Radiative collimation of atomic beams through two-dimensional cooling of atoms by laser-radiation pressure

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The transverse cooling of a beam of sodium atoms in an axisymmetric light field formed by a reflecting axicon is studied. It is shown that transverse cooling leads to a decrease in angular divergence (collimation) of the atomic beam. The transverse velocities of the beam are reduced from 5.5×10^2 to 1.6×10^2 cm/sec, which corresponds to the decrease in effective transverse temperature of the beam from $T = 42$ to $T = 3.3$ mK. The spatial and velocity distributions of the atomic beam are calculated numerically. It is found that theory and experiment are in good agreement.

INTRODUCTION

There is great interest in methods of controlling the motion of neutral atoms by laser-light pressure.[1,2] For many physical applications, radiative cooling of atomic beams is of particular interest. This permits atomic beams to be produced that have an effective temperature 3 or 4 orders lower than that of the atomic-beam source. In recent years a number of experiments have been carried out in which different approaches to the problem of atomic-beam cooling are realized. Atomic-beam deceleration by laser-radiation pressure was first reported in Ref. 3. The experiments demonstrated a possibility of pulsed deceleration of atomic beams by scanning the laser frequency synchronously with the reduction of the atomic-beam velocity. Another method of radiative deceleration of atomic beams, which provides stationary flows of cold atoms, consists of illuminating an atomic beam by resonant high-intensity laser radiation with a fixed frequency tuned within the atomic-beam absorption line. The application of this method made it possible to make a sodium atomic beam monochromatic to an effective temperature of 1.5 K.[4] A further development of the method of continuous tuning of the laser frequency to the resonant transition frequency permitted deceleration of a sodium atomic beam to an effective temperature of 0.07 K.[5] The production of a stationary high-intensity flow of cold atoms was investigated in Ref. 6. In Ref. 7 it was reported that the technique of laser-frequency scanning permitted observation of both the deceleration of an atomic beam and the turning back of cold atoms.

All the experiments referred to were concerned with the action of laser-light pressure on the longitudinal atomic velocities in a beam. However, at a certain stage of longitudinal cooling of an atomic beam the transverse atomic velocities become comparable with the longitudinal velocities. For this reason, to achieve deep cooling of atoms one must solve the problem of transverse (two-dimensional) cooling of the beam. Transverse cooling of the beam in its turn is closely related to beam collimation because it results in a decrease not only of the transverse atomic velocities but also in the beam diameter. Consequently, the transverse cooling of atomic beams by the light pressure helps in solving the problem of the collimation of neutral atomic beams.

The problem of the collimation of particle beams is at present only partially solved in experimental physics. The collimation of charged-particle beams, for example, has found many applications in experimental physics, but, at the same time, we do not know yet how to collimate neutral-particle beams. Many experiments now deal with particle beams, and their results depend to a great extent on the degree of beam compression in both the coordinate and momentum spaces. The measure of compression of beams in a six-dimensional-coordinate space is determined by the phase-space density $\theta(\mathbf{r}, \mathbf{v})$. Experimentally the most important points are the spread of the transverse coordinates and the momenta of the beams. The degree of beam collimation is usually characterized by the product of the transverse dimension of the beam and its transverse dimension in the momentum space. Consider some examples of collimation of charged-particle beams.

The collimation of charged-particle beams is now a well-elaborated problem in nuclear physics.[8] The motion of charged particles is controlled by magnetic and electric fields. These fields enable one to accelerate or decelerate particles and to focus them into given points. The forces that control the motion of charged particles derive from potentials. Accordingly, for these forces the Liouville theorem, according to which the phase volume of particles is independent of time and is invariant of motion, is valid. In a different formulation the Liouville theorem states that the density of particles in a phase space is a constant defined by the initial conditions. The potential forces thus can only change the shape of the phase volume of the beam; they cannot change its value or increase the phase density. The phase density can be increased only by dissipative forces that are responsible for the transfer of energy from some of the particles to an external system.

There are several ways of compressing charged-particle beams on the bases of dissipative forces.[9] For light particles

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(electrons, positrons) the radiative-friction technique is used. Protons and antiprotons are compressed by using the electron-cooling method. The ionization-loss technique is used to compress heavy particles. In the radiative-friction technique the loss of some energy of the particles increases the degree of particle collimation. This is so because of the radiative deceleration of the particles in external electromagnetic fields. This method can be applied at high energies of low-mass particles. In the electron-cooling method the collimation is obtained as a result of an energy exchange between the proton (antiproton) beam and the cold electron gas because of their Coulomb collisions. In the ionization-loss method the mechanism of energy dissipation is similar to that in electron cooling.

The degree of particle compression of the beams is characterized by two basic parameters: an increase in phase density and a decrease in transverse temperature. In the method of electron cooling the phase density of protons may be increased by 10^8 and the transverse temperature decreased by 10^2 times.

In the case of neutral-atom beams the introduction of dissipative forces (the light-pressure force, for example) is also necessary for collimation. This idea was analyzed first in Ref. 9. It was shown that the irradiation of an atomic beam by an axisymmetric light field could provide collimation. The collimation scheme was experimentally demonstrated in Ref. 10. The tentative estimates[10] showed that a beam of Na atoms was transversely cooled to a temperature of a few millikelvins.

It should be noted that the possibility of decreasing transverse velocities with the use of laser radiation was pointed out in Ref. 11.

The present paper contains the results of studies of the collimation of a thermal beam of Na atoms based on transverse cooling of atoms by resonant laser-radiation pressure.

