Observation of a stimulated radiation pressure of amplitude-modulated light on atoms

V. S. Voĭtsekhovich, M. V. Danileĭko, A. M. Negriĭko, V. I. Romanenko, and L. P. Yatsenko

Institute of Physics, Academy of Sciences of the Ukrainian SSR

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A stimulated radiation pressure on atoms which arises because of an ordering of photon-absorption and photon-emission events in the field of counterpropagating amplitude-modulated waves has been observed experimentally for the first time.

The radiation pressure which results from the transfer of a momentum $\hbar k$ to an atom in the resonant scattering of photons has been studied thoroughly and is widely used to control the motion of atoms.[1] The momentum of an atom can be changed significantly if the interaction of the atom with a field can be made cyclic. This is possible only if there is a transition from a ground (or metastable) state to a short-lived level which decays spontaneously and exclusively to a lower-lying state. For a traveling plane wave, the maximum force (F_p) of the resonant radiation pressure is determined by the rate of the 2γ decay of the upper level and is given by $F_p = \hbar k\gamma$.

The need for large values of γ and for a cyclic interaction of the atom with the field makes it difficult to observe a radiation pressure exerted on molecules and most atoms. It is thus interesting to examine the stimulated radiation pressure that can arise in the field of two waves which differ in propagation direction.[2,3] Since the photon reradiation rate is not limited by the value of γ in this case, one can expect both a radiation-pressure force significantly higher than F_p and a substantial increase in the list of entities which can be studied (including molecules).

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The possibility of ordering absorption events and stimulated-emission events in such a way that a stimulated radiation pressure develops can be illustrated in the ideal case in which each of two counterpropagating waves consists of a train of π pulses with a repetition period $T \ll 1/\gamma$. Over a time T an atom absorbs a photon from one wave and reverts to the ground state, emitting a photon into the other wave. As a result of the recoil, the total momentum change of the atom is $2\hbar k$. If the duration (T_{int}) of the interaction of the atom with the field is short, satisfying $T \ll T_{\text{int}} < 1/\gamma$, the force acting on the atom,

$$F = 2\hbar k/T, \tag{1}$$

will be significantly greater than F_p. If this duration is instead long, satisfying $T_{\text{int}} > 1/\gamma$, the force F is given by the following expression for a two-level atom which is interacting with short pulses of one of the waves at time nT and with short pulses of the other wave at times $nT + \tau$ the analysis which leads to this expression will be reported in a more-detailed paper):

$$F = \frac{2\hbar k}{T}\left(1 - \frac{2\tau}{T}\right)\phi\left(\sin^2 \frac{\theta}{2}\right), \tag{2}$$

where $\phi(x) = x(\sqrt{1-x} + \sqrt{1+x})[\sqrt{1+x}(1+\sqrt{1-x^2})]^{-1}$, and θ is the area under the pulse. It can be seen from expression (2), which was derived for arbitrary θ, that the condition $\theta = \pi$ is not a necessary condition for the occurrence of a stimulated radiation pressure. Points of fundamental importance here are the modulation of the amplitudes of the counterpropagating waves and the difference between the phases of this modulation: $\tau \neq 0, T/2$. The simplest example of a field of this type is the field of two standing waves with different frequencies $\omega_1 \neq \omega_2$:

$$E = \mathcal{E} \sin \omega_1 t \sin k_1 z + \mathcal{E} \sin \omega_2 t \sin k_2 z\,. \tag{3}$$

This field essentially consists of two counterpropagating amplitude-modulated traveling waves, for which the amplitude modulations differ in phase by $\varphi = (k_1 - k_2)z = (\omega_1 - \omega_2/c)/z$. A calculation[3] of the force F which is acting on a two-level item in a field of this sort shows that this force differs from (2) by a factor of only 2–2.5. The role of the time delay φ is played by the phase difference φ, and the force F is an odd periodic function of φ with a period of π.

Figure 1 shows the experimental arrangement used to observe the stimulated radiation pressure. The cw dye laser 5 operated at two frequencies, which were separated by 1.67 GHz. The field in the resonator of this sort is a fairly close approximation of field (3). The phase difference φ was determined by the distance (l) from mirror M_3, which was 0 at the mirror itself and which changed by π at $l = 9$ cm. The maximum field intensity in the resonator was $\sim$20 W/cm^2. A beam of sodium atoms passing through the resonator in the direction perpendicular to the laser beam had a divergence of 5×10^{-3} rad. The beam diameter in the region of the interaction with the field was 0.5 mm; the density of atoms in the beam was $\sim 10^7$ cm^{-3}; and the average velocity of the atoms was 830 m/s. The diameter of the laser beam was 2 mm. The transverse spatial distribution of the atoms in the beam was measured at a point

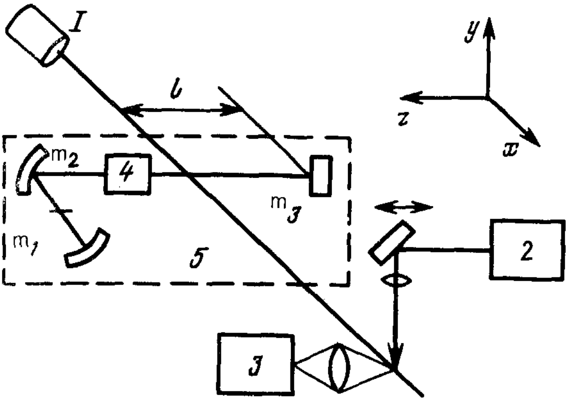

FIG. 1. Experimental layout. 1—Source of atoms; 2—probing laser; 3—photomultipler; 4—frequency selector; 5—deflecting laser; M_1, M_2, M_3—mirrors of the laser resonator.

