Focusing atomic beams by the dissipative radiation-pressure force of laser light

V. I. Balykin, V. S. Letokhov, and A. I. Sidorov
Institute of Spectroscopy, Academy of Sciences of the USSR

(Submitted 15 January 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 4, 172–174 (25 February 1986)

The focusing of a beam of sodium atoms by the dissipative radiation-pressure force of laser light has been demonstrated experimentally. An optics of neutral-particle beams can be developed.

1. The effect of the forces of resonant radiation pressure on the motion of atoms has recently become the subject of active research in atomic physics. Longitudinal retardation and cooling of atomic beams and a collimation through transverse cooling have been achieved experimentally.[1,2] The focusing of an atomic beam by means of a gradient potential force has been demonstrated.[3] In the present letter we report an experimental realization of the focusing of an atomic beam by a spontaneous (dissipative) radiation-pressure force. The use of a spontaneous radiation-pressure force changes the situation radically, since the spontaneous (dissipative) force exceeds the gradient force at a given laser beam power by a ratio $F_{\rm sp}/F_{\rm gr} \simeq a/\lambda$, where a is the diameter of the laser beam, and λ is the wavelength of the light. This circumstance makes it possible to work with atomic beams with a large aperture ($\simeq$1 cm) and a significant initial divergence ($\Delta\varphi_0 \simeq 0.1$ rad); it also means that the region of the field-atom interaction can be localized quite well. In other words, it is possible to develop a "laser lens" for neutral-particle beams.

2. One of the simplest configurations of a light field for focusing an atomic beam might be that formed by four divergent Gaussian laser beams which are propagating along the $\pm x$ and $\pm y$ directions of a Cartesian coordinate system. The caustics of the beams lie at identical distances from the origin of coordinates. The atomic beam is propagating along the z axis. We assume that the laser frequency is tuned to resonance with the frequency of an atomic transition. An atom displaced from the symmetry axis (the axis of the atomic beam, i.e., the z axis) then experiences a spontaneous radiation-pressure force which tends to return the atom to the axis, as has been shown in some studies[4,5] of optical confinement systems for neutral atoms. The physical reason for the appearance of this restoring force is a disbalance of the laser beam intensities and thus of the radiation-pressure forces when an atom is displaced from the symmetry axis of the lens. For a beam with a small divergence (the case of paraxial light beams in optics), the focal length of the laser lens is given by

$$F_l = \frac{1}{\omega^2}\frac{v_{\parallel}^2}{L_l}\frac{1}{G_0}, \tag{1}$$

where $\omega^2 = 4\hbar k\gamma(1/b^2)(q_0^2/\bar{q}^2)$, $b = 2kq_0^2$, $k = 2\pi/\lambda$, 2γ is the natural width of the absorption line, l is the distance from the caustic of the laser beams to the center of the lens, q_0 and $\bar{q}$ are the dimensions of the beams at the caustic and at the center of the "lens," L_l is the dimension of the laser lens along the axis of the atomic beam, $v_{\parallel}$ is the longitudinal velocity of the atoms which are interacting resonantly with the field, and G_0 is the saturation parameter of the atomic transition at the center of the lens. For a thin laser lens ($L_l = v_{\parallel} t_{\text{in}} \ll v_{\parallel}/\omega$, where t_{in} is the time over which the atoms interact with the light), the equation of the laser lens reduces to the ordinary lens equation

$$\frac{1}{F_l} = \frac{1}{S} + \frac{1}{L}, \tag{2}$$

where S and L are the distances from the laser lens to the source of the atomic beam and to its "image," respectively.

3. Figure 1 is a schematic diagram of the experimental apparatus used to focus an atomic beam. The basic properties of the laser lens can be seen most simply in the

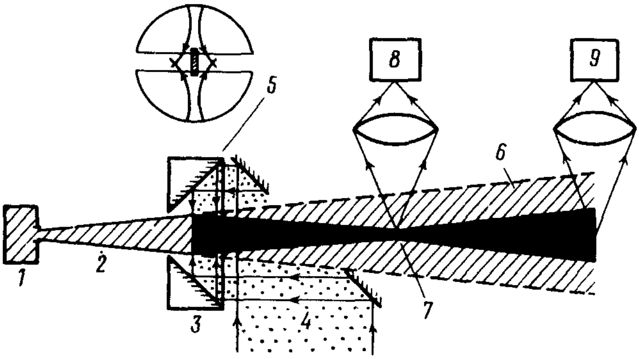

FIG. 1. Experimental arrangement for laser focusing of an atomic beam. 1—Source of atomic beams; 2—atomic beam; 3—cut conical mirror; 4—focusing laser beam; 5—caustic of laser beams inside the conical mirror; 6—original atomic beam; 7—atomic beam after its focusing; 8,9—photomultipliers.

particular example of a one-dimensional laser lens. Experimentally, a one-dimensional laser lens is formed by reflecting a Gaussian laser beam (4) from a conical mirror (3). The conical mirror is cut into two identical parts in the plane passing through the symmetry axis of the cone and perpendicular to the plane of the figure; the two parts are displaced symmetrically, by equal distances (2 mm) from the axis. The caustics of the laser beams after reflection from the split conical mirror are shown in the upper part of Fig. 1. The length of the region in which the atoms interact with the light is 35 mm. In the present experiments we use a beam of sodium atoms, formed by two diaphragms. The diaphragm at the source is a circular aperture with a diameter $d = 1$ mm, and the other diaphragm is a rectangular slit with dimensions $l_1 = 3.7$ mm and $l_2 = 0.25$ mm. The distance between these diaphragms is $L = 125$ mm. Two-frequency laser light[6] and a four-level excitation scheme[7] are used for cyclic excitation of the sodium atoms. One frequency is tuned to resonance with the sodium atom transition $3S_{1/2}$, $F = 1 \rightarrow 3P_{3/2}$, $F' = 2$, while the other is tuned to resonance with the transition $3S_{1/2}$, $F = 2 \rightarrow 3P_{3/2}$, $F' = 3$.

