Radiative redistribution of the velocities of free sodium atoms by resonance laser radiation

V. I. Balykin, V. S. Letokhov, and V. G. Minogin

Institute of Spectroscopy, Academy of Sciences of the USSR
(Submitted 5 November 1980)
Zh. Eksp. Teor. Fiz. **80**, 1779–1788 (May 1981)

The results of a study of the deformation of the velocity distribution of a sodium-atom beam to the radiation pressure of resonance laser light are presented. The laser radiation was produced by two axial modes. The frequency difference of $\sim$ 1770 MHz between the modes was equal to the hyperfine splitting of the $3^2S_{1/2}$ ground state; this ensured cyclic interaction of the atoms with the field in the $3^2S_{1/2}$–$3^2P_{3/2}$ transition. The deformation of the velocity distribution was determined from the change in the fluorescence signal from the resonant atoms. The experimental dependences of the fluorescence intensity on the time of interaction of the atoms with the field are in good argeement with the results of calculations based on the kinetic equation. Comparison of the measured results with numerical solutions of the kinetic equation showed that at the employed interaction length $z = 38$ cm a laser-radiation intensity sufficient to saturate the atomic transition is adequate for efficient deformation of the velocity distribution of the sodium atoms.

PACS numbers: 32.80.Kf, 32.50. + d

1. INTRODUCTION

A number of recent theoretical studies[1-6] have shown that all the principal features of the motion of atoms in a resonance light field are determined by the velocity dependences of the light-pressure force and the velocity-diffusion tensor. In the case of a monochromatic traveling wave, both the force and the diffusion tensor are of resonance type, owing to the resonance interaction of the atom with the light field. As a direct consequence of the resonance character of the force and of the velocity-diffusion tensor, both the force and the diffusion alter the velocities of the atoms mainly in the narrow interval $\Delta v \sim \Delta\omega/k$ determined by the width $\Delta\omega$ of the absorption line; moreover, while the diffusion of the atomic velocities is independent of the wave-propagation direction and broadens the velocity distribution of the resonant atoms symmetrically, the light-pressure force, which distinguishes a particular direction in space, gives rise to an asymmetric distribution. As a result, when the atoms and the light wave propagate in the same direction the peak of the atomic distribution shifts toward velocities above the resonance velocity, and when they propagate in opposite directions, it shifts toward the lower velocities.

This redistribution of the atomic velocities is of special interest in connection with the radiative deceleration of atomic beams,[7,8] since it tends to make the beams monochromatic, and slow monochromatic beams are ideal objects, both for direct use in experiments, and for injecting atoms into traps.[9-11] The successful deceleration of a sodium-atom beam by frequency-scanned laser light was reported earlier.[7] This means of slowing a beam can be used to obtain pulses of cold atoms. Another method of radiative deceleration, which makes it possible to obtain stationary streams of cold atoms, is to irradiate the atomic beam with resonant laser light of fixed frequency propagating in the direction opposite to that of the atomic beam. This method has been recently analyzed[8] for the ideal case of a monochromatic traveling wave. In this paper we present the results of a study of the deformation of the velocity distribution of a beam of sodium atoms under the action of continuous laser radiation at a fixed frequency in order to clarify the conditions necessary for stationary radiative deceleration of atoms.

The principal contents of the paper are presented in Sections 2–5. In Section 2 we make use of features of the level structure of the sodium atom to choose an excitation method that will ensure prolonged cyclic interaction of the atoms with the laser light, and present the considerations on which the experiment is based. The experimental setup and results are presented in Section 3. In Section 4 we give a theoretical analysis of the evolution of the velocity distribution of an atomic beam, taking into account the frequency fluctuations of the laser light that are important in the experiment, as well as the way in which the interaction scheme differs from the ideal two-level scheme. The experimental data are discussed and compared with calculated relationships in Section 5.

2. FORMULATION OF THE PROBLEM

In our experimental study of the evolution of atomic velocities we chose to register the deformation of the velocity distribution on the basis of the change in the intensity of the fluorescence of atoms in resonance with the laser radiation. When atoms are excited in a transition of frequency ω_0 by a counter-propagating light wave of frequency ω the fluorescence signal is proportional to the number of atoms having the velocity $v_{res} = -(\omega - \omega_0)/k$; hence the change in the fluorescence signal reflects directly the change in the atomic distribution function $w(z, v, t)$ at the longitudinal velocity $v_z = v = v_{res}$.