QUALITATIVE CONSIDERATION

The scheme of atomic-beam collimation that we studied is shown in Fig. 1a. The atomic beam (2) coming out of the source (1) was irradiated by an axisymmetric light field with a frequency ω that was red shifted from the atomic-transition frequency ω_0. The axisymmetric field was formed by the laser radiation (3) being reflected from the conical mirror surface of a reflecting axicon (4).

In the axisymmetric field formed by the reflecting axicon, an atom having the transverse velocity $\mathbf{v}_\rho = \mathbf{v}_x + \mathbf{v}_y$ is acted on by a light-pressure force that for $\omega < \omega_0$ is directed opposite the velocity vector v. Such a direction of the light-pressure force is due to the field structure inside the axicon. An atom moving at some angle to the axis of the axicon interacts in the x–y plane with two counterpropagating light waves whose intensities are the same at any space point.

In the atomic rest frame one of the waves has the frequency $\omega - kv_\rho$; the other wave has frequency $\omega + kv_\rho$. Since the laser-radiation frequency is smaller than the atomic-transition frequency ($\omega < \omega_0$), the atom absorbs photons more effectively from the wave propagating antiparallel to the radial velocity vector v_ρ. This means that the light-pressure force reduces the radial velocity $\mathbf{v}_\rho$. The transverse velocity distribution of the atomic beam inside the axicon is thus narrowed by the light-pressure force. Because of this the

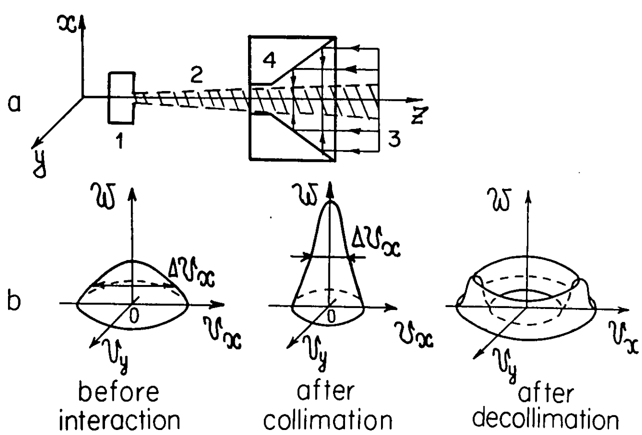

Fig. 1. The scheme of radiative collimation of an atomic beam. a: 1, Source of atoms; 2, atomic beam; 3, collimating radiation; 4, exicon. b: Velocity-distribution narrowing by collimation.

angular beam divergence is decreased and the atomic density is increased, i.e., the degree of atomic-beam collimation increases. The characteristic time of atomic-beam collimation can be estimated from the equation of atomic motion. In the field of two counterpropagating waves the atom is acted on by a light-pressure force that, in a rate-equation approximation, has the form[12,13]

$$\mathbf{F} = \hat{e}_\rho \hbar k \gamma G(L_+ - L_-)/[1 + G(L_+ + L_-)]. \tag{1}$$

Here $L_\pm$ are the Lorentzian functions of radial velocity:

$$L_\pm = \gamma^2/[(\Omega \pm kv_\rho)^2 + \gamma^2],$$

where $\hat{e}_\rho$ is a unit vector in the x–y plane, $G = z(dE_0/\hbar\gamma)^2/2\rho$ is the saturation parameter, d is the matrix element of the atomic-dipole moment, 2γ is the natural line width, $\Omega = \omega - \omega_0$ is the detuning of the radiation frequency ω about the atomic transition frequency ω_0, and $\rho = (x^2 + y^2)^{1/2}$. For small velocities $v_\rho \ll |\Omega|/k$, the force [Eq. (1)] is

$$\mathbf{F} = -\beta m \mathbf{v}_\rho, \tag{2}$$

where

$$\beta = \frac{4\hbar k^2}{m}\left|\frac{\Omega}{\gamma}\right| G(1 + \Omega^2/\gamma^2)^{-1}(1 + \Omega^2/\Omega^2 + 2G)^{-1} \tag{3}$$

is the dynamic friction coefficient.

The equation of atomic motion under the frictional force [Eq. (2)] shows that the characteristic time of transverse velocity distribution narrowing is given by the quantity $\tau_c = \beta^{-1}$. With the typical parameters $|\Omega|/\gamma = 2$ and $G = 1$ the characteristic collimation time is $\tau_c \simeq 2 \times 10^{-5}$ sec. If the time of flight of atoms through the axicon exceeds β^{-1}, the atomic ensemble evolution in the axicon field is determined not only by the radiation pressure but also by the diffusion of atomic momenta. The joint action of the radiation pressure and diffusion leads to the establishment of a stationary atomic velocity distribution with the effective temperature

$$T_{\min} = \hbar\gamma(\gamma/|\Omega| + |\Omega|/\gamma)/2k_B, \tag{4}$$

where k_B is the Boltzmann constant. Using this value of temperature, one can find the angle of atomic-beam collimation at the axicon outlet:

$$\Delta\varphi_{\min} = (2k_B T_{\min})^{1/2}/\bar{v}_z m^{1/2} = (\hbar\gamma/m)^{1/2}/\bar{v}_z. \tag{5}$$

Here $\bar{v}_z$ is the average atomic velocity along the beam axis. For a thermal atomic beam the minimum collimation angle ranges from 10^{-3} to 10^{-4} rad.

