Efficient transverse deflection of neutral atomic beams using spontaneous resonance-radiation pressure

J. E. Bjorkholm, R. R. Freeman, and D. B. Pearson
Bell Laboratories, Holmdel, New Jersey 07733
(Received 19 May 1980)

We report the efficient transverse deflection of all atoms in a well-collimated sodium atomic beam by the spontaneous radiation pressure of a beam of resonance light which illuminates the atomic beam at right angles. Our results are obtained using two cw single-mode dye lasers to excite the two ground-state levels of sodium; this enables all atoms to interact with the light and it also eliminates optical pumping of the ground state. We obtained deflection angles greater than 5×10^{-3} rad which was ten times the divergence angle of the undeflected atomic beam; these deflections are due to the spontaneous scattering of more than 200 photons by each atom. The distribution of deflection angles is well described by a simple calculation. Fitting theory to experiment indicates that a fractional atomic excitation of 24 percent was obtained at an intensity of approximately 1 W/cm^2. When single-frequency light was used, only a fraction of the atoms were deflected, and the deflection angles were much smaller due to optical pumping.

I. INTRODUCTION

We report on an experimental study of the transverse deflection of a beam of neutral sodium atoms by a beam of resonance light from a laser which illuminates the atomic beam at right angles. Transverse deflection of atoms by the spontaneous force of resonance-radiation pressure[1] has been observed previously by others in two types of experiments. In the first type, all the atoms in the atomic beam were deflected through small angles by the light from conventional resonance lamps.[2,3] In the second type of experiment, narrow-band light from a laser was used to deflect a fraction of the atoms in the atomic beam through much larger angles.[4,5] Not all atoms were deflected in these latter experiments because not all initially populated ground states were resonant with the nearly monochromatic laser light. In addition, it is possible for the fraction of atoms resonant with the light to be further reduced by optical pumping of atoms from resonant ground-state levels to nonresonant ground-state levels. Optical pumping also severely limits the amount of deflection obtainable since it limits the number of photons that an atom can spontaneously scatter.

The motivation for our present experiment was a need to measure quantitatively the magnitude of the spontaneous force of resonance-radiation pressure in the real multilevel sodium atom for experimental conditions which avoid optical pumping and which allow all the atoms in the atomic beam to be deflected through relatively large angles. Calculation of the spontaneous force of resonance-radiation pressure is straightforward for the idealized two-level atom.[1] However, most atoms are not represented well by the simple two-level model and realistic calculations can be complex. Such is the case for the sodium atom and we opted to measure the spontaneous force directly instead of relying on approximate computations.

Our interest in experiments of this type stems from the possibility of using the forces of resonance-radiation pressure to create an optical trap for neutral atoms.[6,7] There are two types of resonance-radiation pressure forces and an understanding of each is necessary to successfully construct an optical trap. In previous experiments[8-10] we studied the transverse dipole force[11,7] which arises from stimulated scattering of light by the atom. In those experiments the effects of the dipole forces were maximized when the light frequency ν differed from the atomic resonance frequency ν_0 by approximately 5–10 GHz. For this situation it was reasonable to approximate sodium as a two-level atom since $\Delta\nu\equiv\nu-\nu_0$, the detuning of the light from resonance, was large compared with the hyperfine splittings of the ground and excited states. On the other hand, the spontaneous force of resonance-radiation pressure arises from spontaneous scattering of the light by the atom and, in a two-level atom, it is maximized for $\nu\equiv\nu_0$. Thus, in studying the spontaneous force exerted on a real atom, the ground-state and excited-state level structure play an important role.

In our experiments we used essentially monochromatic light at 5890 Å to excite sodium atoms from the $3S_{1/2}$ ground state to the $3P_{3/2}$ excited state. The hyperfine splittings of both states are non-negligible and this gives rise, in general, to optical pumping.

