The laser optics of neutral atomic beams

V. I. Balykin and V. S. Letokhov

The Institute of Spectroscopy, Academy of Sciences of the USSR, Troitsk, Moscow Region

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History. The radiative Force Acting on Atoms in a Resonant Light Field. Collimation. Focusing an Atomic Beam. Constructing an "Image" of a Source of Atoms. The Reflection of an Atomic Beam.

1. INTRODUCTION AND HISTORY

The interaction of electromagnetic radiation with matter enables one to control the motions of both photons and also of charged and neutral particles. This forms the basis of both photon optics (or the optics of light and x-ray beams) and also of particle optics (the optics of electron or neutron beams). There are profound analogies and similarities between them, but the interaction effects which form their bases are considerably different. It is probably that, under suitable conditions, each effect of the interaction of electromagnetic radiation with matter which affects the motion of a photon or particle can be used to create the elements of a suitable optics. This also applies to the pressure of light on neutral atoms, which can form the basis for creating the optics of neutral atomic beams that is described in the present paper.

Light pressure is a consequence of the classical Maxwell theory. In his fundamental investigation "*A Treatise on Electricity and Magnetism*", James Clerk Maxwell wrote: "... in a medium in which waves are propagated there is a pressure in the direction normal to the waves, and numerically equal to the energy in unit of volume."[1] Notwithstanding the small amounts of light pressure from ordinary light sources, it was experimentally detected by Peter Lebedev in Russia[2] and was later confirmed by E. F. Nichols and G. F. Hull in the U.S.A.[3] P. N. Lebedev also experimentally demonstrated the existence of light pressure on gases and predicted the possibility for its sharp increase under conditions of radiation resonance with atoms or molecules.[4] Albert Einstein's well-known paper,[5] in which he considered the question of light pressure fluctuations caused by atoms emitting and absorbing radiation in light quanta having discrete values of momentum, became the next important step. An experimental demonstration of momentum transfer from photons to a free atom was obtained in O. Frisch's paper,[6] in which the deflection of a beam of sodium atoms by the resonant radiation from a sodium lamp was observed.

The invention of the laser made available to researchers a fundamentally new source of intense, coherent light possessing high spectral brightness, monochromaticity, and high directivity of its radiation. The light pressure of laser radiation changed a barely observable phenomenon to a method for affecting the motions of atoms. New ideas and suggestions for controlling the motions of atoms by laser light appeared. Let us note only the most interesting among them. These are the suggestions for localizing and channeling atoms in a standing light wave,[7] the levitation of elementary particles at the focus of a laser beam,[8] and cooling of atoms[9] and ions,[10] and the localization of cooled atoms in a three-dimensional standing light wave.[11] The first experiments on the effect of laser light on the motion of atoms were also done soon: the focusing of atoms by a light pressure gradient force,[12] the slowing down of the longitudinal motions of atoms in a laser beam,[13] the monochromatization and temperature reduction of longitudinal motion to 1.5 K,[14] a further temperature reduction to 0.07 K[15] and the attainment of the limiting temperature predicted by theory[16] of 0.00025 K,[17] the resonant collimation of an atomic beam by means of its two-dimensional cooling,[18] the stopping of a beam,[19] and finally, the localization of atoms in magnetic[20] and optical traps.[21] These experiments already showed that a new, fairly powerful instrument for affecting the motions of atoms has presently appeared in the hands of physicists which, in principle, one could try to use to develop one more form of optics; the optics of neutral atomic beams.

The experiments that have already been performed on the collimation, focusing, and specular reflection of atomic beams which, as it appears to us, one may consider as the first steps on the way to creating the elements of the optics of neutral atomic beams, are discussed in this paper. It is easy to understand this by considering those forces which act on an atom in a resonant laser field.

2. THE RADIATIVE FORCE ACTING ON ATOMS IN A RESONANT LIGHT FIELD

We shall call the total force which arises upon the action of laser light on an atom the radiative force. Depending on the space-time structure of the light field, its intensity, and its wavelength, the radiative force may be a very complicated function of the atom's position and velocity. However, since all known papers on the use of light pressure forces have been done by using three forms of light fields or of combinations of them, a plane light wave, a Gaussian laser beam, and a standing light wave, we shall limit ourselves to consideration of only these types of fields. The theory of the motions of atoms in such fields is well developed at present (see the reviews in Ref. 22). We shall examine the behavior of the light pressure force in such fields only qualitatively.

