed quantitatively for arbitrary parameters of the field and the particle beam through direct numerical simulation of the motion of the particles in potential (4) using the exact expressions for the field distribution.

When the atoms are incident normally on the aperture, the problem reduces to a 2D problem. The temporal dynamics of the trajectories of the beam particles is inconsequential for a determination of the focusing properties of this near field. After we eliminate the time and impose energy conservation, the complete system of 2D equations of motion reduces to a system of two first-order differential equations:

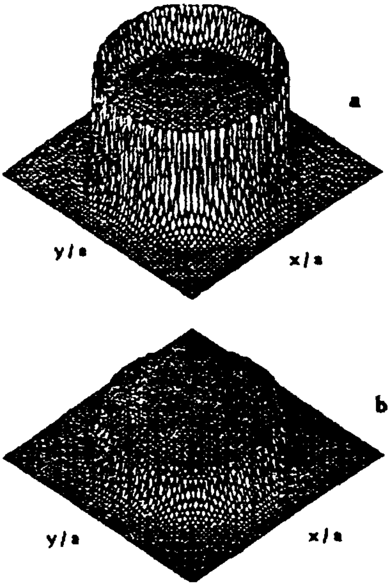

FIG. 2. Field intensity distribution in the near zone upon the diffraction of a light wave by a small circular aperture in a plane, at a distance $z=0.05a$ (a) and at $z=0.15a$ (b).

$$\frac{\partial x}{\partial z}=\frac{p}{q(x,z,p)}, \quad \frac{\partial p}{\partial z}=\frac{\partial}{\partial x}q(x,z,p),$$

$$q=-\sqrt{(T_0-U_g)2M-p^2}. \tag{5}$$

Here T_0 is the initial kinetic energy, and p is the radial momentum of the atom.

Now imposing initial conditions on (5), we obtain a correct Cauchy problem, whose solution has been found by the fourth-order Runge–Kutta method. The results of the simulation show that for essentially any parameters of the problem there is a pronounced focusing of a single-velocity atomic beam. The position of the focus varies over a wide range as the intensity and frequency detuning of the laser light and the initial velocity of the atoms are varied. The situation is illustrated by Fig. 3, which shows trajectories of a beam of helium atoms at a velocity $v_0=100$ m/s. We can clearly see the formation of a standard caustic of the cusp type at a distance $z_0=480a=76\lambda$. The focus is shown in larger scale in Fig. 3b.

To find a quantitative analytic description of the particle trajectories near the focus, we consider the case in which the potential of the gradient force is small in comparison with the kinetic energy of the beam particles, i.e., $4G\ll 1+\kappa^2$ and

$$\frac{\eta}{2}\left(\frac{ka}{3\pi}\right)^2\frac{G}{1+\kappa^2}\ll 1, \quad ka\ll 1,$$

where $G=I/I_s$ is the saturation parameter of the atomic transition, $\kappa=2\Omega/\Gamma$, and $\eta=\hbar\Gamma/2T_0$. We then find an expression for the focal length z_c,

$$\frac{z_c}{a}=-\frac{1}{23\pi\epsilon}=-\frac{4}{23\pi}\left(\frac{3\pi}{ka}\right)^2\frac{1+\kappa^2}{G\kappa}\frac{T_0}{\hbar\Gamma}, \tag{6}$$

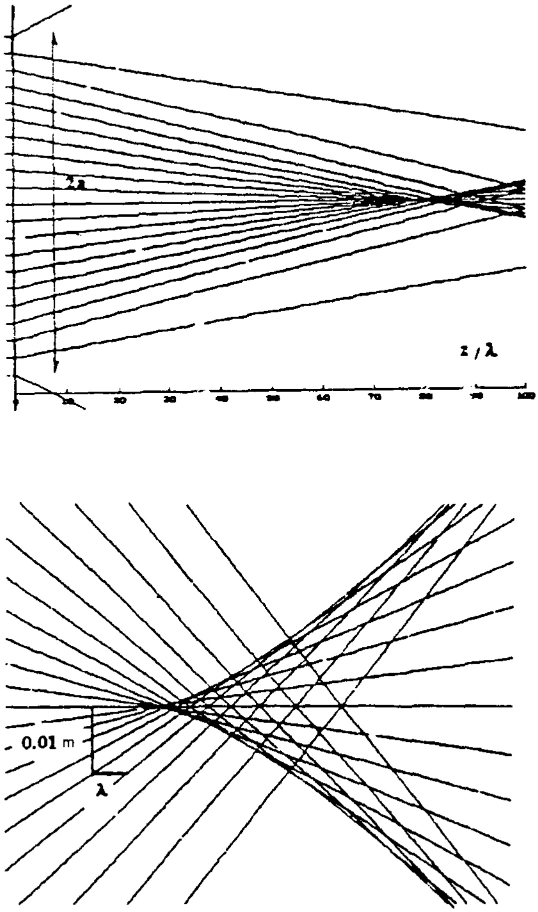

FIG. 3. Focusing of a beam of He* atoms with a velocity $v_0 = 100$ m/s in an interaction with a field at $\lambda = 1.08\ \mu$m on the transition $^3S_1 - {}^3P_2$ for a detuning $\Omega = -400\Gamma$ and for $G = 10^6$. The size of the aperture is $a = \lambda/2\pi$. The region of the focus is shown in a scale larger by a factor of 40 at the right.

and we can find an expression for the caustic surface $r_c(z)$. It turns out to be a semicubical parabola:

$$\frac{r_c}{a} = \frac{23ka}{18}\sqrt{\frac{46\pi|\epsilon|}{3}}\,\frac{(z-z_c)^{3/2}}{a^{3/2}}. \tag{7}$$

If the atoms of the beam have a velocity spread, there will be chromatic aberration, and the focus will correspondingly become larger. The magnitude of this effect can be estimated from expression (7). The width of the focal spot is determined by the dimensions of the caustic from the particles with the lowest velocity at the point at which the particles with the maximum velocity are focused:

$$\frac{\delta r}{a} = \frac{2(ka)}{9\sqrt{3\pi|\epsilon|}}\left(\frac{\delta v}{v_0}\right)^{3/2}. \tag{8}$$

An exact calculation shows that for an initial velocity spread $\delta v/v \approx 0.1$ and for the parameter values shown in Fig. 3 we would have $\delta r \simeq 5 \times 10^{-2} a \simeq 10^{-2} \lambda$, a value in the nanometer range.

In summary, we have examined the tight focusing of a beam of neutral atoms by the near field of laser light. We have shown on the basis of classical dynamics that a near field of this sort leads to a focusing of the particles of the incident beam in the case of a negative frequency detuning. In the approximation of a small scattering potential we have derived explicit expressions for the particle trajectory and the for the caustic surface, and we have evaluated the defocusing which would result from a velocity spread of the beam atoms.

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