The problems which this causes in sodium are widely recognized and a variety of techniques have been used to prepare a fraction of the atoms in an atomic beam into states which cannot be optically pumped[12,13]; if only a single level in each state is involved, the atom behaves in the idealized two-level fashion. In general, however, these techniques work well only at low light intensities. With high light intensities it usually is impossible to avoid optical pumping of even these special levels because of experimental difficulties.[13] For instance, low-intensity circularly polarized light can be used to excite a single transition out of many degenerate ones. In practice, however, light cannot be perfectly circularly polarized and at high intensities the remnant light of opposite polarization can be intense enough to significantly excite, or even saturate, one of the undesired transitions. Another problem with high-intensity illumination is that the excitation rate of nonresonant, but allowed, transitions can become large. Since we were specifically interested in studying the high-intensity situation, it was necessary for us to emply a different technique to combat optical pumping.

In sodium the $3S_{1/2}$ ground state is split by the hyperfine interaction into levels characterized by $F=1$ and $F=2$ which are separated by 1.77 GHz. In our work we used two independently tunable cw dye lasers to simultaneously excite the $3S_{1/2}(F=1) \rightarrow 3P_{3/2}$ and $3S_{1/2}(F=2) \rightarrow 3P_{3/2}$ transitions. With both lasers applied all ground-state levels were strongly optically coupled to an excited-state level and optical pumping was avoided for all atoms in the atomic beam. As will be demonstrated, the use of two lasers greatly increased the atomic deflection as compared with the case of a single laser beam. Our use of two lasers to provide excitation of all atoms and to prevent optical pumping of the ground state in sodium is analogous to the previous use of two lasers of very different frequencies to prevent the accumulation of barium atoms in a metastable excited state.[14,15]

Study of means of effectively applying the spontaneous force to a real atom is warranted because of the various possible applications of this radiation pressure. For instance, atomic-beam deflection has been used to carry out isotope separation,[14] laser spectroscopy,[16] and as an analytical tool in physics experiments[5]; it might be useful for energy selection in atomic-beams work.[1] Other uses of the spontaneous force include cooling of atoms in a gas,[17] possibly creating beams of slow atoms,[17,18] and cooling of ions in an electromagnetic ion trap[15,19] or of atoms in an optical trap.[20]

II. DEFLECTION OF A BEAM OF TWO-LEVEL ATOMS

Consider the idealized situation depicted in Fig. 1. A two-level atom travels along the z axis with speed v and its initial transverse position is $x=0$. In the interaction region of length L, $-l-L/2 \leq z \leq -l+L/2$, it is transversely irradiated by uniform plane-wave light of frequency ν. The *average* spontaneous force exerted by the light on the atom is

$$\bar{F}_{\text{spon}} = \frac{h}{\lambda\tau} f, \tag{1}$$

where λ is the wavelength of the light and τ is the natural lifetime of the excited state of the atom. The factor f, the fractional atomic excitation, is the probability of finding the atom in its excited state. For a two-level atom

$$f = \frac{1}{2}\,\frac{1}{1+1/p}, \tag{2}$$

where p is the saturation parameter and is equal to the ratio of the stimulated to spontaneous transition rates. Explicitly,

$$p = \frac{I}{I_s}\,\frac{\Delta\nu_N^2/4}{\Delta\nu^2+\Delta\nu_N^2/4}, \tag{3}$$

where I is the intensity of the applied light, $I_s = \pi h\nu/\lambda^2\tau$ is the saturation intensity for the two-level atom (19 mW/cm^2 for sodium), $\Delta\nu_N = 1/2\pi\tau$ is the natural linewidth (FWHM) of the atomic transition, and $\Delta\nu = \nu - \nu_0$ where ν_0 is the atomic resonance frequency.

During its passage through the interaction region the atom gains momentum in the x direction, resulting in an average deflection through the angle $\theta = (h/m\lambda)(fL/\tau v)1/v$, where m is the atomic mass. The factor $h/m\lambda$ is the atomic recoil velocity due to the absorption of a single photon (~2.9 cm/sec for sodium) and the factor $fL/\tau v$ is equal to $\bar{N}$, the average number of photons