2.1. A plane wave

Let us imagine a plane wave directed along the z axis whose frequency is tuned to resonance with the absorption frequency of an atom which is located in this wave. The atom absorbs laser photons directed along the z axis and re-radiates spontaneous photons symmetrically in all directions (see Fig. 1). As a result of this process, a radiative force

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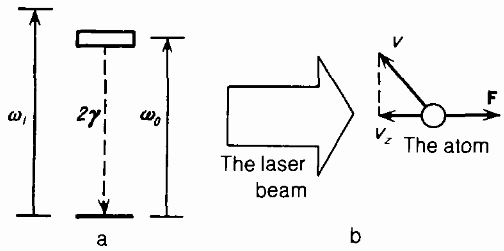

FIG. 1. An explanation of the occurrence of the resonant light pressure force of a plane wave on an atom. a) An ideal two-level diagram of the resonant interaction of waves with frequency ω_l and with the quantum transition at frequency ω_0 with the radiative damping rate 2γ for the population of the excited state, b) The orientations of the wave direction, of the light pressure force **F**, and of the velocity **v** of the atom.

whose maximum value is determined by the product of the momentum of a photon $\hbar k$ and the rate of photon scattering γ acts on the atom in the direction of the wave: $F_{max} = \hbar k\gamma$, where $k = 2\pi/\lambda$, and $\hbar$ is Planck's constant. If the atom is not in exact resonance with the laser radiation and has a velocity v_z projected onto the z axis in the direction of the light wave, then the light pressure force depends on the projected velocity and on the detuning of the field frequency ω_l from the absorption frequency ω_0 of the atom in the following manner:

$$F = \frac{\hbar k\gamma G}{\{1+G+[(\Omega - kv_z)^2/\gamma^2]\}}, \tag{1}$$

where $G = I/I_s$, I is the intensity of the wave, I_s is the saturation intensity of the atomic transition, and $\omega = \omega_l - \omega_0$. The acceleration of an atom under the action of this force reaches a magnitude of 10^8 cm/sec^2, which is 10^5 times greater than the acceleration of gravity.

2.2. A Gaussian beam

In a laser beam of limited diameter, besides the force considered along the laser beam, a gradient force caused by the transverse non-uniformity of the field (see Fig. 2) also acts on an atom.[23] The origin of this force is most simply understood from a classical examination of the interaction of an atom with a non-uniform field. An atom in a laser field acquires a dipole moment, and a non-uniform field exerts an effect on this dipole moment. Depending on the detuning of the laser radiation frequency with respect to the frequency of an atomic transition, this field either expels atoms from the beam ($\Omega > 0$) or pulls atoms towards the center of the beam ($\Omega < 0$). The gradient force depends on the atomic and laser parameters in the following manner:

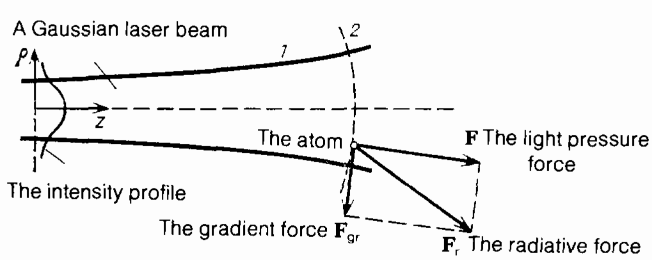

FIG. 2. A Gaussian light beam which, because its transverse intensity profile is nonuniform, produces a gradient force on the dipole moment which the intense light induces in the atom.

$$F_{gr} = \frac{\hbar\,(\rho/\rho_0^2)\,(\Omega - kv_z)\,G}{1 + G + [(\Omega - kv_z)^2/\gamma^2]}, \tag{2}$$

where ρ_0 is the radius of the laser beam, and ρ is the distance from the axis of the laser beam.

2.3. A plane standing light wave

This wave is formed from two plane waves traveling towards each other. At low radiation intensity ($G \ll 1$), the radiative force in a standing wave is determined by the sum of the forces from each traveling wave. Modulation of the laser field intensity with a period of $\lambda/2$ begins to show up with increasing radiation intensity, which leads to the appearance of the gradient force effect. Besides, at high intensity ($G \gg 1$), the stimulated processes of re-radiation of photons between two traveling waves by an atom exert an effect on the motions of atoms which, with spatial non-uniformity present in the field, lead to the so-called delayed component of the light pressure force.[24,25] This force arises during the motion of an atom in an intense, strongly nonuniform field, when the intensity of the field acting on the atom changes noticeably over the spontaneous decay time. The force exerts an effect on the motions of atoms with low velocities along the z axis: $v_z \sim k/\gamma$. Unlike the light pressure force, the delayed force in the traveling wave is not limited in magnitude and increases with increasing light intensity.