This value of the collimation angle characterizes the beam divergence at the axicon outlet. Inside it the divergence is weaker because it is determined not by a free flight of atoms but by a slow diffusion broadening of the beam. The corresponding ultimate collimation angle at the distance l from the point where the atoms enter the axicon is[9]

$$\Delta\varphi_{\mathrm{min}}' = \lambda(\gamma/e\bar{v}_z)^{1/2}. \tag{6}$$

For an atomic beam irradiated by a light field with the interaction length $l = 10$ cm the collimation angle is $\Delta\varphi_{\mathrm{min}}' = 10^{-4}$–$10^{-5}$ rad. Thus the estimate shows that the use of an axicon permits a considerable collimation of an atomic beam. The atomic density can be increased on account of beam collimation $[(\Delta\varphi_{\mathrm{init}}/\Delta\varphi_{\mathrm{fin}})^2 \simeq 10^6$ rad] when beams with the initial divergence $\Delta\varphi_{\mathrm{init}} \simeq 1$ rad are used. The phase density in this case may be increased $[(\Delta\varphi_{\mathrm{init}}/\Delta\varphi_{\mathrm{fin}})^4 \simeq 10^{12}$ rad].

SCHEMES OF CYCLIC ATOMIC INTERACTION WITH RESONANT RADIATION

We have examined two possible schemes for excitation of Na atoms by laser radiation. In one scheme the radiation is resonant with the transition $3S_{1/2}$–$3P_{1/2}$ (Fig. 2); in the second one, to the transition $3S_{1/2}$–$3P_{3/2}$ (Fig. 3).

The ground state of the Na atom is split into two hyperfine-structure sublevels. Because of this we used two-mode laser radiation to excite the atoms. The frequency interval between laser modes was equal to the hyperfine-structure interval of the ground state of the Na atom. Two different excited sublevels were chosen to be upper levels in order to avoid coherent population trapping at the sublevels of the ground state.[14] Thus we used four-level schemes of atom–radiation interaction.

For effective collimation of an atomic beam it is necessary that the laser-radiation frequency be red shifted from the transition frequency by several units of natural linewidth. Therefore the use of the scheme given in Fig. 2 seems to be preferable to using the scheme in Fig. 3 since the distance between the sublevels of the $3P_{1/2}$ state exceeds that between the sublevels of $3P_{3/2}$. However, the transition $3S_{1/2}$–$3P_{1/2}$ cannot be used for cyclic ineraction of Na atoms with laser radiation (Fig. 2a). The atom, excited by linearly polarized light by optical pumping, reaches the sublevels $F = 1$, $m_F = 0$ and $F = 2$, $m_P = 0$ and ceases to interact with the radiation. When the atoms are excited by circularly polarized radiation, the states $F = 1$, $m_F = 1$ and $F = 2$, $m_F = 2$ become the trapping sublevels.

Analysis of different possibilities for the D_2 line has shown that there are transitions between pairs of sublevels that can be used to collimate the atomic beam; for example, the transitions $F = 1 \rightarrow F' = 2$ and $F = 2 \rightarrow F' = 3$ (Fig. 3). The considerations stated above were thus checked. The dependence of the fluorescence signal from a beam of Na atoms excited according to the schemes in Figs. 2a and 3a was measured as a function of the laser-radiation power (Fig. 4). The measurements showed that for the laser-radiation intensity $I = I_{\mathrm{sat}}$, saturation of the fluorescence intensity takes place for the transition $3S_{1/2}$–$3P_{1/2}$ (curve 1). This indicates optical pumping of the atoms to the trapping sublevels.

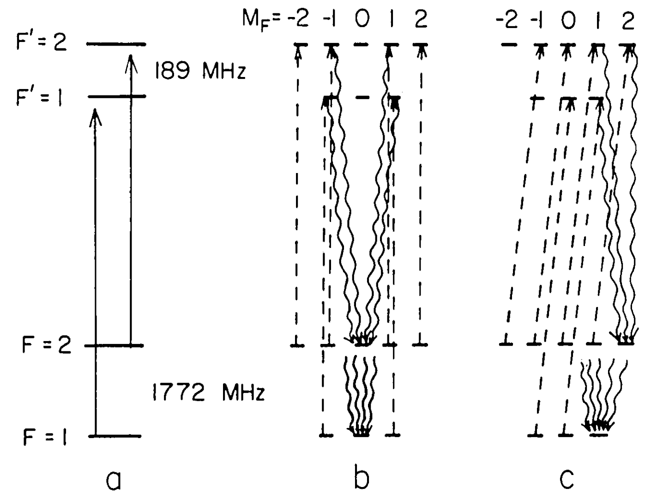

Fig. 2. Structure of the D_1 line of a Na atom. a, The mode frequencies red shifted about the transition frequencies. b, The transitions between the magnetic sublevels of the ground and excited states for the case of linearly polarized laser radiation. c, The case of circularly polarized radiation.

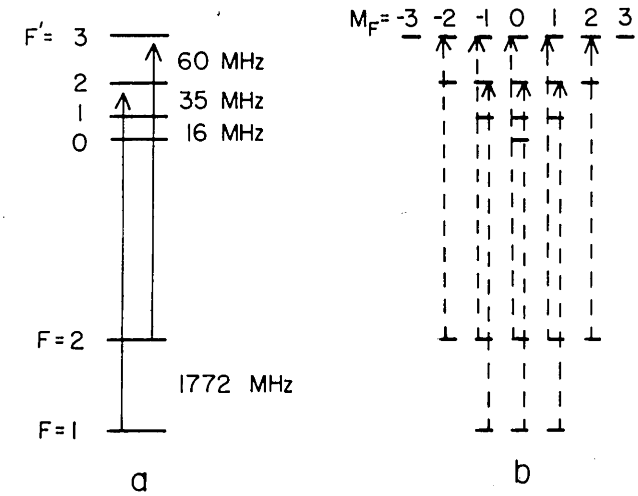

Fig. 3. The structure of the D_2 line of a Na atom. a, The mode frequencies red shifted about the transition frequencies. b, The transitions between the magnetic sublevels in the case of linearly polarized laser radiation.