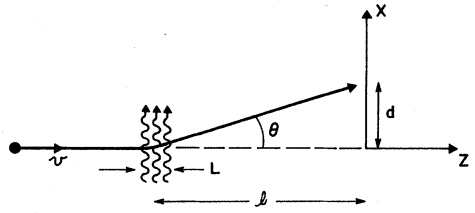

FIG. 1. A schematic diagram of the physical situation we consider. An atom with longitudinal velocity v passes through an interaction region of length L in which it is transversely illuminated by resonance radiation. Radiation pressure deflects the atom through the angle θ which results in a transverse displacement d after a free-flight zone of length l.

spontaneously scattered by an atom as it passes through the interaction region. The deflected atoms are detected in the plane $z=0$; their position is $d=\theta l\equiv\alpha/v^2$, where $\alpha=hLlf/m\lambda\tau$.

In making this simple calculation we have assumed that the fractional excitation, f, is independent of transverse velocity; that is, we have assumed that the Doppler shift of the light which results from transverse motion is negligible. For an atom initially on resonance, $\Delta\nu=0$, the Doppler shift reduces f by no more than a factor of 2 as long as $(\bar{N}h/m\lambda)/\lambda<\frac{1}{2}\Delta\nu_N(1+I/I_s)^{1/2}$. For atomic sodium $\Delta\nu_N=10$ MHz and this restriction reduces to $\bar{N}<100$ or $v_x<300$ cm/sec for the case $I/I_s \ll 1$; for a typical effusive sodium atomic-beam velocity of 10^5 cm/sec the requirement is $\theta<3\times10^{-3}$ rad. For our experiments, we had $I/I_s \geq 50$ and the severity of this restriction was much reduced. Thus fairly substantial deflections can be brought about before Doppler shifts become a limiting factor. Compensating for such Doppler shifts can be accomplished using converging light so that atoms of a given velocity are always illuminated at right angles.[1]

Atoms in an atomic beam have a distribution of velocities and this results in a distribution of deflected atoms along the detection plane. The slowest atoms experience the greatest deflections. For an effusive atomic beam the velocity distribution is

$$j(v)=\frac{2}{\beta}\left(\frac{v}{\beta}\right)^3\exp\left(-\frac{v^2}{\beta^2}\right), \tag{4}$$

where $\beta^2=2kT/m$ and T is the temperature of the atomic source. The corresponding distribution of deflected atoms along the plane $z=0$ is simply found to be

$$g(d)=\frac{\beta^2}{\alpha}\left(\frac{\alpha}{\beta^2 d}\right)^3\exp\left(-\frac{\alpha}{\beta^2 d}\right). \tag{5}$$

The fraction of the incident atoms deflected between d and $d+\Delta d$ is $g(d)\Delta d$. The quantity α/β^2 is a measure of the strength of the atomic deflection. Letting $\delta\equiv\beta^2 d/\alpha$ be the normalized deflection, the universal curve $g'(\delta)$ is plotted in Fig. 2(a). Note that $g'(\delta)$ has been defined such that $\int_0^\infty g'(\delta)d\delta=1$. The peak of the distribution is seen to occur for $\delta=\frac{1}{3}$ or $d=\alpha/3\beta^2$; the velocity corresponding to the peak of the distribution of deflections is $(6kT/m)^{1/2}$ whereas the most probable velocity in the atomic beam is $(3kT/m)^{1/2}$ and atoms with this speed are deflected to $\delta=0.67$. In Fig. 2(b) the distribution $g(d)$ is shown for parameters typical of our experiment ($L=1$ cm and $l=30$ cm) and for various values of f. It is seen that very substantial deflections are predicted for values of f greater than 0.1.