Let us now consider how one can use all the fields mentioned and the forces created by them to control the motions of atoms.

3. COLLIMATION

The need to collimate particle beams always arises when one needs to increase the phase density of particles, i.e., to compress the particles both over their velocities and also in space. Collimation (compression) of beams enables one to increase the accuracy of experimental research and the effectiveness of using particle beams. Different methods of solving the problem of collimating particles are used, depending on the kind of particles. The use of dissipative processes is general for them. For example, the radiative friction method is used for light charged particles, the electron cooling method is used for protons and antiprotons, and the ionization loss method is used for heavy particles.

The light pressure force of laser radiation is the most efficient dissipative force for neutral atomic particles. Two types of experiments on collimating atomic beams[9] by using the radiative force [Eq. (1)][26] and the delayed force[27] have been carried out at present. Each of the schemes has its advantages and drawbacks. By using the radiative force [Eq. (1)], it is possible to obtain smaller angular divergences for the atomic beams and, correspondingly, higher phase densities for the beams. Faster time collimation of a beam is an advantage of using the delayed force. However, the minimum collimation angle is larger in this case.

Let us consider in more detail collimation by using the force of Eq. (1). This scheme was first suggested in Ref. 28. An atomic beam (see Fig. 3) is irradiated from all directions by an axially-symmetric light field whose frequency ω_l is shifted redward with respect to the atomic transition frequency ω_0. The axially-symmetric field is formed by means of reflecting laser radiation from the inner surface of a conical reflection axicone. In the plane of Fig. 3 this field consists

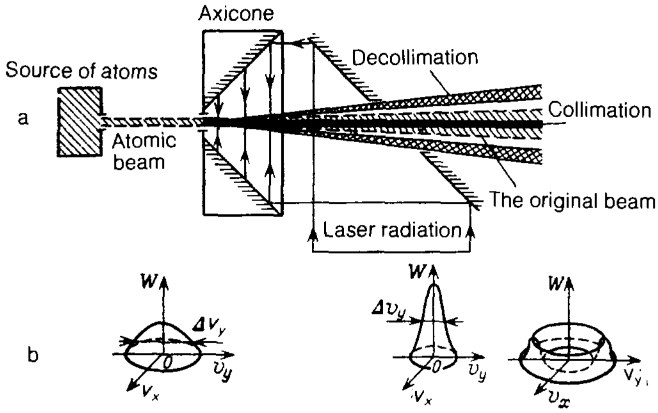

FIG. 3. The collimation of an atomic beam by a light field. a) An atomic beam passing through an axicone (a conical reflector) is irradiated from all directions by laser light whose frequency is detuned to the red with respect to the atomic transition frequency. The resulting light pressure force narrows the angular divergence of the atomic beam (see the atomic beam profiles in b). Detuning the laser frequency to the blue decollimates an atomic beam.

of two light waves moving towards each other whose intensities are the same at any point of space in the axicone.

In an axially-symmetric light field, a light pressure force acts on an atom having a transverse velocity $\mathbf{v}_\rho$; for $\omega_l < \omega_0$, the force is directed opposite to the radial velocity vector $\mathbf{v}_\rho$, and for $\omega_l > \omega_0$, it is directed along the vector $\mathbf{v}_\rho$. This direction of the light pressure force is caused by the fact that, because of the Doppler shift of the atomic transition frequency, an atom most efficiently absorbs photons from the wave which propagates towards the velocity vector $\mathbf{v}_\rho$. In turn, this means that, for $\omega_l < \omega_0$, the total force from the two waves is directed towards the atom's radial velocity vector. Thanks to the action of this force in the inner region of the axicone, for $\omega_l < \omega_0$ a rapid narrowing of the transverse velocity distribution occurs for the atomic beam leading to a reduction of the beam's angular divergence and to an increase of its density, i.e., to an increase of the degree of the beam's collimation. The combined action of radiative friction and of momentum diffusion leads to the establishment of a steady-state velocity distribution which determines a limiting collimation angle:

$$\Delta\varphi_{\min} = \frac{1}{v_z}\left(\frac{\hbar\gamma}{M}\right)^{1/2}, \tag{3}$$

where M is the mass of the atom and v_z is the velocity along the z axis. The limiting collimation angle for a thermal atomic beam is of order 10^{-3} to 10^{-4} rad. If the beam's initial divergence is 0.1 rad, then one can expect an increase of the beam's intensity at its center by 10^4 to 10^6 times.

