Observation of a magnetooptic radiation force

R. Grimm, V. S. Letokhov, Yu. B. Ovchinnikov, and A. I. Sidorov
Institute of Spectroscopy, Academy of Sciences of the USSR, 142092, Troitsk, Moscow Oblast'

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A new magnetooptic force has been observed in some experiments reported here. This force acts on atoms in a magnetic field and in the resonant field of two counterpropagating monochromatic laser beams with polarization vectors in different directions.

A static magnetic field can alter the effect of light on the translational motion of atoms. The effect exerted by a static magnetic field on the spontaneous radiation-pressure force as a result of the Zeeman shift of the magnetic sublevels of atoms[1] was studied in Refs. 1 and 2. In this letter we are reporting the first experimental proof of the existence of a new *magnetooptic radiation force*. The reason for this force is that, for an atom in a magnetic field, an anisotropy arises in the *stimulated* reradiation of photons between counterpropagating light waves whose polarization vectors are in different directions.

The mechanism for the appearance of this force has a simple classical interpretation. We consider an atom in a static magnetic field. Counterpropagating, linearly polarized, monochromatic waves are applied to this atom. The angle between the polarization vectors of these waves is $\varphi = 45°$ (Fig. 1). These waves are tuned to resonance with a transition of the atom. The absorption of a photon from wave 1, in the course of which an atom acquires a recoil momentum $+\hbar k$, directed along the z axis, is associated with an induced electric dipole moment which is oriented along the y axis. Since there is a magnetic field,[3] this induced electric dipole moment precesses around the z axis at the Larmor frequency $\omega_L = B(e/2mc)$ (the Landé factor is $g = 1$). We assume that the optical Rabi frequency ω_R has been chosen in such a way that the maximum probability for the stimulated emission of a photon is reached at the time $\tau = \pi/\omega_R = \pi/(4\omega_L)$, over which the induced electric dipole moment rotates through an angle of 45°. The direction of this moment is then the same as that of the polarization vector of wave 2 (Fig. 1). The probability for a stimulated emission into wave 2 is higher than that for emission into wave 1. Overall, the atom undergoes a momentum change of $+2\hbar k$ during the absorption of a photon from wave 1 and the emission of a photon into wave 2.

At a time τ after the absorption of a photon from wave 2, the induced electric dipole moment rotates through an angle of 45°. As a result, the angle between this moment and the polarization vector of wave 1 becomes equal to 90°. The probability for a stimulated emission into wave 1 (and thus a change $-2\hbar k$ in the momentum of the atom) is therefore greatly reduced.

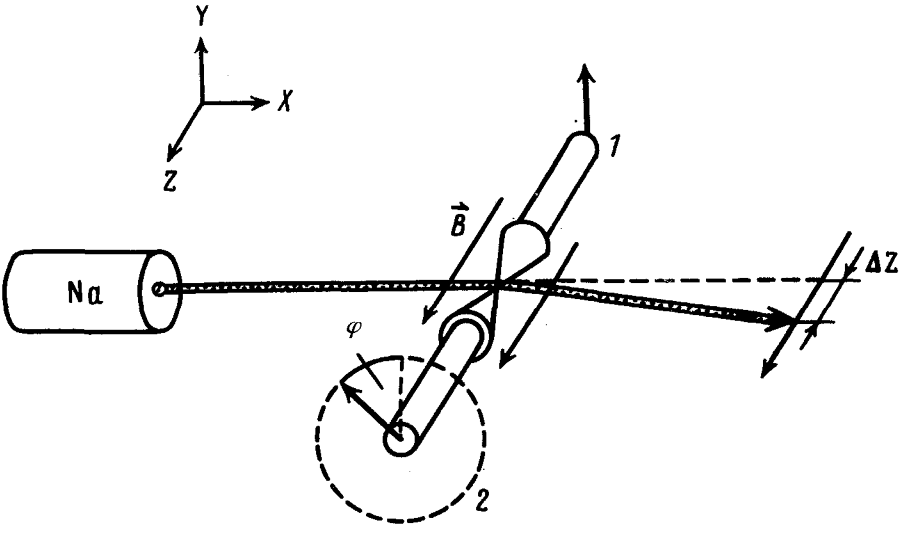

FIG. 1. Experimental layout for observing the deflection of an atomic beam by the magnetooptic force.

In the ideal case, the minimum time for the transfer of two photons from wave 1 to wave 2 and for a change of $+4\hbar k$ in the momentum of the atom is determined by the Larmor precession period $2\pi/\omega_L$. Correspondingly, the force can be written

$$F_{MO} = \alpha 2\hbar k\omega_L/\pi, \tag{1}$$

where α (the photon transfer efficiency) depends on the parameters of the laser light and the parameters of the atomic transition. We would like to call attention to two properties of this force. First, its magnitude is zero in the case $\varphi = n\times 90°$ $(n = 0,1,2,...)$, because the probabilities for the stimulated reradiation of photons between waves are equal. Second, this force reverses direction upon a change in the sign of φ or a reversal of the magnetic field. The magnetooptic force can also be discussed in terms of a rectified dipole force.[4,5]

Figure 1 shows the layout of an experiment carried out to test the existence of a magnetooptic force. A beam of Na atoms is formed by two diaphragms 0.25 mm in diameter, separated by a distance of 290 mm. At a distance of 10 mm from the last diaphragm, the atomic beam intersects, at right angles, the two counterpropagating laser beams (Fig. 1). The diameter of the laser beams is $2q = 0.4$ mm. The radiant power in each beam is $P = 8$ mW, and the corresponding Rabi frequency is $\omega_R \simeq 2\pi\times 200$ MHz. The direction of the polarization of one of the beams can be varied continuously with the help of a $\lambda/2$ plate. The frequency of the laser light is tuned to resonance with the $3^2S_{1/2}(F=2)\rightarrow 3^2P_{3/2}(F'=3)$ transition of the Na atom.