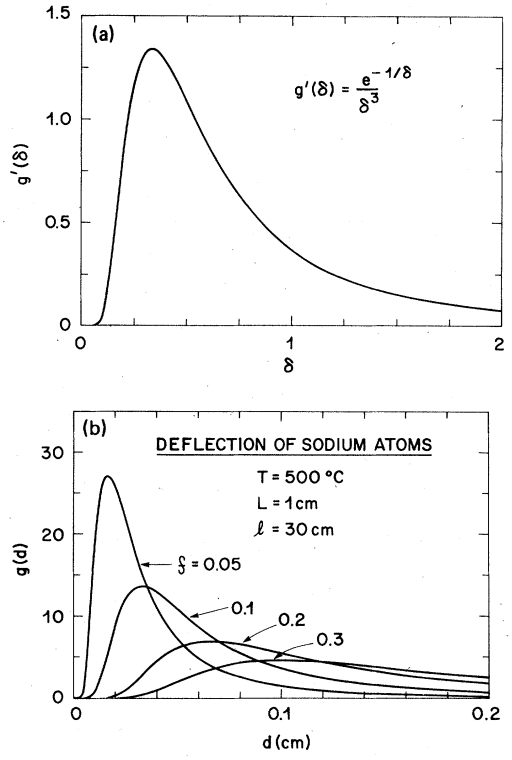

FIG. 2. (a) Normalized density of deflected atoms along the detection plane as a function of the normalized deflection δ for an effusive atomic beam. (b) Distribution of sodium atoms along the detection plane for parameters typical of our experiment and for various values of the parameter f, the atomic excitation.

To this point only the average force exerted on the atom has been considered; the quantum nature of the atom-light interaction which leads to fluctuations in the force and in the resulting deflections has been entirely neglected. Quantum fluctuations arise from two sources. First, N, the number of photons scattered by an atom as it passes through the interaction region, is a random variable obeying sub-Poisson statistics for resonant excitation.[21] For off-resonance excitation the photon statistics can be sub-Poissonian, Poissonian, or super-Poissonian.[22] Second, the recoil experienced by an atom in a single spontaneous scattering event can be in any direction and its magnitude varies correspondingly from 0 to $2h/m\lambda$; only the average recoil is in the direction of the light propagation. The effects of these fluctuations have been discussed elsewhere[23,24] and have been observed experimentally.[3,5,10] For the present experiment, fluctuations mean that the deflection of a given atom is a random variable distributed around the average value and this has not been accounted for.[25] How-

ever, the fractional width of the distribution is approximately $(\bar{N})^{-1/2}$ and, consequently, the errors introduced by not including quantum fluctuations in the derivation of Eq. (5) are most important for small values of $\bar{N}$. This will not be a major problem for most of the situations we will consider here.

III. EXPERIMENTAL

Our experiments were carried out using a moderately collimated atomic beam of sodium having a full divergence angle of approximately 5×10^{-4} rad. The source of atoms was a stainless-steel oven containing metallic sodium at a temperature of approximately 500 °C; the atoms effused from a 125-μm-diameter hole. The atomic beam was formed by this hole and a 75-μm-wide slit placed approximately 40 cm downstream; the slit height was approximately 400 μm. The interaction region was centered 5 cm after the slit and the atoms were detected after a free-flight region of length $l = 30$ cm. The total distance between the source and the detector was only 75 cm. The atoms were detected using an iridium Langmuir-Taylor hot-wire detector[26] which was mounted on a precision translation stage so that the beam profile could be scanned; its resolution was determined by a 75-μm-wide slit placed in front of the iridium ribbon.

The resonance light was obtained from two cw dye lasers, each of which was operated on a single axial mode. The lasers were tuned to 5890 Å to excite the $3S_{1/2} \rightarrow 3P_{3/2}$ resonance transition in sodium. The primary laser (laser I) was a ring laser (Spectra-Physics model 370); its output was spatially filtered to provide a clean and well-characterized transverse mode. The frequency jitter of this laser was approximately ± 30 MHz; in addition, there was a troublesome random frequency drift of about ± 100 MHz. In practice, approximately 250 mW of power from laser I was delivered to the atomic beam. The secondary laser (laser II) was a standing-wave dye laser (Spectra-Physics model 580 Å); this laser delivered only about 30 mW to the atomic beam. Its spatial mode was not as clean or as well characterized as that of laser I; its frequency jitter was approximately ± 15 MHz, and its frequency drift was not as troublesome as that of laser I. The radiation from both lasers was linearly polarized; the polarization directions were orthogonal so that the two laser beams could be combined using a beam-splitting calcite Thompson prism.