An experiment on collimation was performed with sodium atoms.[26] The profiles of the atomic beam before and after interaction with a laser field are presented in Fig. 3b. The collimation process is very sensitive to the position of the laser radiation frequency. To achieve collimation, the laser radiation frequency has been detuned towards the red ($\omega_l - \omega_0 = -13$ MHz). The longitudinal velocity of the beam's atoms $v_z = 73{,}000$ cm/sec. A comparison of the profiles of the beam before and after its interaction with the field shows first, a significant increase (by five times) of the intensity of atoms at the beam's center, and second, the presence of significant narrowing (collimation) of the atomic beam. Significant beam broadening (decollimation) occurs upon shifting to positive frequency detunings. Here the intensity of atoms at the beam's center changes by over 10^3 times.

4. FOCUSING AN ATOMIC BEAM. CONSTRUCTING AN "IMAGE" OF A SOURCE OF ATOMS

In any kind of optics, one must be able to focus a particle beam of photons, electrons, or, in our case, of neutral atoms. Therefore, one must find out which laser field configurations are capable of achieving focusing for atomic beams. At least two possibilities exist for focusing an atomic beam. These are first, by means of the gradient force, and second, by use of the spontaneous light pressure force.

The possibility of focusing an atomic beam with the gradient force was first considered by colleagues at the Bell Telephone Laboratory.[29,30] In their scheme, the atomic beam propagates along and inside a narrow laser beam. The laser radiation frequency is tuned lower than the atomic transition frequency. In this case, the gradient force is directed towards the center of the laser beam. For a sufficiently long flight path for the atoms inside the beam, the atoms in its cross-section are constricted towards the axis of the laser beam. A maximum compression of the atomic beam is observed at some point. The minimum recorded size of an atomic beam was 26 μm.

The authors of Ref. 31 used another laser field configuration (see Fig. 4). In the general case, it consists of four

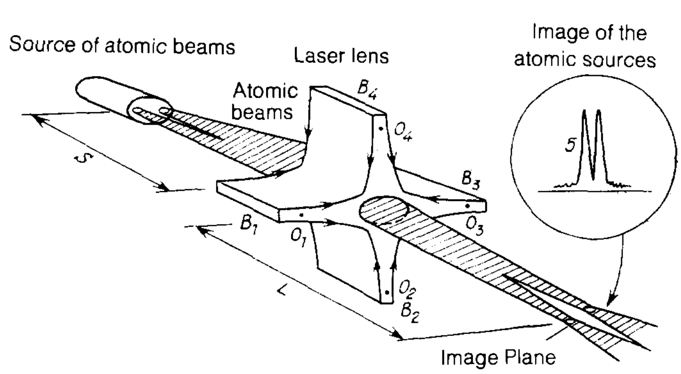

FIG. 4. Focusing and image construction with an atomic beam by means of laser light. Four diverging Gaussian beams irradiate an atomic beam, forming a "laser lens". Because of the fact that the wavelength of the radiation is in resonance with a particle moving along a trajectory off the axis, the beam is repelled back towards the axis so that the point of the source of the atoms is imaged at another point. The beam profile in the image plane 5 has a double peak corresponding to the image of the two slits of the atomic source.

diverging Gaussian beams propagating towards each other. The caustics of the beams are situated at the same distance from the center of the configuration. The laser frequency is tuned to resonance with the absorption frequency of the atoms. Under these conditions, a spontaneous light pressure force [see Eq. (1)] acts on an atom moving away from the axis of the atomic beam and returns the atom towards the axis of the beam.

The effect of the gradient force on the motion of an atom is insignificant in this case. Such a configuration is actually a "laser lens" for a beam of neutral atoms, since one can show that an atomic beam emerging from a point (analogous to a point source in the optics of light) is, after interaction with the laser field configuration under consideration, also focused to a point. Furthermore, one can obtain an expression for the focal distance of such a lens

$$F=\frac{v^2}{w^2 d}\left[\left(1+4G_0+\frac{\Omega^2}{\gamma^2}\right)G_0^{-1}\right], \tag{4}$$

and also an equation for a laser lens

$$\frac{1}{S}+\frac{1}{L}=\frac{1}{F}\left(1-\frac{d}{2L}\right), \tag{5}$$

where d is the thickness of the laser lens, S is the distance from the source of atoms to the lens, L is the distance from the lens to the image of the source, G_0 is the saturation parameter on the lens axis, $w=(8\hbar k\gamma l/M)(q_{0z}^2 l/b_z^2 q_z^2)$, l is the distance from the lens axis to the caustic of a laser beam, q_{0z} and q_z are the radii of the beams along the z axis at the lens axis and at the beam caustic, respectively. A laser lens is fairly localized in space: its characteristic size d along the beam axis is many times less than the distances S from the source to the lens and L from the lens to the image. Under these conditions ($d \ll S,L$), the equation (5) for the lens is the same as the equation for an optical lens.