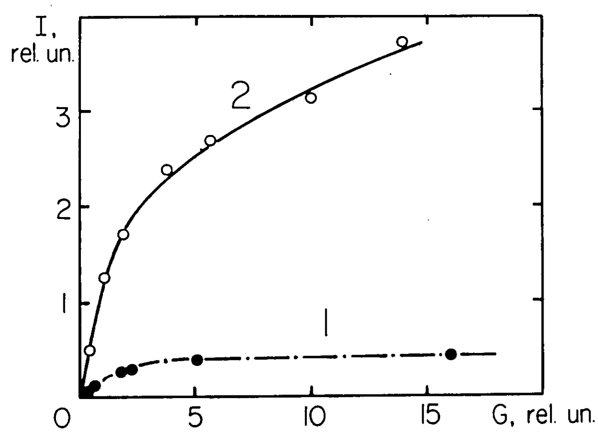

Fig. 4. The dependence of the fluorescence signal of Na atoms excited by the schemes in Fig. 2 (curve 1) and Fig. 3 (curve 2) on laser-radiation intensity. $G = I/I_{\mathrm{sat}}$. I_{sat} is the atomic-transition saturation intensity.

The behavior of curve 2 is different. This curve agrees well with the dependence of the fluorescence intensity of a two-level atom on the intensity of excitation by single-frequency laser radiation.[15]

EXPERIMENTAL SCHEME

Figure 5 shows the experimental setup schematically. It consists of the following basic elements: a source for the atomic beam, a reflecting axicon, two dye lasers, a mechanical modulator for the laser radiation (M), photomultipliers (PM's), and a reflecting prism (P). The beam of Na atoms was shaped with two 1-mm-diameter diaphragms. One of them was placed near the aperture of the atomic oven and the other 14 cm from the oven. The initial beam divergence was $\Delta\varphi_0 = 1.4 \times 10^{-2}$ rad. The axicon was placed 2 cm from the second diaphragm. The length of the atom–radiation interaction inside the axicon was 35 cm. The distance from the atomic oven to the detection zone was 52 cm.

The radiation of the two-frequency laser (laser 1 in Fig. 5) was used to collimate the atomic beam.[16] The frequency difference between the axial modes was 1712 ± 2 MHz, and the atoms were exited according to the scheme shown in Fig. 3. The radiation was directed inside the axicon by using a telescope with two lenses. The lens placed near the axicon had a hole for the atomic beam to pass through. Part of the two-frequency laser radiation crossed the atomic beam at an angle of 90° and was used for absolute calibration of the frequency scale.[17]

The atomic-beam density profile was measured by detecting the fluorescence induced by the single-mode dye laser (laser 2). For this purpose the radiation focused by a long-focus lens crossed the atomic beam (Fig. 5) at an angle of 10°. The diameter of the laser beam was essentially smaller than the diameter of the atomic beam. In the plane perpendicular to that of the figure the laser beam traveled parallel within several diameters of atomic beam owing to the rotation of a lens (M) fixed to the mechanical chopper. The probing laser frequency was tuned to the frequency of the atomic transition $3S_{1/2}$–$3P_{3/2}$. The length of interaction of the probe field with the atomic beam seen by the photomultiplier cathode was 1 mm. Thus the atomic-beam profile was measured as a function of its radius. The measuring

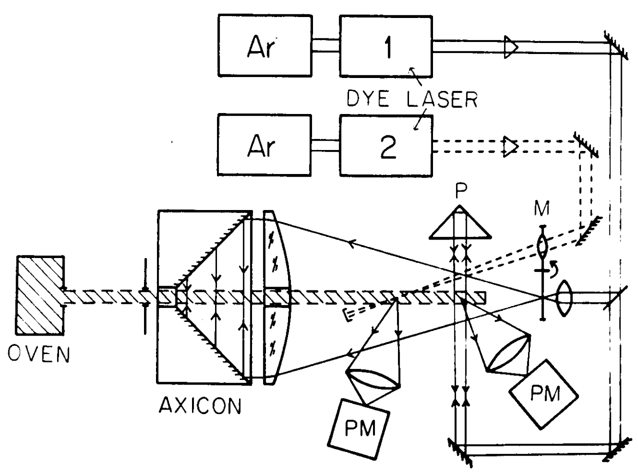

Fig. 5. Scheme of an experimental setup for radiative collimation of atomic beam: 1, two-mode dye laser; 2, probe single-mode laser; PM's, photomultipliers; P, prism; M, mechanical modulator.

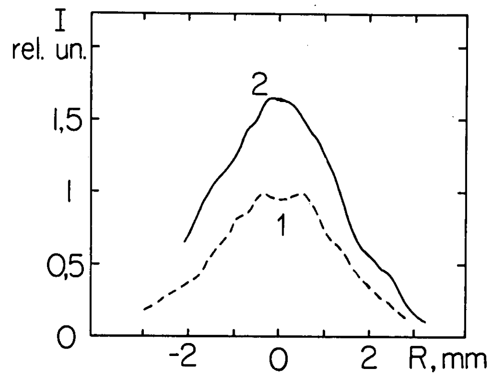

Fig. 6. Detection of the spatial distribution of an atomic beam exposed to single-mode radiation in an axicon. The beam is not narrowed (no collimation). An increase in signal is due to optical pumping to the sublevel $F = 2$.

time of the transverse distribution of the atoms was $\tau_d = 150$ μsec.