Precise tuning of the lasers was critical to achieving maximum deflection. The energy-level diagram for sodium and typical tunings for the two lasers are shown in Fig. 3. Laser I is tuned into resonance with the strongest of the various possible transitions, the $3S_{1/2}(F=2) \rightarrow 3P_{3/2}(F'=3)$ transition. This transition is particularly important because there is no optical pumping of the ground state if it is the only transition excited; the reason for this is that an atom in $F'=3$ can only decay spontaneously into $F=2$. In reality, however, the $F=2 \rightarrow F'=3$ transition is not the only one excited by laser I; the $F=2 \rightarrow F'=2$ transition is only 63 MHz off resonance and it is relatively weakly excited. For low intensities the excitation rate of this transition is about 2×10^{-3} of that for the $F=2 \rightarrow F'=3$ transition. An atom excited to $F'=2$ can decay into the $F=1$ ground state where it will remain since it would then be very far off resonance. Thus, optical pumping of the ground state can occur through the relatively weak $F=2 \rightarrow F'=2$ transition. Optical pumping sets in more rapidly as the laser intensity is increased because the $F=2 \rightarrow F'=3$ transition is the first to saturate while the $F=2 \rightarrow F'=2$ transition rate continues to grow with increasing intensity until an intensity level is reached at which it also saturates. When both transitions are fully saturated optical pumping sets in very rapidly and the atoms can spontaneously scatter only several photons. Our experiments were carried out with a fairly high intensity for laser I such that $p \sim 10$ for the $F=2 \rightarrow F'=3$ transition. However, the actual optical pumping problem is worse than the foregoing analysis implies. The reason for this is the frequency jitter of laser I which increases the average excitation rate of the $F=2 \rightarrow F'=2$ transition relative to the average excitation rate of the $F=2 \rightarrow F'=3$ transition. Even in the absence of optical pumping there is a prob-

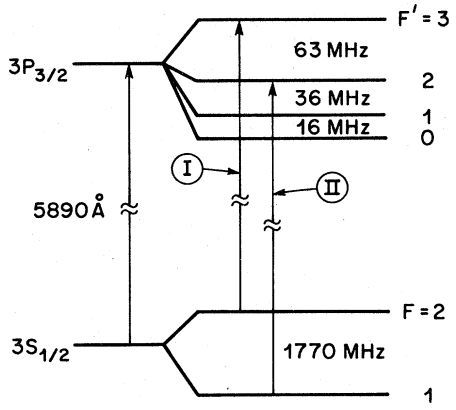

FIG. 3. The atomic energy levels of sodium relevant for our experiments. Typical tunings for lasers I and II are also shown.

lem with the use of a single laser; namely, only $\frac{5}{8}$ of the incident atomic beam is initially in the $F=2$ ground state and only these atoms can be deflected. Both problems are easily circumvented by the introduction of light from laser II, tuned, for example, as shown in Fig. 3. With light from both lasers simultaneously present, all ground-state levels are resonantly optically coupled to an excited state. Thus there is no possibility of optical pumping of the ground state and all atoms can be deflected.

In making our measurements, the frequencies of the two lasers were adjusted in the following way. First, the hot-wire detector was positioned at the peak of the undeflected atomic beam. Then the light beam from laser I was allowed to illuminate the atomic beam. Its frequency was adjusted to minimize the signal from the detector, which corresponded to best deflection of the atomic beam. For this tuning, the on-axis atomic-beam current was typically reduced to about 50 percent of its value with no light present, nearly the maximum reduction since three-eighths of the atoms are undeflected. The tuning of laser I was critical, with a required precision of better than ± 50 MHz; this bandwidth was probably primarily determined by the laser frequency jitter. While the corresponding absolute frequency of laser I was not measured to better than 100 MHz, we are convinced that it was tuned to the $F=2 \rightarrow F'=3$ transition as shown in Fig. 3. With laser I tuned as just described, the light from laser II was added to the atomic-beam illumination and its frequency was slowly scanned over the various transitions. When both lasers were tuned to the $F=2 \rightarrow F'=3$ transition no additional reduction of the on-axis atomic-beam current was observed. In fact, with this tuning either laser alone gave as large a reduction as the two together. However, dramatic results were obtained when the frequency of laser II was tuned to the $3S_{1/2}(F=1) \rightarrow 3P_{3/2}$ transitions. In this case the detector current was reduced to essentially zero (less than 1 percent of the no-light case), the result of interacting with all the atoms and of greatly enhanced atomic-beam deflection (because of no optical pumping). The precise frequency of laser II was not crucial and good results were obtained over a range of approximately ± 100 MHz which encompasses all the transitions from the $F=1$ ground state to the $3P_{3/2}$ level. Data were taken by scanning the atomic-beam profile with the detector for the various conditions just discussed. Results are shown in Figs. 4 and 5.