In the experiments, the intensity distribution of the atoms in the beam along the transverse coordinate is determined from the fluorescence signal from a single-frequency probing beam which is spatially scanned. The frequency of this probing beam is tuned to the transition $3S_{1/2}$, $F = 2 \rightarrow 3P_{3/2}$, $F' = 3$ and is placed in a particular part of the Doppler lineshape of the atomic beam, so that atoms of the beam with a particular longitudinal velocity are selected. The diameter of the probing beam in the measurement zone is 0.4 mm at the $1/e^2$ level.

Figure 2(a) shows profiles of the atomic beam before and after its interaction with the laser beam in the plane of the "image" of the beam source. The distance from the laser lens to this image plane is $L_1 = 170$ mm. In Fig. 2(b), the distance from the laser lens to the point at which the beam profiles are measured is $L_2 = 470$ mm. In each of these figures, curve 1 corresponds to the initial atomic beam, curve 2 is the profile after the focusing laser beam has been turned on, and curve 3 is the profile of the beam after its focusing, according to calculations from Eqs. (1) and (2), which correspond to the geometric optics of atomic beams. The power of the laser beam is

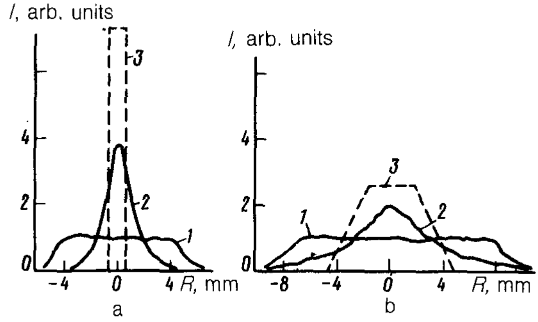

FIG. 2. (a) Profiles of the atomic beam in the plane of the "image" of the beam source. 1—Initial beam profile; 2—beam profile after focusing; 3—profile of the atomic beam according to calculations from Eqs. (1) and (2), from the geometric optics of atomic beams. The distance from the "laser lens" to the image plane is $L_1 = 170$ mm. (b) Profiles of the atomic beam for $L_2 = 470$ mm.

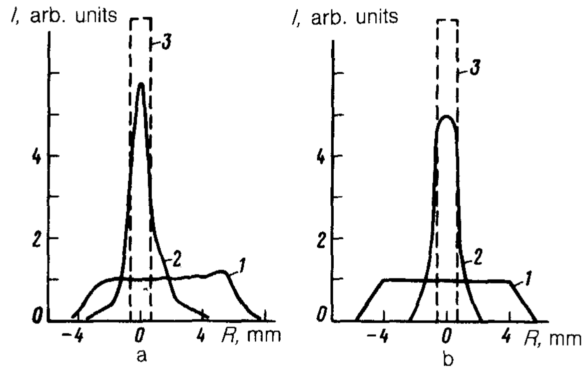

FIG. 3. Profiles of the atomic beam in the plane of the image of the beam source (the notation is the same as in Fig. 2). (a) 2—Profile measured during optimization of the experimental conditions; (b) 2—profile calculated for the experimental conditions.

$P_l = 8$ mW; all the measurements are carried out for atoms with a longitudinal velocity $v_{\|} = 3.8 \times 10^4$ cm/s at a low density, at which there are no collisions. From a comparison of curves 2 and 3 in Fig. 2(a) we conclude that the laser lens plots the "source" of atoms quite accurately. The width of the atomic beam beyond the image plane also agrees with the width of the atomic beam constructed from the geometric-optics equations. We have also carried out numerical calculations on the focusing of an atomic beam, for the particular laser field and for a finite dimension of the atomic beam. The profile of the atomic beam found from the results of these calculations is represented by curve 2 in Fig. 3(b). Curve 2 in Fig. 3(a) shows the beam profile after the beam has been focused during an optimization of the parameters of the laser lens. Comparison of the two curves leads to the conclusion that the wings of the profile can be attributed to the imperfections of the laser lens (spherical aberration).

In summary, the laser lens demonstrated in these experiments opens up the possibility of gaining control over such parameters of atomic beams as their density and divergence.

We wish to thank V. G. Minogin for useful discussions.

[1] V. I. Balykin, V. S. Letokhov, and V. G. Minogin, Ukrainian J. Phys. **14**, 117 (1985).
[2] W. D. Phillips (ed.), Laser-Cooled and Trapped Atoms (Vol. 8, Progress In Quantum Electronics), 1984.
[3] J. E. Bjorkholm, R. R. Freeman, A. Ashkin, and D. B. Pearson, Phys. Rev. Lett. **41**, 1361 (1978); Opt. Lett. **5**, 11 (1980).
[4] A. Ashkin and J. P. Gordon, Opt. Lett. **8**, 511 (1983).
[5] V. G. Minogin, Opt. Lett. **10**, 179 (1985).
[6] V. I. Balykin and A. I. Sidorov, Kvantovaya Elektron. (Moscow) **11**, 2001 (1984) [Sov. J. Quantum Electron. **14**, 1342 (1984)].
[7] V. I. Balykin, V. S. Minogin, Y. V. Rogdestvensky, and A. I. Sidorov, J. Opt. Soc. Am. B **2**, 1776 (1985).

Translated by Dave Parsons