A static magnetic field with an induction $B \simeq 35$ G ($\omega_L = 2\pi \times 50$ MHz) is produced by Helmholtz coils in the volume in which the light interacts with the atoms. To compensate for the optical pumping, which depopulates the $F = 2$ level, we use an auxiliary perpendicular laser beam, tuned to resonance with the $F = 1 \rightarrow F' = 2$ transition. The transverse spatial distribution of the atoms in the beam is detected at a distance $L = 290$ mm from the interaction volume, with the help of a spatially scannable laser beam. The angle between the latter beam (the test beam) and the atomic beam is 78°. The frequency of the test light is 250 MHz away from the $F = 2 \rightarrow F' = 3$ transition, so only atoms with a longitudinal velocity $v_{\|} = 700$ m/s are detected.

Figure 2 shows profiles of the atomic beam found for the case $\varphi = 45°$ (Fig. 1). In this case, the frequency of the deflecting field was tuned exactly to resonance with the $F = 2 \rightarrow F' = 3$ transition. As expected on the basis of the theoretical model, the direction in which the atomic beam was deflected was determined by the direction of the magnetic field. When the field was oriented along the $\pm z$ direction, the average displacement of the center of the beam turned out to be ± 0.15 mm. This result corresponds to an average magnetooptic force $\langle F_{\mathrm{MO}} \rangle = Mv^2 \Delta z / 2qL \simeq \pm 0.7\hbar k \gamma$. The efficiency of the reradiation of photons is $\alpha \simeq 0.11$.

In a separate experiment we measured the behavior of the beam deflection as a function of the polarization angle φ, for the magnetic field direction indicated in Fig. 1. In this case we did not compensate for the optical pumping. The deflecting laser light was tuned to a frequency 50 MHz above that of the $F = 2 \rightarrow F' = 3$ transition. Because of the optical pumping, only a fraction $\sim 1/60$ of the initial number of atoms remained in the $F = 2$ working sublevel. The measurements showed that the magnetooptic force disappears in the parallel and orthogonal polarizations of the laser beams. The maximum displacement is observed at $\varphi \simeq \pm 45°$.

A noteworthy property of this force is that it is based on stimulated transitions, so its absolute value is in principle not limited by the value of $\hbar k \gamma$, as it would be in the

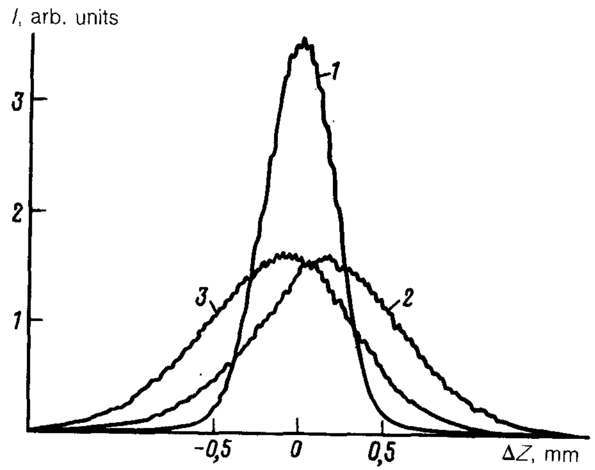

FIG. 2. Profiles of the atomic beam. 1—With the laser field turned off; 2,3—with the laser field turned on, with the magnetic field directed as in Fig. 1 and in the opposite direction.

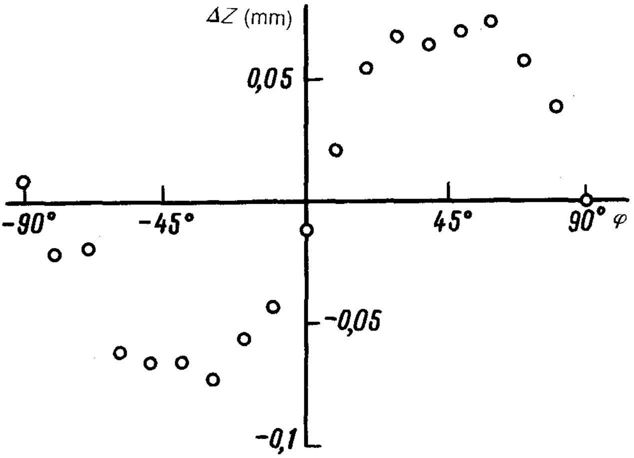

FIG. 3. Displacement of the atomic beam versus the angle φ.

case of a spontaneous radiation-pressure force.[1] The magnetooptic force thus looks very interesting for gaining effective control over the motion of atoms, in particular, for developing new, ultradeep magnetooptic traps for atoms.

In conclusion we thank our colleagues in the Atomic Physics Department of the Max Planck Institute of Nuclear Physics and at Heidelberg University for some useful discussions.

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