The first successful experiment on focusing an atomic beam with a laser lens was done with a beam of sodium atoms.[31] The laser lens was formed by two Gaussian beams moving towards each other. Such a laser lens is similar to a cylindrical lens in the optics of light. Fig. 4 shows how one obtains an image of a "two-point source", which was an atomic gun with two apertures of 0.5 mm diameter with a 2 mm distance between them. Without a laser lens, the atomic beam profile was a broad, diffuse spot. After turning on the laser radiation and the formation of the laser lens on the paths of atoms, the trajectories of the atoms are subject to the laws of neutral beam optics. The beam profile in the plane of the image consists of two well resolved peaks, each of which corresponds to one of the sources of the atoms.

A significant drawback of the laser lens under consideration is that its resolution is not high enough (about 50 μm). The limitations on the resolution arise because of momentum diffusion, which smears the trajectory of an atom during its interaction with the field of the lens.

One can achieve a significant increase in resolution by returning to the idea of using the gradient force which is essentially potential in nature but using a different laser field configuration and geometry for the interaction of an atom with the field. The creation of an "atomic objective" with a resolution of several Angstroms is suggested in Ref. 32. Such an atomic objective is a rigidly formulated laser field with a TEM_{01}^* mode configuration whose frequency is fairly far detuned from the atomic transition frequency (see Fig. 5). The atoms propagate near the axis of the atomic objective. The strong focusing of the laser radiation forming the objective enables one to make its size sufficiently localized in space (a thin lens), and the choice of the TEM_{01}^* mode and the large detuning of the field frequency enable one to bring the char-

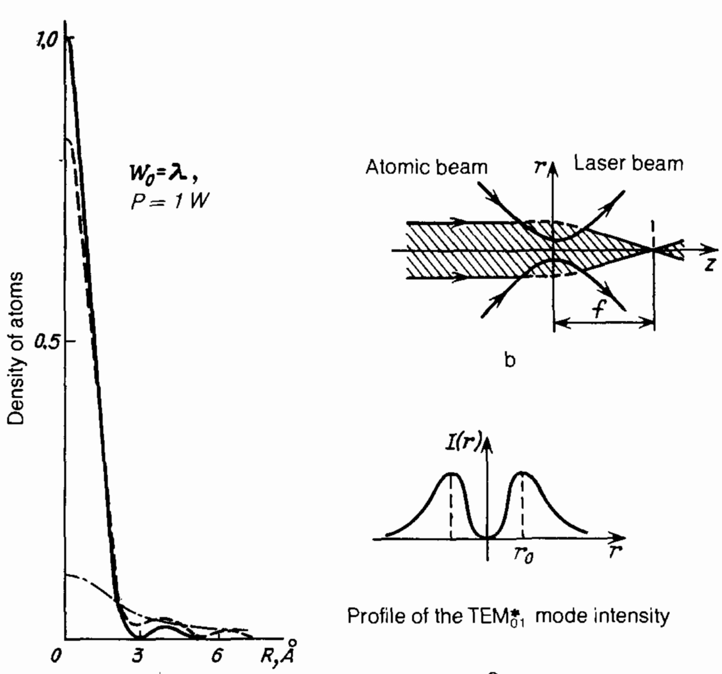

FIG. 5. a) A laser lens can focus atomic beams into a spot with a size of at most several Angstroms, which is confirmed by calculating the profile of an atomic beam. b) The focused atomic beam passes through the focused laser beam that is formed by the TEM_{01}^* mode. The radial intensity profile of the mode has a minimum at its center, as is shown in Fig. 5c.

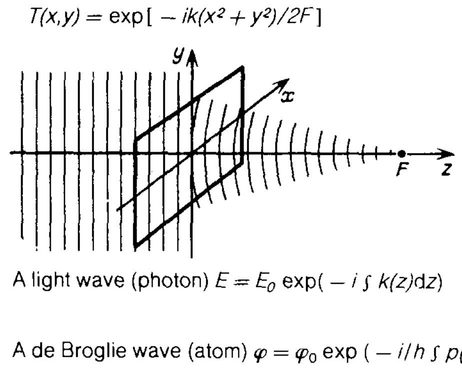

FIG. 6. An ideal objective for a light wave and de Broglie waves.

acteristics of the atomic objective close to the properties of an ideal lens.