A more direct experimental technique would be to use a separate light beam to excite the fluorescence and then to record the fluorescence both at various distances from the point at which the atoms enter the decelerating laser field and at various times. Such a method could provide a good deal of information about the variation of

 0038-5646/81/050919-06$02.40

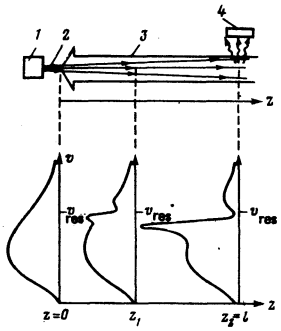


FIG. 1. Deformation of the velocity distribution of an atomic beam due to its interaction with a resonance light wave propagating in the opposite direction. The resonance velocity of the atoms is $v_{res} = -\Omega/k$, with $\Omega = \omega - \omega_0$. 1—source, 2—atomic beam, 3—laser beam, 4—detector.

the atomic distribution function $w(z, v, t)$. Because of experimental limitations, however, we chose a simpler scheme (Fig. 1) in which the fluorescence detector was mounted at a fixed distance $z = l$ from the source of the atomic beam, and the fluorescence was excited by the same radiation as was used to decelerate the atoms. In such a scheme, all the information on the evolution of the velocity distribution is contained in the dependence of the fluorescence intensity on the irradiation time of the atoms. This dependence has two characteristic features: first, it is a decreasing function of time because of the deceleration of the resonant atoms to lower velocities; and second, it always falls only to a certain value since, the interaction length $\Delta z = l$ being fixed, the velocity distribution is deformed only to a certain limit.

In principle, this method of investigating the deformation of the velocity distribution could be used with any atoms and the light field. In the case of sodium atoms, cyclicity of the interaction can be achieved either by orienting the atoms optically, using circularly polarized radiation[7] (also see Ref. 12), or by exciting the atoms with a two-frequency light field (Fig. 2). The second method is preferable since it assures reliable excitation of the atoms from either of the $F = 1$ and $F = 2$ hyperfine-structure sublevels of the $3^2S_{1/2}$ ground state, regardless of the polarization of the laser radiation. In our experiment we used this second (two-frequency)

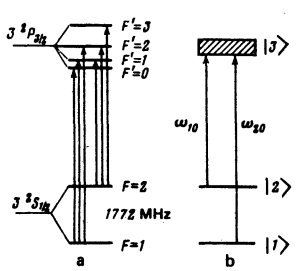
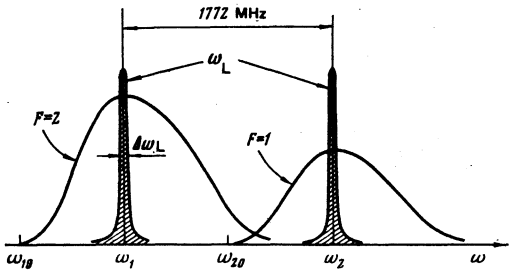


FIG. 2. a—hyperfine structure of the $3^2S_{1/2}$ ground state and the $3^2P_{3/2}$ excited state of the sodium atom and the resonance transitions in two-frequency excitation of the atom by laser radiation; b—equivalent three-level scheme used to calculate the redistribution of the atomic velocities.



FIG; 3. Absorption spectra of a sodium-atom beam for the $3^2S_{1/2}(F=1)$—$3^2P_{3/2}(F'=0, 1, 2)$ and $3^2S_{1/2}(F=2)$—$3^2P_{3/2}(F'=1, 2, 3)$ transitions and the positions of the laser-radiation modes with frequencies ω_1 and ω_2 (hatched regions).

method of excitation. To generate the two-frequency light field we used two axial modes of a cw dye laser. One of the modes excited the $3^2S_{1/2}(F=1)-3^2P_{3/2}$ transition in the sodium atoms, and the other mode, the $3^2S_{1/2}(F=2)-3^2P_{3/2}$ transition (Fig. 2).