It should be noted that the method used for laser probing of the atomic beam's spatial distribution has some advantages over the conventional hot-wire method. First, it permits measurements to be made in a short time; second, it makes it possible to measure the atomic-beam collimation as a function of the longitudinal atomic velocity; third, it makes it possible to measure directly the intensity of atoms in a beam as a function of its radius. The shortcoming of the method is that it measures the spatial distribution not of all the atoms in the beam but only of the atoms at a certain sublevel of the ground state ($F = 1$ or $F = 2$ in our case), the population of which can vary during their interaction with an intense field.

The true distribution was determined by measuring the populations at the both hyperfine-structure sublevels $F = 1$ and $F = 2$. Control measurements were also carried out for the spatial distribution of the atomic beam when only one mode of the intense field was tuned to resonance with the transition $F = 1 \rightarrow F' = 2$ and the second one was off resonance with the transition $F = 2 \rightarrow F' = 3$ (Fig. 6). Because of the absence of atom–radiation cyclic interaction the collimation efficiency in this case is low, and the only result of the action of the intense field is optical pumping, that is, the transfer of almost all the atoms to the sublevel $F = 2$. This causes the fluorescence signal from the probe field to increase. The spatial distribution detected in this case is similar to the initial one and differs from the latter by increasing beam intensity in the ratio of the population of atoms at the both sublevels to the population at the sublevel $F = 2$, which, according to the statistical weights of the sublevels, is $[(2F_2 + 1) + (2F_1 + 1)]/(2F_1 + 1) = 1.6$.

Only the spatial distribution of the atomic beam was detected in the experiment. It was impossible to measure the velocity distribution since for the initial beam collimation the Doppler width of the absorption line was equal to the homogeneous width $\Delta\omega_{\mathrm{Dop}} = kv_\rho \simeq \gamma$.

EXPERIMENTAL RESULTS

Figure 7 shows the dependence of the atomic-beam transverse profile before and after interaction with the laser field. The laser power was 45 mW. The frequency detuning $\Delta\nu$ for

Mechanical Effects of Light

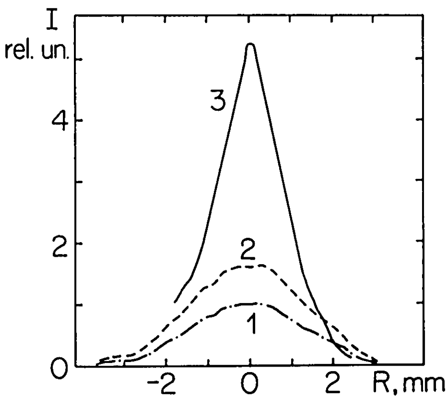

Fig. 7. Atomic-beam collimation by laser radiation. Curves 1 and 2 denote the spatial distribution of atoms at the sublevel $F = 2$ and at the both sublevels, respectively; curve 3 is the distribution of atoms in a beam after it is irradiated by laser field.

the curves given in Fig. 7 was chosen so that the collimation was maximum. As shown below, the optimal detuning for the chosen value of initial divergence varies in the range $\Delta\nu = \gamma$–4γ with radiation power.

The atomic-beam profile was measured in the experiment for the sublevels $F = 2$ and $F = 1$. Curve 1 shows the beam profile at the sublevel $F = 2$, and curve 2 shows it for the atoms at the sublevels $F = 1$ and $F = 2$ before their interaction with the laser field.

It must be said that measurement of the profile only at the sublevel $F = 2$ is sufficient to measure the atomic-beam profile after the interaction. This can be easily understood from Fig. 3. With both laser frequencies red shifted ($\Delta\nu \simeq \gamma$), all the atoms after their interaction with the field in the axicon reach the sublevel $F = 2$ since from the sublevel $F' = 3$ they can go only to $F = 2$ and from $F' = 2$ they can go both to $F = 2$ and to $F = 1$. The measurements show that more than 95% of all the atoms are located at the sublevel $F = 2$. Thus the true beam profile can be attained with high accuracy from the measurements at the sublevel $F = 2$.

The comparison of the beam profiles before and after interaction with the radiation shows that, first, the number of atoms in the center of the beam increases considerably (3.5 times). Second, the beam becomes narrow (collimated). The measurements of the beam diameters before and after interaction with the radiation, with the dimension of the probe-beam diameter taken into account, made it possible to estimate the variations of the transverse velocity of atoms during their collimation. In the case illustrated in Fig. 7 the transverse velocity decreases from 5.5×10^2 to 1.6×10^2 cm/sec. This fact shows that the temperature of transverse motion decreases from 42 to 3.5 mK.

As follows from expression (4), the atomic-beam collimation is very sensitive to the position of the laser-field frequency relative to the atomic-transition frequency. We measured the intensity of atoms in the center of the beam as a function of the collimating laser-field frequency (Fig. 8). The figure shows that at negative detunings the beam is collimated and, on the contrary, at positive detunings it is decollimated. Such behavior of the curves indicates that the observed effect is interpreted correctly since the light-pressure force changes its sign with the detuning $\Omega = \omega - \omega_0$. In addition to the light-pressure force, the atomic motion can be affected by the gradient force that was used at high-power values for focusing the atomic beams.[17] The estimations showed that its influence in the experiment under consideration was negligible.

It should be noted that for every value of laser power there is an optimal value of collimating-field frequency. According to Ref. 12, the laser-frequency detuning optimal for atomic cooling depends on the intensity as $\sim\gamma(1 + G)^{1/2}$. Figure 9 shows an experimental dependence of the optimum detuning on laser-radiation intensity. This curve is similar to the dependence $\sim G^{1/2}$.