In order to understand just what the resolution of such an atomic objective equals, one must consider the atomic beam in the form of de Broglie waves: $\psi = \psi_0 \exp(-i\hbar^{-1}\int p(z)dz)$ (see Fig. 6). These waves acquire a definite phase lead on the laser field $T(x,y)$, which leads to the subsequent focusing of them in the focal plane. The smallest spot into which one can focus an atomic beam is primarily determined by the diffraction of the de Broglie waves by the finite size of the atomic objective. However, besides this fundamental limitation on resolution, there exist more limitations on the limiting resolution because of different aberrations such as spherical and chromatic aberrations and, in addition to them, the diffusion aberration associated with the momentum diffusion of an atom in a laser field. Nevertheless, it turns out that one can choose the parameters of the laser field and the atomic beam such that, even with allowance for all the aberrations mentioned, the resolution does not differ greatly from the limiting diffraction resolution. For example, if one chooses the transverse size of the atomic objective equal to several wavelengths and the laser power equal to several hundred milliwatts, then the size of the atomic spot in the focal plane should not greatly exceed several Angstroms (see Fig. 5a).

5. THE REFLECTION OF AN ATOMIC BEAM

The mirror is another element of any optical system that is no less important than the lens. It can be used for both focusing and also for reflection. Focusing by means of a concave mirror has definite advantages in comparison with focusing by a lens; there is no chromatic aberration in the first case. That last property is especially significant for optics in which particle beams are used instead of light beams, since chromatic aberrations are especially large in the case of particle beams.

The idea of creating an atomic mirror was considered in Ref. 33. A layout for such an atomic mirror is presented in Fig. 7. It is formed by the very thin surface wave which arises upon the total internal reflection of a laser beam from a boundary separating a dielectric and a vacuum. The surface wave thickness can vary from fractions of to several wavelengths. The laser radiation intensity on the surface of the dielectric equals the intensity of the original laser wave in the dielectric, but the intensity in the vacuum decreases sharply, practically to zero at a distance of several wavelengths from the surface.

An enormous light intensity gradient, the maximum possible in optics, is created in such a surface wave. A gradient force pushing an atom out of the surface wave into the vacuum will act on an atom placed in a surface wave whose frequency is higher than an atomic transition frequency. But if an atom is incident on the surface wave from the direction of the vacuum, then its motion consists of a rectilinear trajectory section in the vacuum, of sharp slowing down in the surface wave leading to a decrease of the normal velocity component to zero, of subsequent acceleration in the wave in the opposite direction away from the surface, and finally, again a rectilinear section in the vacuum. Moreover, it turns out that the angle of incidence of the atom on the mirror equals its angle of reflection. A specular law of reflection is fulfilled only for atoms whose transverse velocities do not exceed some maximum velocity. The latter velocity is determined from the condition that the kinetic energy of an atom's transverse motion equals the height of the surface wave's potential barrier, and equals $v^{\perp}_{\max} = (2u_{\mathrm{gr}}(0)/M)^{1/2}$, where $u_{\mathrm{gr}}(0)$ is the height of the surface wave's potential barrier. If the atom's transverse velocity is greater than $v^{\perp}_{\max}$, then the atom reaches the surface of the dielectric and is then reflected diffusely from it. For typical parameters of continuous laser radiation with a power $P = 1$ W and, for example, a sodium atom with a thermal velocity $\bar{v} = 60{,}000$ cm/sec, the maximum transverse velocity $v^{\perp}_{\max} = 500$ cm/sec and, correspondingly, the maximum angle of reflection is $\alpha_{\max} = 0.01$ r;ad. With the use of beams slowed by laser radiation or of pulsed dye lasers, there are no limitations on the maximum angle of incidence; reflection is even possible with normal incidence of a beam on an atomic mirror.

Reflection from an atomic mirror was first observed in Ref. 34. The experiment was done with sodium atoms. The atomic mirror was a plane-parallel fused quartz plate into which laser radiation was introduced through a side slanted surface. Multiple total internal reflections of the laser beam were used to increase the surface of the atomic mirror. The arrangement of the reference, incident, and reflected atomic beams is shown relative to the atomic mirror on the left in

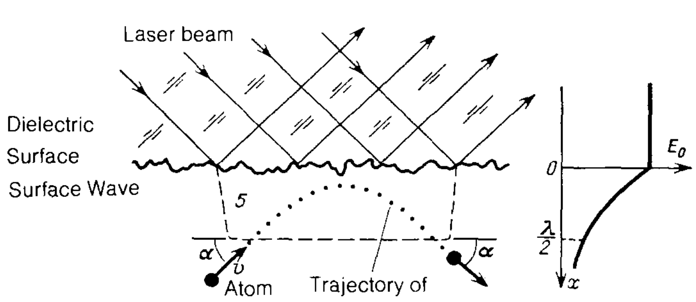

FIG. 7. An atomic mirror. A laser beam experiences total internal reflection from the internal surface of a quartz plate, forming a very thin surface light wave 5 outside the plate. The enormous gradient of the surface wave's intensity forms a gradient force sufficiently strong so as to turn around trajectories of atoms approaching the surface.