It is evident that, in principle, the use of a two-frequency light field could alter the simple picture of the deformation of the velocity distribution drawn above, since the two light waves might act on groups of atoms having different velocities. Actually, at the oven temperatures we used to produce the atomic beam, the overlap of the $3^2S_{1/2}(F=1)-3^2P_{3/2}$ and $3^2S_{1/2}(F=2)-3^2P_{3/2}$ absorption lines may be neglected (Fig. 3). Accordingly, the low-frequency mode of the laser radiation, of frequency ω_1, excites atoms only in the $F=1$ substate, while the high-frequency mode of frequency $\omega_2 = \omega_1 + 1772$ MHz practically excites atoms only in the $F=1$ state. Moreover, since the frequency difference $\omega_2 - \omega_1$ between the modes was equal to the frequency difference $\omega_{20} - \omega_{10} = 1772$ MHz between the two resonance transitions, both modes acted on atoms belonging to the same velocity group and deformed the velocity distributions for the $F=1$ and $F=2$ levels in the same manner.

3. EXPERIMENTAL SETUP AND RESULTS

The experimental setup for investigating the redistribution of atomic velocities is diagramed in Fig. 4. It consists of the following principal elements: a cw dye laser 1, a vacuum chamber 2 containing the atomic-beam source 3, and a recording system comprizing the FÉU-79 photomultipliers 4 and a dual trace oscilloscope 5. To monitor the laser frequency and adjust it to the sodium absorption line we used a supplementary sealed cell 6 containing sodium vapor. The fluorescence signal picked up from the monitor cell by a photomultiplier was displayed on the same oscilloscope 5. To excite the sodium atoms we used a two-frequency dye laser, the separation between the two laser frequencies being equal to the hyperfine-structure splitting $\Delta\omega_{hfs} = 1772$ MHz of the sodium ground state.

The desired operation of the dye laser was achieved as follows. The optical length of the laser resonator, formed by the mirrors M_1, M_2, and M_3, was so chosen that the frequency difference between neighboring axial modes of the laser resonator would be a submultiple of

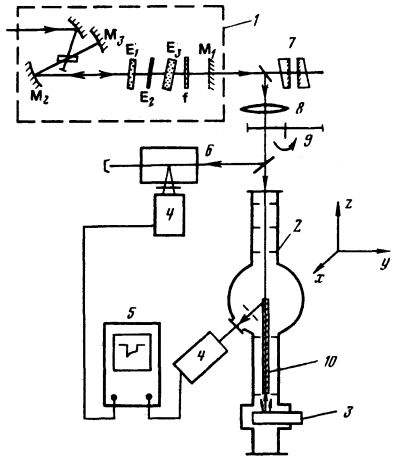


FIG. 4. Experimental setup: 1—continuous dye laser (M_1, M_2, M_3—resonator mirrors; E_1, E_2, E_3—Fabry-Perot étalons; f—metallic absorbing film), 2—vacuum chamber, 3—atomic-beam source, 4—photomultipliers, 5—oscilloscope, 6—monitor cell containing sodium vapor, 7—Fabry-Perot étalon, 8—lens, 9—mechanical interrupter, 10—region in which the atomic and laser beams interact.

the hyperfine splitting of the sodium ground state: $\Delta\omega_r = \Delta\omega_{hfs}/m$, with $m = 1, 2, 3, \ldots$. In our experiment $\Delta\omega_r = 354$ MHz and $m = 5$. By using three Fabry-Perot étalons E_1, E_2, and E_3 within the resonator we were able to narrow the laser spectrum beforehand to ~2 GHz. To pick, out of the six or seven laser active axial modes, two with a frequency difference $\Delta\omega_{hfs} = 1772$ MHz, and suppress the remaining ones, we made use of the spatial inversion burning effect[13] and a thin metallic absorbing film f within the resonator (the Troitskiĭ selector[14]).

The radiation of the dye laser was directed into the vacuum chamber 2 containing the atomic-beam source 3. The chamber was pumped down to $p = 5\times10^{-6}$ Torr. The atomic beam was collinear with the laser beam. The diameter of the atomic beam was fixed by a set of diaphragms, the smallest diameter of the holes in the diaphragms being larger than the diameter of the laser beam, so that the region in which the atomic beam interacts with the laser light is determined by the diameter of the laser beam. The diameter of the laser beam was $d_1 = 0.9$ mm near the opening in the atomic-beam oven and $d_2 = 1.1$ mm in the region from which the fluorescence signal was picked up. The interaction region 10 was 38 cm long. The working temperature of the atomic-beam oven was $t = 300$°C.