The data displayed in Fig. 4 were obtained under conditions which approximated uniform illumination of the atomic beam in the interaction region.

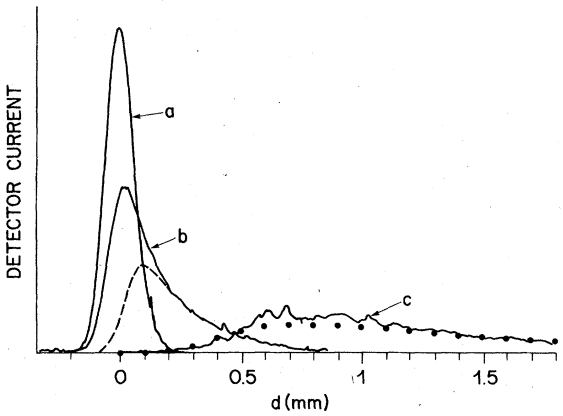

FIG. 4. Experimental profiles of the deflected atomic beam obtained with a 1 cm interaction length and approximately uniform illumination. Curve (a): the undeflected atomic-beam profile; curve (b): deflected profile obtained using only laser I (~250 mW); the dashed curve is curve (b) modified by subtracting the contribution of undeflected atoms; curve (c): deflected profile obtained using both laser I (~250 mW) and laser II (~30 mW); the dots show the theoretical best fit ($f=0.24$) to curve (c).

Cylindrical lenses were used to expand the laser beams along the propagation direction of the atomic beam and light stops were used to precisely define a 1-cm-long interaction region. The e^{-2} radii of the beam from laser I were approximately 1.1 cm long by 0.12 cm high; the resulting peak intensity was roughly 1 W/cm^2.

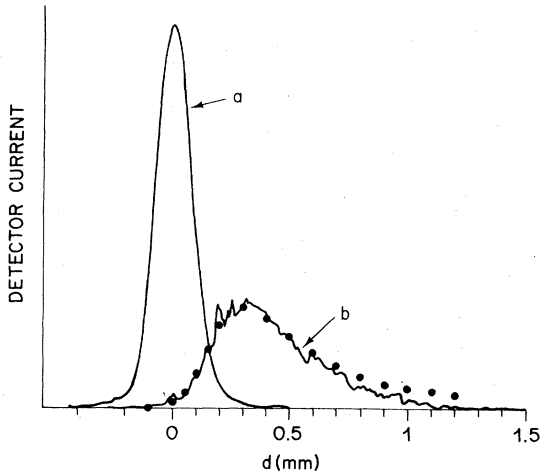

FIG. 5. Deflected atomic-beam profile using the Gaussian laser beams for illumination. Curve (a): the undeflected beam profile: curve (b): deflected beam profile using both laser I and laser II. The dots show the theoretically calculated profile for $fL=8.6\times10^{-2}$ cm (best fit).

The spot sizes for the beam from laser II were roughly the same. In Fig. 4, curve a shows the profile of the undeflected atomic beam, curve b shows the profile obtained with only laser I applied, and curve c is the profile obtained with both lasers. Substantial deflection of the atomic beam is observed in both cases b and c, but the deflection is obviously much greater when both lasers are utilized. The broken curve shows the result of subtracting three-eights of curve a from curve b; this curve, then, shows the profile of the deflected atoms for the situation when only one laser is used. Large deflections are obtained when both lasers are used; the peak of profile c occurs at a deflection angle of 2.7×10^{-3} rad, which is more than five times the full divergence angle of the undeflected atomic beam. A sizable fraction of the atoms undergo deflections of twice that amount. The data presented here are the most highly resolved observation of atomic-beam deflection made to date.