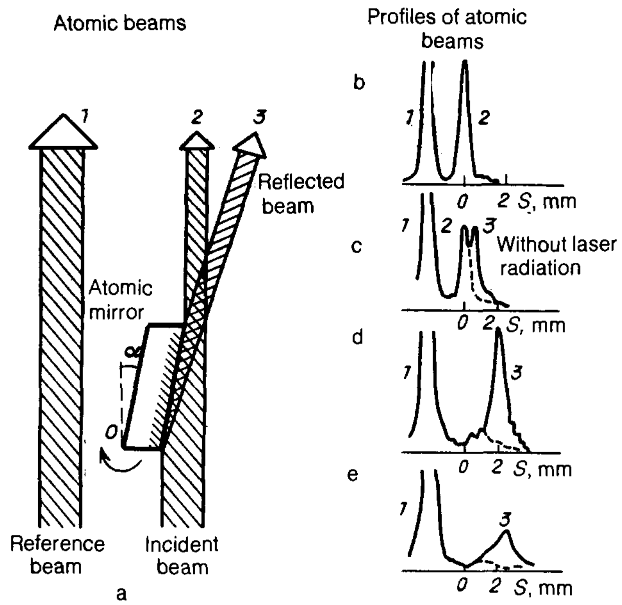

FIG. 8. The reflection of atomic beams. An atomic mirror a) similar to the one depicted in Fig. 7 was used to reflect an atomic beam. This mirror can be tilted with respect to the atomic beam. When the mirror does not overlap a beam b), the beam profile (on the right) has two peaks corresponding to the reference beam (1) and the undisturbed beam (2). By tilting the mirror, one can partially overlap the atomic beam, and then a peak (3) appears which corresponds to the specularly reflected atoms c). Upon further tilting of the mirror d), one can completely overlap the atomic beam and observe the reflected beam. For a very strong tilt, when the velocity of the atoms normal to the surface is too large, the coefficient of reflection decreases e).

Fig. 8; also shown are the corresponding recorded profiles of the atomic beams. When the atomic mirror is parallel to the axis of a beam and the atoms fly past the mirror, only the reference (Peak 1) and incident (Peak 2) atomic beams (on the right in Fig. 8b) are recorded. If one tilts the mirror so that it overlaps the atomic beam, then the beam's reflection is observed (Peak 3). For a further increase of the tilt angle, the angle of reflection also increases, but the number of reflected atoms decreases, since some of the atoms reach the surface of the mirror and are diffusely reflected. The maximum angle of reflection which was observed in the experiment was about 4 degrees. Here the mirror's coefficient of reflection approached 100%.

Its ability to reflect atoms selectively according to their quantum states is another remarkable property of an atomic mirror. This selectivity arises from the dispersive nature of the dependence of the gradient force on the laser radiation frequency: for positive detuning of the laser field frequency with respect to the absorption frequency of the atom, the gradient force repels atoms from the surface, and for negative detuning, it attracts them towards the surface, after which the atoms are scattered diffusely. Let us imagine that a beam in which the atoms are distributed over several sublevels of the ground state falls on an atomic mirror. Then the atoms which turned out to be in a sublevel for which the transition frequency to an excited state is lower than the laser frequency are reflected from the atomic mirror, and the remaining atoms are diffusely scattered. Thus, only the atoms which are in one quantum state will be present in the reflected beam. The selective reflection of the atoms in two sublevels of the hyperfine splitting of the ground state of the sodium

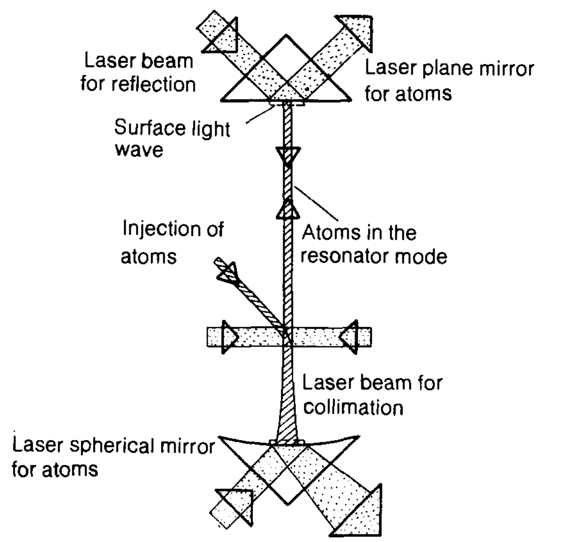

FIG. 9. A resonator for atoms that is formed by plane and spherical laser-induced mirrors.

atom was observed in the experiment of Ref. 35. The ratio of the coefficients of reflection for the $F = 2$ and $F = 1$ sublevels (selectivity of reflection) was at least 100.

