Reflection of an atomic beam from a gradient of an optical field

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A specular reflection of a thermal atomic beam from the gradient of a laser field has been seen experimentally for the first time. The reflection coefficient of this "atomic mirror" is close to 100%.

An atom in a nonuniform electromagnetic field experiences a force proportional to the induced dipole moment of the atom and to the gradient of the field. Askar'yan[1] was the first to point out that the gradient of an optical field might have an effect on the motion of atoms. It has been suggested that a gradient force might be used to capture atoms at the antinodes of a standing light wave[2] or in the field of a sharply focused laser beam.[3] Pearson *et al.*[4] have demonstrated the focusing of an atomic beam by a gradient force. Cook and Hill[5] have suggested using the gradient of an optical field to reflect atoms.

In the present letter we report the first experimental demonstration of the specular reflection of a thermal atomic beam from the gradient of a laser field. To produce this "atomic mirror" we made use of the total internal reflection of a laser beam from a dielectric-vacuum interface[5] (Fig. 1). The field in vacuum decays over a distance $\sim\lambda/2$. A huge gradient in the electric field is created here. The reflection of an atom from this mirror may be treated as the motion of an atom in a potential field[6]

$$U_{\mathrm{grad}}(x)=\frac{1}{2}\hbar(\Delta-kv_{\parallel})\ln\{1+G/[1+(\Delta-kv_{\parallel})^2/\gamma^2]\}, \tag{1}$$

where $\Delta=\omega-\omega_0$ is the positive deviation of the laser frequency ω from the frequency of the atomic transition, ω_0; 2γ is the natural width of the absorption line; $v_{\parallel}$ is the longitudinal velocity of the atoms; $G(x)=I(x)/I_s$ is the saturation parameter of the atomic transition; I_s is the transition saturation intensity; and $I(x)$ is the intensity of the laser beam. Using energy conservation, one can prove that it would be possible to achieve a specular reflection of an atom from a potential of this type.

If an atom, as it is moving in the potential field, nevertheless reaches the surface of the dielectric, there will be an ordinary diffuse reflection from the dielectric, instead of a specular reflection. This circumstance imposes an upper limit on the transverse velocity:

$$v_x^{max}=\left[\frac{2U_{\mathrm{grad}}(0)}{M}\right]^{1/2}=\left\{\frac{\hbar(\Delta-kv_{\parallel})}{M}\ln\left[1+\frac{G(0)}{1+(\Delta-kv_{\parallel})^2/\gamma^2}\right]\right\}^{1/2}. \tag{2}$$

For the typical parameter values of, for example, Na atoms and tunable laser light

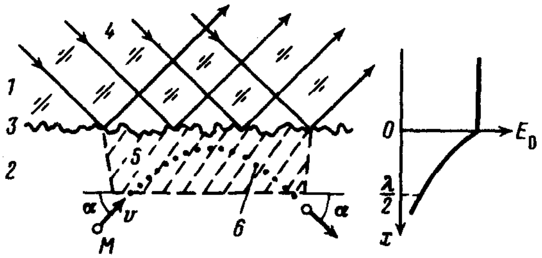

FIG. 1. Layout of the "atomic mirror." 1—Dielectric: 2—vacuum; 3—interface; 4—laser field in the dielectric; 5—laser field in a vacuum; 6—trajectory of an atom in the laser field.

($M = 4\times 10^{-23}$ g, $v_{\parallel} = 6\times 10^4$ cm/s, $\gamma/2\pi = 5$ MHz, $k = 10^5$ cm^{-1}, $P_l = 1$ W, $G = 10^5$, and $\Delta/2\pi = 2.6$ GHz), we find $v_x^{\max} = 410$ cm/s; correspondingly, the maximum glancing angle is $\alpha_{\max} = v_x^{\max}/v_{\parallel} = 7\times 10^{-3}$ rad.

In the present experiments, a beam of sodium atoms is produced by an aperture 0.4 mm in diameter in the source and by a rectangular slit 220 mm from the gun. The horizontal dimension of this slit is 0.1 mm, and its vertical dimension is 0.4 mm. The "atomic mirror" which reflects atoms in a horizontal plane is positioned 15 mm from the slit. This mirror consists of a parallel-face plate of fused quartz 0.4 mm thick and 25 mm long, which the laser beam enters through a skewed face. The diameter of the laser beam is 0.4 mm at the I/e level. We make use of multiple total internal reflection