The laser beam was modulated near the entrance to the vacuum chamber by the mechanical chopper 9. The rise time of the laser beam intensity was $\tau_{rise} = 12$ μsec; this is much shorter than the average time of flight of the atoms through the interaction region ($\tau_{fl} = 0.4$ msec). The time during which the atomic beam was irradiated with the interrupter open was 2.5 msec. Figure 5 shows the measured fluorescence signal from the sodium atoms as a function of the time of interaction with the laser radiation at an irradiation $I_L = 0.42$ W/cm^2 (we denote the saturation parameter by $G = I_L/I_S$, where $I_S = 0.01$ W/cm^2 is the saturation intensity). The

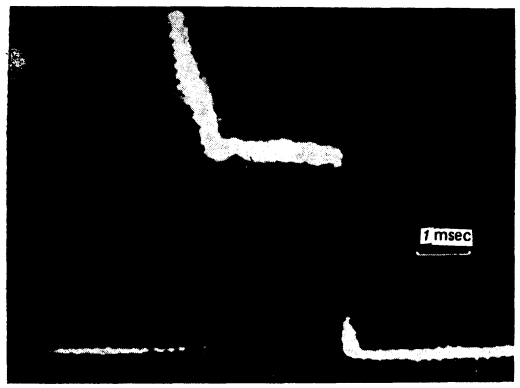


FIG. 5. Oscillogram showing the fluorescence signals from sodium atoms at the point $z = 38$ cm from the origin of the beam as a function of the time since the beginning of irradiation of the atomic beam by the laser light.

nature of the time dependence of the fluorescence intensity is in full agreement with what is to be expected on the basis of qualitative considerations (Fig. 1). When the laser radiation is turned on rapidly (the bottom horizontal lines correspond to zero fluorescence signal) the fluorescence reaches its maximum value corresponding to the initial (undeformed) velocity distribution. Afterwards the deformation of the velocity distribution (Fig. 1) is accompanied by a decrease in the relative number of resonant atoms, and this causes the fluorescence signal to fall. This decrease continues for a time that is characteristic of the deformation of the distribution and is equal to the time of flight of the atoms through the light beam. In the oscillogram of Fig. 5, the time during which the fluorescence signal decreases (0.5 msec) agrees well with the average time of flight of the atoms through the interaction region. After a time equal to the average time of flight, the fluorescence signal becomes steady at a level corresponding to the deformed distribution.

As was noted in Sec. 2, from the amount by which the strength of the fluorescence signal changes one can determine the degree of deformation of the atomic absorption-line shape and, consequently, the degree of deformation of the velocity distribution of the atomic beam. We measured the change in the fluorescence signal as a function of the intensity of the laser light. The results

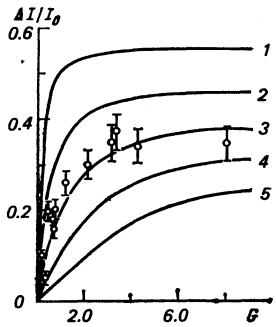


FIG. 6. Relative change in the fluorescence signal from the sodium atoms as a function of the intensity of the laser radiation. The curves were calculated for the following values of $\Delta\omega$ (in MHz): 1—30, 2—50, 3—70, 4—90, 5—110.

of these measurements are represented by the points in Fig. 6. With the radiation intensity used in the experiment (up to 800 mW/cm^2, $G=80$) the relative change in the fluorescence signal strength reached $\Delta I/I_0=0.36$.

4. THEORETICAL ANALYSIS OF THE EVOLUTION OF THE ATOMIC VELOCITIES

A complete description of the evolution of the velocity distribution of the atoms in the case of interest to us in which the natural width 2γ of the absorption line ($2\gamma=10$ MHz for the $3S-3P$ transition of the sodium atom) exceeds the recoil energy r ($r=25$ kHz) can be obtained from the kinetic equation for the distribuiton function $w(z, v, t)$.[2, 15, 16] For the case of ideal two-level atoms moving one-dimensionally along the z axis in the direction opposite to the propagation of a monochromatic traveling light wave, the kinetic equation takes the form[15, 16]

$$\frac{\partial w}{\partial t}+v\frac{\partial w}{\partial z}+\frac{\partial}{\partial v}(Aw)=\frac{\partial^2}{\partial v^2}(Dw), \tag{1}$$

where

$$A=-\gamma v_r\frac{G}{1+G+(\Omega+kv)^2/\gamma^2} \tag{2}$$

is the acceleration of the atom due to the light-pressure force and

$$D=\frac{1}{2}\gamma v_r^2\left\{1+\alpha+G\frac{(\Omega+kv)^2/\gamma^2-3}{[1+G+(\Omega+kv)^2/\gamma^2]^2}\right\} \tag{3}$$

is the component of the velocity-diffusion tensor along the z axis. In Eqs. (2) and (3), $v_r=\hbar k/M$ is the recoil velocity (M is the mass of an atom), $G=I/I_S$ is the saturation parameter, which is equal to the ratio of the intensity of the wave to the saturation intensity, $\Omega=\omega-\omega_0$ is the difference between the frequency ω of the light wave and the frequency ω_0 of the atomic transition, and the parameter α determines a component of the continuous-diffusion tensor.[15]