The solid dots in Fig. 4 show the theoretically calculated profile of the deflected atomic beam for $\alpha/\beta^2=0.24$ cm. The calculation was carried out numerically and it specifically accounted for the actual profile of the undeflected atomic beam and for the finite resolution of the detector; Eq. (5) was used as a Green's function describing the profile of a deflected "delta-function" atomic beam. There are no adjustable parameters in the calculation except for α/β^2; the value 0.24 seemed to give the best fit to the experimental data. The corresponding value for f, the fractional excitation of the atom beam, is also 0.24.

The data displayed in Fig. 5 were obtained using Gaussian laser beams for illumination; only the data obtained with illumination by both lasers are shown. The e^{-2} radii of the beams were approximately 0.12 cm and the peak intensity for laser I was about 11 W/cm^2. The solid dots show the theoretically calculated profile for $\alpha/\beta^2=8.5\times10^{-2}$ cm, which gives the best fit; the corresponding value for the product (fL) is 8.6×10^{-2} cm. Since the laser intensity profile was nonuniform, the product (fL) actually represents the integral of f over the interaction path. Because the functional dependence of f upon I is not known for the case being studied, the measured value of (fL) is not sufficient to determine the value of f corresponding to the peak illumination. For example, if the "two-level atom" behavior given by Eqs. (2) and (3) is assumed to hold, then the integration of f over the interaction path is easily carried out. This procedure indicates a peak value for f of 0.39 and a corresponding value for p of 3.5. These values, however, are not simultaneously consistent with Eq. (3) and the data of Fig. 4 which were obtained with uniform illumination of 1 W/cm^2. In that case an unambiguous value of 0.24 was found for f; this corresponds to $p\approx1$ if Eq. (2) is assumed valid. The nonlinear dependence of p upon I which we find violates the initial assumption of the validity of Eq. (3) and it shows that, for the present conditions, the sodium atom does not exhibit two-level behavior, as was expected. Another estimate for f is obtained by taking f to be constant over the interaction length L which, however, is not well defined. Somewhat arbitrarily taking $L=2w_0=0.24$ cm yields $f=0.36$. From these considerations we conclude that the data of Fig. 5 indicate a fractional atomic excitation of somewhere between 0.30 and 0.40 for an intensity of 11 W/cm^2. Since $f=0.24$ for $I=1$ W/cm^2, it is clear that the atom is quite strongly saturated, in fact, more so than would be indicated by the two-level model.

The agreement of the theoretical profiles for the deflected atomic beam with the experimental observations is reasonable even though some discrepancies are readily apparent. There are several possible explanations for the differences. First, the model we have used is very simple and the quantum fluctuations, for example, have not been included. Second, we have not verified that the atomic beam is actually effusive and that it has the usual Maxwellian velocity distribution. The most important and likely reason for discrepancies, however, was the slow drift of the central laser frequencies during scanning of the atomic-beam profiles. Drift of approximately 25 MHz greatly affected the magnitude of the atomic-beam deflection and such drifts were a continuing experimental problem. The discrepancies between the theoretical and experimental profiles observed in Figs. 4 and 5 could easily be explained by laser frequency drift alone. Finally, as previously discussed, the Doppler shifts associated with the induced transverse velocities are not important because of power broadening. For example, in Fig. 4, the largest atomic deflections are about 2 mm which corresponds to $\Delta\theta\approx7\times10^{-3}$ rad, $v\approx8\times10^4$ cm/sec, and a transverse velocity of about 600 cm/sec. This corresponds to a Doppler shift of 10 MHz, but the power broadened linewidth is about 70 MHz. For a deflection of 2 mm, the corresponding value for $\bar{N}$ is 200.