35 cm from the interaction region, with the help of a second two-frequency cw dye laser, whose output was directed perpendicular to both the atomic beam and the beam of the deflecting laser; it was focused into a spot $\sim 80\ \mu$m in size. The beam from this laser was scanned in the direction perpendicular to the atomic beam; the fluorescence signal was detected with a photomultiplier.

When the deflecting laser was tuned to the sodium D_2 line, we observed a deflec-

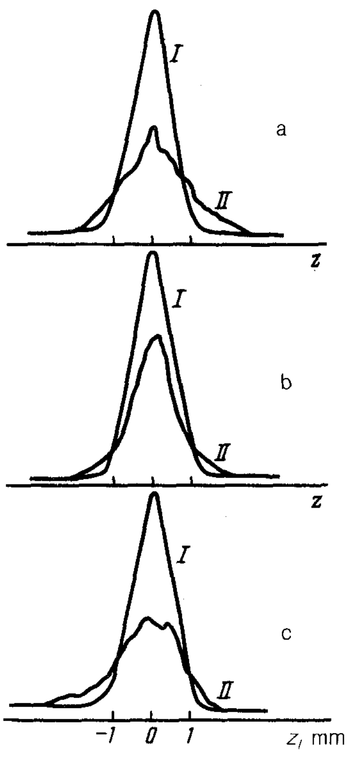

FIG. 2. Shape of the atomic beam (I) without and (II) with the application of light from the deflecting laser. a—$\varphi = \pi/4$; b—$\varphi = 0$; c—$\varphi = \pi/4$.

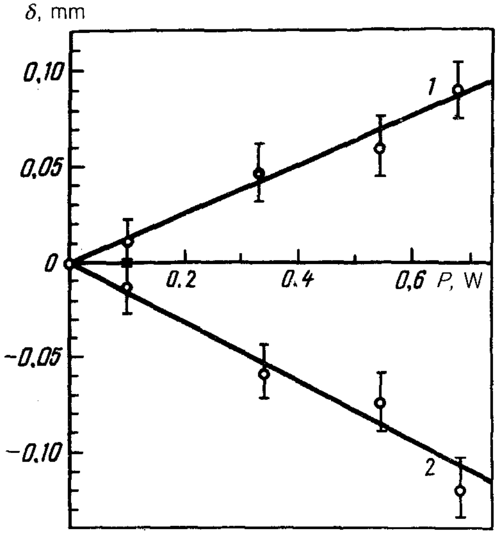

FIG. 3. Shift of the center of gravity of the beam profile versus the power inside the resonator. 1—$\varphi = \pi/4$; 2—$\varphi = -\pi/4$.

tion of the atomic beam, with a magnitude and sign which depended periodically on the phase difference φ. Figure 2 shows the shape of the atomic beam for $\varphi = 0$, $\pm \pi/4$. In addition to the beam broadening which is characteristic of an interaction with the field of an intense standing wave,[4] at $\varphi = \pm \pi/4$ there is a shift of the center of gravity of the beam profile; and the sign of this shift is different in the cases $\varphi = \pi/4$ and $\varphi = -\pi/4$. At $\varphi = 0$ the spatial distribution of the atoms in the beam remains symmetric. The shift (δ) of the center of gravity of the beam profile is a nearly linear function of the power inside the resonator (Fig. 3). This result agrees qualitatively with expression (2) at $\theta \ll 1$.

These features of the observed deflection of the atomic beam in the field of two standing waves with different frequencies are consistent with the conclusion that this deflection is caused by the force of a stimulated radiation pressure. The maximum force observed was $F \approx 0.8\hbar k\gamma$; a significantly higher value could be achieved through a corresponding increase in the power of the deflecting laser.

The stimulated radiation pressure, seen first in these experiments, may prove useful for effectively controlling the motion of atoms and molecules. In particular, the dependence of the stimulated radiation pressure on φ and thus on the coordinate z would make it possible to devise an optical trap for neutral atoms with a potential well of depth $(\hbar k/2\pi[(\omega_1 - \omega_2)^2 a^2/c]$, where a is a length scale of the trap, according to our estimates. With $a \approx 1$ mm, $\omega_1 - \omega_2 = 1.7$ GHz, and $\lambda = 0.6\ \mu$m the value of ΔU would be ~ 5 K.

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