Strictly speaking, Eq. (1) cannot be applied directly to the motions of atoms in the experimental scheme presented above. First, that scheme makes use of two light waves (two axial modes of the laser) with different frequencies ω_1 and ω_2. Second, the spectral width $\Delta\omega_L$ of each of the laser modes is comparable with the natural line width of the atomic transition. Finally, because of the hyperfine structure of the $3^2P_{3/2}$ excited state, each of the laser modes interacted with what amounts to several coupled two-level atomic systems (Fig. 2).

It is not difficult to show that taking account of the presence of two light waves does not alter the form of the equation. Actually, to describe the two-frequency excitation of sodium atoms via the two different transitions $3^2S_{1/2}(F=1)-3^2P_{3/2}$ and $3^2S_{1/2}(F=2)-3^2P_{3/2}$, one must write down two equations of the form of Eq. (1). Since, however, as was explained in Sec. 2, each atom actually interacts with only one of the laser-radiation modes, and since the two equations have the same parameters, when we add the equations we again arrive at Eq. (1).

To take account of the frequency fluctuations of the laser radiation, Eq. (1) must be averaged over a time τ exceeding the reciprocal width of the frequency spectrum: $\tau\gg\Delta\omega_L^{-1}$. When so averaging, we note that the function $w(z, v, t)$ is already a time-averaged function since it describes the atomic ensemble on a time scale $\Delta t\gg\gamma^{-1}$.[15] Finally, taking account of the fact that $\Delta\omega_L\sim\gamma$ under the experimental conditions, we arrive at the conclusion that in averaging Eq. (1) we need average only its coefficients A and D. Moreover, since the time dependences of A and D are due only to the time dependence of the frequency ω, we actually need to average the coefficients of Eq. (1) only over the frequency ω.

Averaging the acceleration A and the diffusion D over the frequency spectrum of the laser radiation allows us to take account of the hyperfine structure of the upper level of the resonance transition in a simple manner. Since the width $\Delta\omega_L=10$ MHz of the laser radiation is comparable with the hyperfine structure splitting of the $3^2P_{3/2}$ state, it is accurate enough as far as the experiment is concerned to assume that the presence of the hyperfine structure is equivalent to a random scattering of the resonance frequencies ω_0 within the limits of the effective width $\Delta\omega_{hfs}$ of the hyperfine structure. Then taking the finite width $\Delta\omega_L$ of the laser radiation and the hyperfine structure of the $3^2P_{3/2}$ state into account reduces to averaging the coefficients in Eq. (1) over the frequency deviation $\Omega=\omega-\omega_0$. Before writing the averaged equation out explicitly, we not again that an estimate of the part played by diffusion in the averaged equation shows that, at the values used in the experiment for the length l of the interaction region and the effective width $\Delta\omega$ of the interaction, the contribution of diffusion to the deformation of the velocity distribution is small as compared with the light-pressure force. Then taking only the light-pressure force into account, we finally write down the basic equation for the experiment:

$$\frac{\partial w}{\partial t}+v\frac{\partial w}{\partial z}+\frac{\partial}{\partial v}(\langle A\rangle w)=0, \tag{4}$$

in which, under the simple assumption that the frequency deviations Ω are uniformly distributed throughout the effective region $\Delta\omega$, the average acceleration $\langle A\rangle$ is given by

$$\langle A\rangle=\frac{1}{\Delta\omega}\int_{-\Delta\omega/2}^{+\Delta\omega/2}A\,d\Omega$$
$$=-\gamma v_r\frac{\gamma}{\Delta\omega}\frac{G}{(1+G)^{1/2}}\operatorname{arctg}\frac{(\Delta\omega/\gamma)(1+G)^{1/2}}{1+G+(\Delta\omega/2\gamma)^2+(\Omega+kv)^2/\gamma^2}. \tag{5}$$

In Eq. (5) $\bar\Omega=\bar\omega-\bar\omega_0$ represents the average frequency deviation; it is the difference between the central frequency $\bar\omega$ of the laser radiation and the frequency $\bar\omega_0$ of the atomic transition averaged over the hyperfine structure.