The case of atomic-beam decollimation is shown in Fig. 10. Curve 2 shows the transverse distribution of the atomic beam before its interaction with the laser field. Curve 3 shows its transverse distribution after interaction. Curve 1 denotes the transverse distribution at the sublevel $F = 2$ (without field).

The degree of atomic-beam collimation depends on the time of interaction with the laser radiation and accordingly on the longitudinal atomic velocity v_z. The collimation efficiency was measured in the experiment as a function of

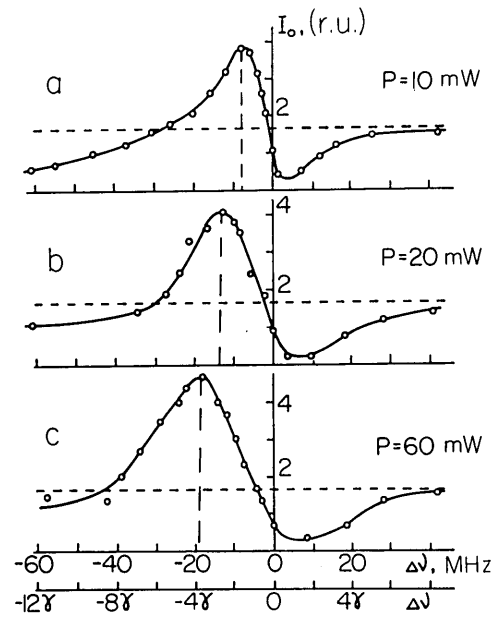

Fig. 8. The dependence of the atomic intensity in the center of an atomic beam on laser-frequency detuning at different values of the collimating laser power.

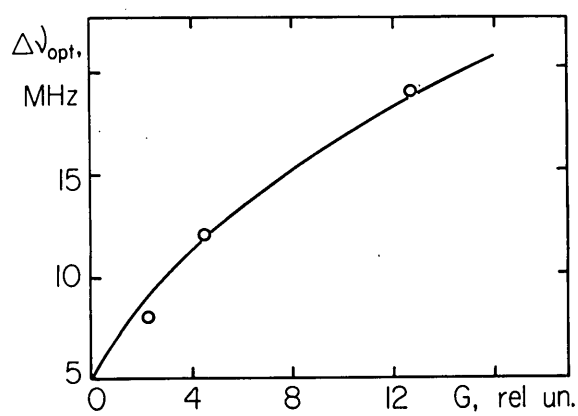

Fig. 9. The dependence of the optimal detuning of collimating laser frequency on laser intensity.

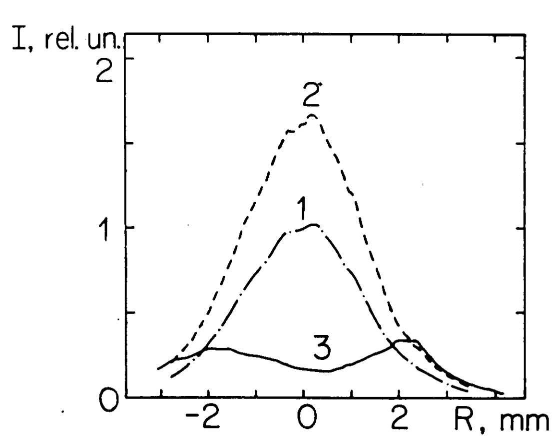

Fig. 10. Atomic-beam decollimation.

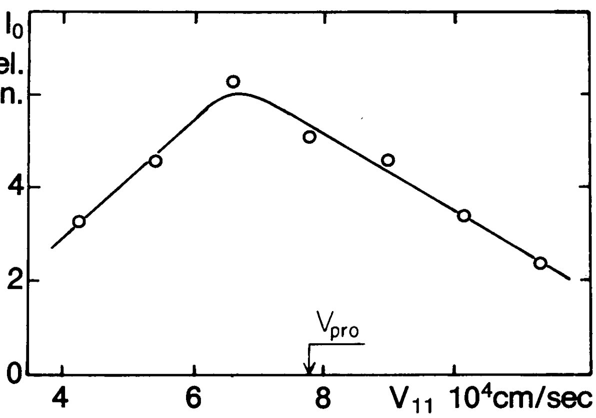

Fig. 11. The dependence of the atomic intensity in the center of a beam on the longitudinal velocity of the atoms being collimated.

longitudinal atomic velocity. Figure 11 shows how the relative intensity of the atoms in the center of the beam varies with their longitudinal velocity at a given initial divergence of the atomic beam. It can be seen that at high velocities the collimating action of laser radiation falls off. The optimum longitudinal velocity lies near the most probable velocity. The drop in collimation efficiency at low velocities is explained by the following factor. When the transverse atomic velocities are so small that the corresponding Doppler shift of the absorption frequency of an atom is smaller than the homogeneous half-width of the atomic transition, the optimum detuning of the standing light-wave frequency is $\sim\gamma(1 + G)^{1/2}$. With a further decrease of detuning the light-pressure force tends to zero.[12] So the collimation will be most efficient for a beam with its transverse velocity $v_1 \simeq \gamma(1 + G)^{1/2}/k$. This value of transverse velocity is consistent with the optimum longitudinal velocity $v_z \simeq 2\gamma(1 + G)^{1/2}\lambda/\Delta\varphi$. With the saturation parameter $G \simeq 1$ and the initial divergence $\Delta\varphi_0 = 1.4 \times 10^{-2}$ rad, $v_z \simeq 6 \times 10^4$ cm/sec, which agrees well with the experimental value.