Let us notice that one can expect a similar selective reflection for molecules too. The possibility also to obtain spectroscopy of a beam of molecules in a single specified vibrational-rotational state is opened up in this case.

Let us also notice the possibility for creating spherical atomic mirrors and resonators for atomic de Broglie waves that are based on them.[36,37] One of the possible configurations of an atomic resonator is shown in Fig. 9. Its layout is similar to an optical resonator with material mirrors replaced by light-induced mirrors. The introduction of atoms from an external source by using laser collimation of the atomic beam being introduced is a possible mechanism for injection of the atoms into such a resonator (see Fig. 9). The maximum steady-state density of atoms in the resonator will be determined by the rate of injection of atoms into the resonator and by the time an atom stays in the resonator. The amount of degeneracy, which equals the number of photons in the resonator's mode, is one of the basic parameters which characterizes the light field in an ordinary light resonator. The degeneracy parameter is very large for the radiation of a laser. Estimates show[36,37] that, in principle, the creation of a light-like resonator for de Broglie atomic waves enables one to reach a high degeneracy of atomic waves for a comparatively low density of atoms (about 10^9 atoms/cm^3) and a moderate rate of injecting them into the resonator (about 1,000 atoms/sec). However, to inject atoms, one needs them in a narrow solid angle and with a sufficiently high degree of velocity monochromaticity $v/\Delta v$, when the longitudinal coherence length of an atomic wave

$$l_{\text{ког}} \approx \lambda_{\text{Б}} \frac{v}{\Delta v} \qquad (6)$$

(where λ_{DB} is the de Broglie wavelength) is considerably larger than the size of an atom. For example, for $\lambda_{\text{DB}} = \lambda(v_{\text{sep}}/v) = 2\pi\hbar/Mv \approx 1\,\text{Å}$ and $\Delta v/v \approx 0.001$ of the atomic wave coherence length $l_{\text{coh}} \approx 1000$ Å. It is such a large size for l_{coh} combined with the small divergence of the atomic beam that enables one in principle to achieve degeneracy of the atoms in the resonator for moderate densities of them.

7. CONCLUSION

Notwithstanding the fact that essentially only the first experiments on affecting the motion of atoms have been done, nevertheless one can already say now that a fundamentally new method for controlling different parameters of atomic beams has appeared in the hands of researchers. With further development of laser technology, not only the improvement of the main elements considered of the optics of neutral atomic beams, but also the transition to molecular beams is possible. Some possible uses of the optics of neutral atomic beams are clear even now. The collimation of atomic beams enables one to change the spatial parameters of atomic beams, to reduce their divergences, and to increase the density of atoms in phase space,and moreover, one can achieve all these effects with isotopic selectivity for the elements of the periodic table. Besides increasing the density of atoms, the most interesting use of focusing atomic beams is the possibility of building an atomic scanning microscope. It is easy to imagine the layout of such a microscopy; it may be similar to an electron scanning transmission or reflection microscope. One can record scattered or reflected atoms by well developed laser methods of detecting single atoms.

One can use atomic mirrors as high-speed deflectors, modulators, and shutters for neutral atomic beams, and also to create traps for ultracold atoms. One can use concave atomic mirrors as the elements of an atomic microscope since, because of the short time of interaction of the atoms with the laser radiation, momentum diffusion does not hinder the focusing of beams over distances that are comparable with the de Broglie wavelength. Atomic beams sharply focused into spots with sizes of a few Angstroms enable one to observe the collision of atoms with each other and to investigate their scattering each other under highly controlled conditions. The extension of this method to molecular beams will be especially interesting, since this will enable one to penetrate deeper into the dynamics of molecule interaction.

We have limited ourselves in this paper basically to a discussion of new possibilities for laser "geometric" optics of atomic beams. The cases of the in-depth focusing of de Broglie atomic waves,when allowance for their diffraction was fundamental, and of the atomic resonator with laser-induced mirrors, in which atomic waves interfere, were exceptions. Naturally the development of "wave" laser optics for atomic beams, where the effects of diffraction and interference of atomic waves play the main role, is the next stop. Several experiments[38–41] on the diffraction and interference of atoms have already been done in this direction, and one can foresee obtaining interesting and unexpected results.

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