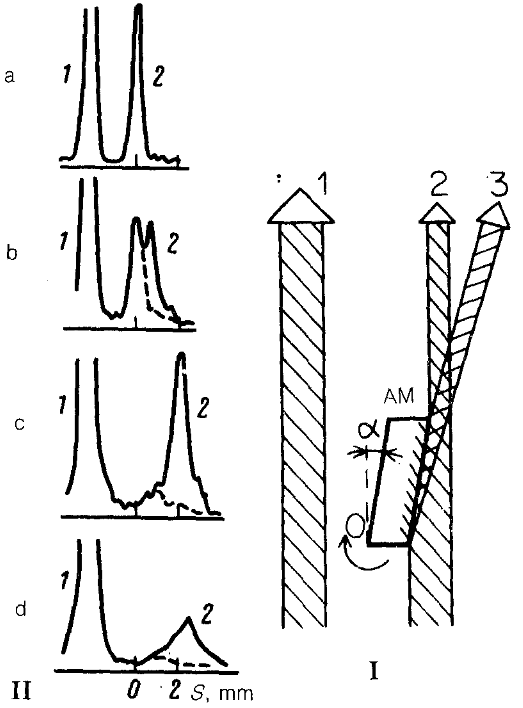

FIG. 2. I: Trajectories of atomic beams in an experiment on the specular reflection of atoms. 1—Calibration atomic beam; 2—beam of atoms that have passed by the mirror; 3—reflected atomic beam; AM—"atomic mirror"; O-rotation axis of the "mirror"; α-glancing angle. II: Profiles of (1) the calibration atomic beam, (2) an atomic beam that has passed by the mirror, and (3) a reflected atomic beam in the measurement zone. The dashed lines show the profiles of the atomic beam in the case $P_l = 0$. The parameters of the laser light and of the atomic beam are $P_l = 650$ mW, $\Delta = 2.6$ GHz, and $v_{\parallel} = 4\times 10^4$ cm/s. The glancing angles α are: a—0; b—1.1×10^{-3} rad; c—3.3×10^{-3} rad; d—5.5×10^{-3} rad.

of the laser beam in this plate. The power of the laser beam is 650 mW. The residual gas pressure in the vacuum chamber is no worse than 5×10^{-6} torr.

In the experiments we also use a second atomic beam, for calibration. We measure the displacement of the reflected beam with respect to this calibration beam and also the number of reflected atoms. The measurement zone is 330 mm away from the slit. Profiles of the atomic beams are recorded with the help of a single-frequency probing beam tuned to the frequency of the $3S_{1/2}\rightarrow3P_{3/2}$ transition. The probing beam makes an angle of 83° with the axis of the atomic beam and is scanned over space. We tune the frequency of the probing beam to a certain part of the Doppler lineshape ($\Delta v_D\sim250$ MHz) and measure the fluorescence from atoms with a certain longitudinal velocity.

Figure 2 shows profiles of the calibration atomic beam and of the deflected atomic beam for the case in which the deviation of the frequency of the strong field from the resonant frequency is $\Delta=2.6$ GHz. The atoms that are probed have a longitudinal velocity of 4×10^4 cm/s. Figure 2a corresponds to the case in which the atomic mirror is parallel to the axis of the beam, and the atoms pass by the mirror. At a small inclination angle α (Fig. 2b), part of the atomic beam passes by the mirror, while part is reflected from it, giving rise to the second peak on the right. As the inclination angle is increased (Fig. 2c), the mirror completely blocks the atomic beam. The number of reflected atoms increases, as does the displacement of the reflected beam. With a further increase in the inclination angle (Fig. 2d), the number of reflected atoms decreases, since the atoms reach the surface of the mirror and are reflected from it in a diffuse manner.

Figure 3 shows a plot of the displacement of the reflected beam, s, in the measurement zone versus the glancing angle α. The solid line represents specular reflection of the atoms. At large values of the glancing angle α we see a significant discrepancy between the course of the experimental points and the calculated line. The reason for this discrepancy is that the divergence of the atomic beam ($\Delta\varphi=2.3\times10^{-3}$ rad) is comparable to the angle α. Atoms with large transverse velocities reach the surface and are reflected in a diffuse manner, so that the transverse velocity distribution is cut off at high velocities. The angle through which the atoms are deflected becomes smaller than the calculated value.

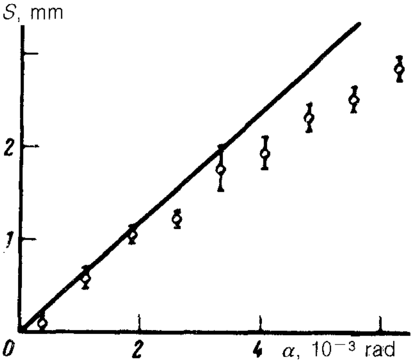

FIG. 3. Displacement of the reflected atomic beam, s, in the measurement zone versus the glancing angle of the incident atomic beam, α.

An important parameter of any mirror is its reflection coefficient. At small glancing angles, the atomic mirror has a reflection coefficient of close to 100%, according to our measurements. As the angle α is increased, a progressively larger number of atoms reaches the surface and is reflected from it in a diffuse manner. The reflection coefficient accordingly falls off, reaching 10% at $\alpha = 6.3\times10^{-3}$ rad.

In summary, these results show that this atomic mirror is suitable for reflecting thermal atomic beams. The angle through which atoms and molecules can be deflected can be increased by using high-power pulsed lasers or by increasing the number of reflections of atoms from the mirror. There is the further possibility of using a concave atomic mirror to focus a thermal atomic beam. Since the duration of the interaction of the atoms with the light is short, velocity diffusion due to spontaneous reradiation of photons is slight. Consequently, an atomic beam can be focused to dimensions comparable to the de Broglie wavelength of the atom. This study hints at some new opportunities for developing an optics of neutral atoms.

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