NUMERICAL CALCULATION OF ATOMIC-BEAM COLLIMATION

In the experiment described above it was impossible to detect directly the velocity distribution of atoms in a beam and hence to determine the transverse temperature. Therefore, we have carried out a numerical calculation of the velocity and spatial distributions of collimated atomic beams in order to find the atomic-beam temperature.

To describe the evolution of an atomic beam in the axicon field we used the Liouville equation for the atomic distribution function $w(\mathbf{r}, \mathbf{p}, t)$:

$$\frac{\partial}{\partial t} w + \mathbf{v} \frac{\partial}{\partial \mathbf{r}} w = - \frac{\partial}{\partial \mathbf{p}} (\mathbf{F} w), \qquad (7)$$

where $\mathbf{F}$ is the light-pressure force [Eq. (1)].

Since the time of flight of an atom through the axicon, $t_{fl} = l/\bar{v}_z \simeq 5 \times 10^{-5}$ sec, was comparable with the characteristic time β^{-1} for the transverse narrowing of the velocity distribution, the beam-distribution function changed only because of the light-pressure force [Eq. (1)]. For this reason the contribution of momentum diffusion that changed the atomic velocity by $\Delta v_{diff} \simeq (Dt_{fl})^{1/2} \simeq 30$ cm/sec, where D is the diffusion coefficient, was neglected in theoretical analysis.[9]

In this experiment the source of the atoms could not be considered a point source because its dimension was comparable with that of the diaphragm designed to form a beam with a given angular divergence (Fig. 12). This means that account must be taken of the atoms flying from different points of the source surface. A discrete set of point sources of atoms placed at different distances from the axicon axis of symmetry $0_1 0_2$ was chosen as a model of a distributed source.

Using the geometry given in Fig. 12, we could solve the Liouville equation (7) for each point source by the characteristics method. The characteristic equations were written in a cylindrical frame of reference, the z axis of which coincided with the axicon axis (Fig. 1):

$$\dot{v}_\rho = F(\rho, v_\rho)/m + v_t^2/\rho, \qquad \dot{v}_t = -v_\rho v_t/\rho,$$

$$\dot{v}_z = 0, \qquad v_\rho = \dot{\rho}, \qquad v_t = \dot{\varphi}\rho, \qquad v_z = \dot{z}. \qquad (8)$$

Here ρ and φ are the polar coordinates in the x–y plane (Fig. 1). It should be noted that the characteristic equations are different for the point source in line with the axis of symmetry $0_1 0_2$ of the axicon and for the point source at a distance from the axis $0_1 0_2$. In the first case the atom moves only along the radius, and in the second case it also moves in the x–y plane (Fig. 1) with the angular velocity $\dot{\varphi}$. The angular dependences in Eqs. (8), however, are not essential because the force depends only on ρ and $v\rho$ resulting in cylindrical symmetry.

Taking into account the contributions of all the point sources, we found the velocity and the spatial distributions

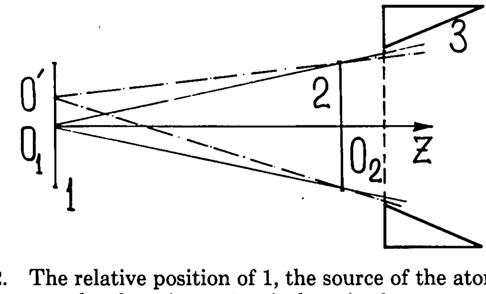

Fig. 12. The relative position of 1, the source of the atoms; 2, the diaphragm; and 3, the axicon. $0_1 0_2$ is the axis of symmetry. $0'$ is the point source shifted off the axis $0_1 0_2$.

Mechanical Effects of Light

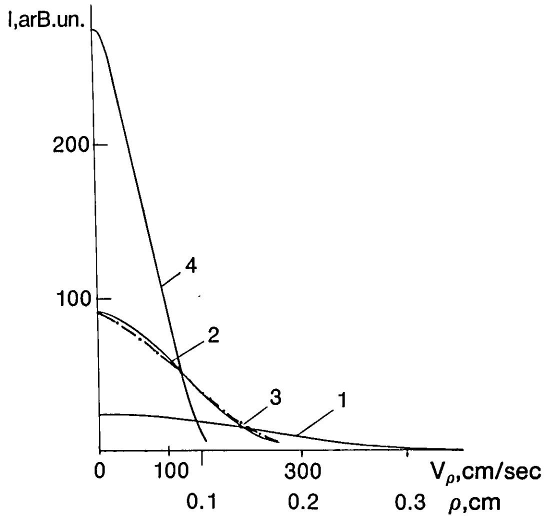

Fig. 13. The spatial and velocity distributions of atoms in a beam for $P = 45$ mW and $\Delta\nu = -3.8\gamma$. 1, The theoretical spatial and velocity distributions of atoms in the detection region in the absence of collimating field. 2, The theoretical spatial distribution of atoms in the detection region after the beam has interacted with the collimating field. 3, The experimental spatial distribution of atoms in the detection region after the beam has interacted with the collimating field. 4, The theoretical velocity distribution of atoms after the collimating field is switched on.

of atoms in the detection region at the laser-radiation power used in the experiment. The frequency detuning in this case was chosen so that the calculated and experimental spatial distributions coincided. This enabled us to determine the atomic-beam temperature from the theoretical value of the velocity distribution.