The solution of Eq. (4) of interest to us has the form

$$w(z, v, t)=\frac{\langle A(v_0)\rangle}{\langle A(v)\rangle}w(z_0, v_0, 0), \tag{6}$$

in which the coordinate z_0 and velocity v_0 of the atom at the initial time $t=0$ are related to the running coordinates z and v at time t by the characteristic equations

$$dt=\frac{dz}{v}=\frac{dv}{\langle A\rangle}, \tag{7}$$

and the initial distribution

$$w(z_0, v_0, 0)=\frac{4}{\sqrt{\pi}\,\bar{v}^3}v_0^2\exp\left[-\left(\frac{v_0}{\bar{v}}\right)^2\right] \tag{8}$$

is a thermal distribution with the average velocity $\bar{v}=(2kT/M)^{1/2}$. Taking Eqs. (6)–(8) into account, we can write the following relationship for the fluorescence intensity:

$$I_{fl}(z,t)\propto\int w(z,v,t)\langle A(v)\rangle\,dv. \tag{9}$$

The presence of the acceleration $\langle A\rangle$ in Eq. (9) is related to the fact that the functional dependence of $\langle A\rangle$ is the same as that of the probability for exciting the atom to the upper level of the resonance transition.

The evolution of the velocity distribution $w(v)$ of the atomic beam as calculated with Eq. (4) for $z=l=38$ cm and $\Delta\omega=70$ MHz is shown in Fig. 7. The quantity $(kv_r)^{-1}=3.2\times10^{-6}$ sec was taken as the unit of time. Because of the finite length of the region in which the atoms interact with the field, the distribution tends to a stationary form at large times ($t\gg\tau_{fl}=l/1.22\bar{v}$).

5. DISCUSSION

The presented analysis of the evolution of the velocity distribution makes it possible to determine the effectiveness of the action of two-frequency laser radiation on the velocity distribution of a beam of sodium atoms under the conditions of our experiment. To do this we first determine the frequency interval $\Delta\omega$ over which Eq. (4) must be averaged. The excited state of the $3^2S_{1/2}$–$3^2P_{3/2}$ transition in the sodium atom is split by the hyperfine interaction into four sublevels $F'=0$, 1, 2, 3 (Fig. 2). The separations between the sublevels are 16, 36, and 60 MHz, respectively. The selection rules allow transitions from the $F=1$ ground-state sublevel to the sublevels $F'=0$, 1, and 2 of the excited state. For this group of transitions, the spectral width within which the atom interacts with the radiation field is $\Delta\omega_{hfs}=52$ MHz. Transitions from the ground-state sublevel $F=2$ to the sublevels $F'=1$, 2, and 3 of the excited state are allowed. In this case $\Delta\omega_{hfs}=96$ MHz. Thus, the average spectral width of the upper level due to hyperfine structure is $\Delta\omega_{hfs}=74$ MHz. This quantity is almost an order of magnitude greater than the line width $\Delta\omega_L=10$ MHz of the laser radiation. The effective frequency interval $\Delta\omega$ in Eq. (5) is accordingly determined mainly by the hyperfine structure of the $3^2P_{3/2}$ state: $\Delta\omega\approx74$ MHz.

Figure 6 shows the strength of the fluorescence signal as a function of the intensity of the laser radiation as calculated with formula (9) for various values of the parameter $\Delta\omega$. The experimental points come closest to fitting the curve calculated for $\Delta\omega=70$ MHz. This value for $\Delta\omega$ agrees well with the estimate given above. Velocity distributions corresponding to $\Delta\omega=70$ MHz are shown in Fig. 7.

On the basis of Fig. 7 and expression (5) for the average force, one can conclude that for effective action on the velocity distribution the saturation parameter must satisfy the condition $G\gtrsim(\Delta\omega/2\gamma)^2$, i.e., the radiation intensity must be sufficient to saturate the effective absorption line of width $\Delta\omega$. At such intensities the resonance laser radiation very quickly equalizes the longitudinal velocities of the atoms.