IV. CONCLUSION

We have utilized illumination by two precisely tuned lasers to bring about large deflections of an atomic beam of sodium. The use of two lasers

makes it possible to interact with all the atoms in the atomic beam and to avoid optical pumping of the sodium ground state. Fractional atomic excitation values of 0.24 for an intensity of 1 W/cm^2, and approximately 0.35 for 11 W/cm^2, have been obtained. Angular deflections as large as 7×10^{-3} rad, many times the atomic-beam divergence angle, have been observed. Even larger deflections should be obtainable with the same laser powers used in this experiment simply by increasing the interaction length. We have demonstrated the possibility of efficiently interacting with an ensemble of atoms for a large number of natural lifetimes without inducing optical pumping. This is important to possible applications of resonance-radiation pressure such as cooling of gases and of atoms in optical traps.

ACKNOWLEDGMENT

The authors are grateful to W. D. Phillips and J. L. Picque for helpful comments on the manuscript.

[1]A. Ashkin, Phys. Rev. Lett. 25, 1321 (1970).
[2]O. R. Frisch, Z. Phys. 86, 42 (1933).
[3]J. L. Picque and J. L. Vialle, Opt. Commun. 5, 402 (1972).
[4]R. Schieder, H. Walther, and L. Woste, Opt. Commun. 5, 337 (1972).
[5]B. Jaduszliwer, R. Dang, P. Weiss, and B. Bederson, Phys. Rev. A 21, 808 (1980).
[6]V. S. Letokhov, V. G. Minogin, and B. D. Pavlik, Opt. Commun. 19, 72 (1976).
[7]A. Ashkin, Phys. Rev. Lett. 40, 729 (1978).
[8]J. E. Bjorkholm, R. R. Freeman, A. Ashkin, and D. B. Pearson, Phys. Rev. Lett. 41, 1361 (1978).
[9]D. B. Pearson, R. R. Freeman, J. E. Bjorkholm, and A. Ashkin, Appl. Phys. Lett. 36, 99 (1980).
[10]J. E. Bjorkholm, R. R. Freeman, A. Ashkin, and D. B. Pearson, Opt. Lett. 5, 111 (1980).
[11]G. A. Askar'yan, Zh. Eksp. Teor. Fiz. 42, 1567 (1962) [Sov. Phys.—JETP 15, 1088 (1962)].
[12]For example, see G. M. Carter, D. E. Pritchard, and T. W. Ducas, Appl. Phys. Lett. 27, 498 (1975); and references therein. Also see, J. A. Abate, Opt. Commun. 10, 269 (1974); and R. E. Grove, F. Y. Wu, and S. Ezekiel, Phys. Rev. A 15, 227 (1977).
[13]M. L. Citron, H. R. Gray, C. W. Gabel, and C. R. Stroud Jr., Phys. Rev. A 16, 1507 (1977).
[14]A. F. Bernhardt, D. E. Duerre, J. R. Simpson, and L. L. Wood, Appl. Phys. Lett. 25, 617 (1974).
[15]W. Neuhauser, M. Hohenstatt, P. E. Toschek, and H. Dehmelt, Phys. Rev. Lett. 41, 233 (1978).
[16]P. Jacquinot, S. Liberman, J.L. Picque, and J. Pinard, Opt. Commun. 8, 163 (1973).
[17]T. W. Hansch and A. L. Schawlow, Opt. Commun. 13, 68 (1975).
[18]V. I. Balykin, V. S. Letokhov, and V. I. Mushin, Zh. Eksp. Teor. Fiz. Pis'ma Red 10, 614 (1979) [JETP Lett. 29, 560 (1979)].
[19]D. J. Wineland, R. E. Drullinger, and F. L. Walls, Phys. Rev. Lett. 40, 1639 (1978).
[20]A. Ashkin and J. P. Gordon, Opt. Lett. 4, 161 (1979).
[21]L. Mandel, Opt. Lett. 4, 205 (1979).
[22]R. J. Cook (private communication).
[23]L. Mandel, J. Opt. (Paris) 10, 51 (1979).
[24]J. L. Picque, Phys. Rev. A 19, 1622 (1979).
[25]Calculations of the distribution of deflection angles due to the photon statistics have been independently carried out by R. J. Cook and J. L. Picque (private communications).
[26]S. Datz and E. H. Taylor, J. Chem. Phys. 25, 389 (1956).