Figure 13 shows the calculated and experimental distributions over the ρ coordinate (curves 2 and 3). With the parameters used the theoretical curve was similar to the experimental one. The difference between them was mainly due to the fact that in the calculations we neglected the multilevel structure of atomic transitions and the contribution of the momentum diffusion and replaced the real source of atoms by a discrete set of point sources. Using the velocity distribution (curve 4), we could find the collimated-beam temperature, $T = 3.3$ mK. This value agrees with the estimation obtained in Ref. 10 within an order of magnitude. To determine the temperature we approximated the velocity distribution with the Gaussian curve using the method of least squares.

In conclusion, it should be noted that in the experiment we measured the dependence of the atomic intensity on the spatial coordinate, which varied along the fixed direction. The difference between the areas under curves 1 and 3 does not mean that the total number of atoms is not preserved. The total number of atoms is a conserved quantity. This quantity can be obtained by integrating the atomic intensity not over the linear coordinate but over the atomic-beam cross section.

CONCLUSION

Using an axisymmetric light field for irradiating an atomic beam, we have obtained a method for collimating neutral particles. The transverse velocity of the atoms was reduced from 5.5×10^2 to 1.6×10^2 cm/sec. Thus, on the basis of the scheme described, the effective temperature of the atomic beam was lowered to $T = 3.3$ mK. The numerical calculation of the spatial distribution of atoms is in good agreement with the experiment.

REFERENCES

1. W. D. Phillips, ed., *Laser-Cooled and Trapped Atoms*, Nat. Bur. Stand. U.S. Spec. Publ. **653** (1983); "Laser-cooled and trapped atoms" Prog. Quantum Electron. **8,** 314 (1984).
2. V. G. Minogin and V. S. Letokhov, *Laser Light Pressure on Atoms* (Nauka, Moscow, to be published).
3. V. I. Balykin, V. S. Letokhov, and V. I. Mishin, "Observation of cooling of free sodium atoms in resonant laser field with scanning frequency," Pis'ma Zh. Eksp. Teor. Fiz. **29,** 614 (1979); "Cooling of Na atoms by resonant laser radiation," Zh. Eksp. Teor. Fiz. **78,** 1376 (1980).
4. S. V. Andreev, V. I. Balykin, V. S. Letokhov, and V. G. Minogin, "Radiative slowing down and monochromatization of a sodium atoms beam in counter-moving laser beam," Zh. Eksp. Teor. Fiz. **82,** 1429 (1982).
5. W. D. Phillips and H. Metcalf, "Laser deceleration of atomic beam," Phys. Rev. Lett. **48,** 596 (1982).
6. V. I. Balykin, V. S. Letokhov, and A. I. Sidorov, "Intense stationary flow of cold atoms formed by laser deceleration of atomic beam," Opt. Commun. **49,** 248 (1984); "Formation of an intense stationary beam of cold atoms by laser deceleration of an atomic beam," Zh. Eksp. Teor. Fiz. **86,** 2019 (1984).
7. R. Blatt, W. Ertmer, and J. L. Hall, "Cooling of an atomic beam with frequency-sweep techniques," in *Laser-Cooled and Trapped Atoms*, W. D. Phillips, ed., Nat. Bureau Stand. U.S. Spec. Publ. **653** (1983), pp. 142–153.
8. G. I. Budker and A. N. Skrinsky, "The electron cooling and new possibilities in elementary particle physics," Usp. Fiz. Nauk. **124,** 561, (1978); A. Septier, *Focusing of Charged Particles* (Academic, New York, 1967), Vols. I and II.
9. V. I. Balykin, V. S. Letokhov, V. G. Minogin, and T. V. Zyeva, "Collimation of atomic beams by resonant laser radiation pressure," Appl. Phys. B **35,** 149 (1984).
10. V. I. Balykin, V. S. Letokhov, and A. I. Sidorov, "Radiative collimation of atomic beam by laser-induced two-dimensional cooling," Pis'ma Zh. Eksp. Teor. Fiz. **40,** 251 (1984).
11. T. W. Hänsch and A. W. Schawlow, "Cooling of gases by laser radiation," Opt. Commun. **13,** 68 (1975).
12. V. S. Letokhov, V. G. Minogin, and B. D. Pavlik, "Cooling and trapping of atoms and molecules by resonant light field," Zh. Eksp. Teor. Fiz. **72,** 1328 (1977).
13. V. G. Minogin, "Kinetic theory of atomic scattering by a resonant standing light wave," Zh. Eksp. Teor. Fiz. **80,** 2231 (1981).
14. H. R. Gray, R. M. Whitley, and C. R. Stroud, "Coherent trapping of atomic populations," Opt. Lett. **3,** 218 (1978).
15. M. L. Citron, H. R. Cray, C. W. Cabel, and C. R. Stroud, Jr., "Experimental study of power broadening in a two-level atom," Phys. Rev. **16,** 1507 (1977).
16. V. I. Balykin and A. I. Sidorov, "A high-power two-frequency cw dye laser," Kvantovaya Elektron. **11,** 2001 (1984).
17. I. E. Björkholm, R. R. Freeman, A. Ashkin, and O. B. Pearson, "Experimental observation of the influence of the quantum fluctuations of resonance-radiation pressure," Opt. Lett. **5,** 111 (1980).

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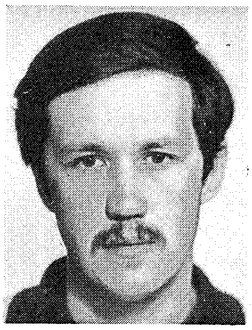

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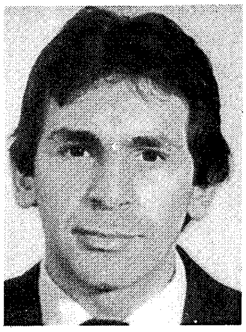

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