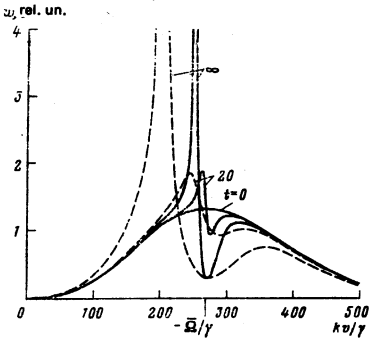


FIG. 7. Velocity distributions at the point $z=38$ cm at various interaction times t for $\Omega=-270\gamma$ and $\Delta\omega=14\gamma$. The average thermal velocity of the atoms was $\bar{v}=220\ \gamma/k=6.5\times10^4$ cm/sec ($2\gamma=10$ MHz, $G=I_L/I_s$, and $I_s=10$ mW/cm^2). The time unit is $(kv_r)^{-1}=3.2\times10^{-6}$ sec.

In concluding, we note that in treating the interaction of an atom with laser radiation we took only the longitudinal component of the light-pressure force into account. In a traveling light wave confined to a beam of finite diameter there is also a transverse component of the light-pressure force[15]:

$$F_\rho=\hbar\frac{\rho}{\rho_0^2}(\Omega+kv)\frac{G}{1+G+(\Omega+kv)^2/\gamma^2}, \tag{10}$$

where ρ is the distance from the center of the laser beam, $2\rho_0$ is the diameter of the laser beam [for a Gaussian beam $E^2=E_0^2\exp(-(\rho/\rho_0)^2)$, where E is the electric field strength]. This component of the force tends either to pull the atoms into the strong-field region or to push them out of it, depending on the velocity v. Under the conditions of our experiment ($\rho_0=5\times10^{-2}$ cm, $\rho\approx\rho_0$) the displacement of an atom under the action of the transverse component of the force amounts to $\Delta\rho\lesssim10^{-2}$ cm, and this is substantially smaller than the diameter of the laser beam.

We thank S. V. Andreev for assistance with the experiment.

[1]A. Ashkin, Phys. Rev. Lett. 25, 1321 (1970).
[2]E. V. Baklanov and B. Ya. Dubetskiĭ, Opt. Spektrosk. 41, 3 (1976) [Opt. Spectrosc. 41, 1 (1976)].
[3]V. S. Letokhov, V. G. Minogin, and B. D. Pavlik, Zh. Eksp. Teor. Fiz. 72, 1328 (1977) [Sov. Phys. JETP 45, 705 (1977)].
[4]Stieg Stenholm, Appl. Phys. (Germany) 15, 287 (1978).
[5]Stieg Stenholm and Juha Javanainen, Appl. Phys. (Germany) 16, 159 (1978).
[6]I. V. Krasnovand N. Ya. Shaparev, Zh. Eksp. Teor. Fiz. 77, 889 (1979) [Sov. Phys. JETP 50, 453 (1979)].
[7]V. I. Balykin, V. S. Letokhov, and V. I. Mishin, Pis'ma Zh. Eksp. Teor. Fiz. 29, 614 (1979) [JETP Lett. 29, 560 (1979)]; Zh. Eksp. Teor Fiz. 78, 1376 (1980) [Sov. Phys. JETP 51, 692 (1980)].

[8]V. G. Minogin, Opt. Commun. 34, 265 (1980).
[9]A. Ashkin and J. P. Gordon, Opt. Lett. (USA) 4, 161 (1979).
[10]J. P. Gordon and A. Ashkin, Phys. Rev. A21, 1606 (1980).
[11]V. S. Letokhov and V. G. Minogin, Opt. Commun. 35, 199 (1980).
[12]V. I. Balykin, Opt. Commun. 33, 31 (1980).
[13]I. V. Hertel and A. S. Stanovic, IEEE J. Quantum Electron. QE-11, 210 (1975); I. M. Beterov, Yu. M. Kirin, and B. Ya. Yurshin, Opt. Commun. 13, 238 (1975).
[14]N. D. Goldina, M. I. Zakharov, and Yu. V. Troitskiĭ, Zh. Priklad. Spektrosk. 10, 43 (1969).
[15]V. G. Minogin, Zh. Eksp. Teor. Fiz. 79, 2044 (1980)[Sov. Phys. JETP 52, 1032 (1980)].
[16]Richard J. Cook, Phys. Rev. A22, 1078 (1980).

Translated by E. Brunner