Quantum-State–Selective Mirror Reflection of Atoms by Laser Light

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We have demonstrated the specular reflection of Na atoms at a nonuniform laser field, the reflection coefficient of the "atomic mirror" being close to 100%. A specific feature of the reflection process is its quantum-state–selective character. The experimentally measured reflection selectivity (the ratio between the reflection coefficients of the sodium atoms in the ground-state sublevels with $F=2$ and $F=1$) was around 100.

The motion of an atom in a nonuniform quasiresonant electromagnetic field is determined by radiation force consisting of two components—the light pressure force and the gradient (dipole) force.[1,2] In the case of a spatially inhomogeneous, sufficiently intense quasiresonant radiation, the translational motion of the atom is governed mainly by the gradient force. Proposals that this force should be used to localize or channel atoms in a standing light wave[3] or to trap atoms in the waist of a sharply focused laser beam[4] have long been known. Experiments were carried out on focusing an atomic beam[5] and trapping atoms in the waist of a Gaussian laser beam,[6] and on channeling atoms in a standing light wave.[7]

Of interest was the suggestion made by Cook and Hill[8] that a nonuniform laser field can be used to reflect slow atoms. In the work reported by Balykin *et al.*,[9] the mirror reflection of a thermal atomic beam from an "atomic mirror" was experimentally realized for the first time. In this paper we present experimental data on the observation of the most important property of the atomic mirror, namely, the property of quantum-state–selective reflection of atoms.

The idea of the atomic mirror is as follows [Fig. 1(a)].[8] When a plane traveling light wave is totally reflected internally at the surface of a dielectric in a vacuum a thin wave is generated on the surface. In the direction OY normal to the surface, this wave decays at a distance of $d=\lambda(\sin^2\theta-n^{-2})^{-1/2}/2\pi\approx\lambda/2$,[10] where λ is the length of the light wave, θ the angle of incidence of the wave, and n the refractive index of the dielectric. It is this surface wave that serves as an atomic mirror for an atom running into it. Indeed, a two-level atom near the surface experiences the gradient force[8]

$$\frac{F_{\text{grad}}(y)=\alpha\hbar(\Delta-k_1 v_x)G(y)}{1+G(y)+(\Delta-k_1 v_x)^2/\gamma^2},\qquad(1)$$

where $\alpha=k(\sin^2\theta-n^{-2})^{1/2}$ and $k_1=k\sin\theta$ are the imaginary and real components of the wave vector k, $\Delta-k_1 v_x=\omega-\omega_0-k_1 v_x$ is the detuning of the laser frequency ω relative to the transition frequency ω_0 with ac-

count being taken of the Doppler shift $k_1 v_x$, v_x is the x component of the atomic velocity, $2\gamma=1/\tau$ is the natural linewidth, τ is the lifetime of the excited state, and $G=I(y)/I_{\text{sat}}$ is the saturation parameter, $I(y)$ being the laser intensity and I_{sat} the transition saturation intensity.

With a positive detuning $(\Delta-k_1 v_x>0)$, the gradient force expels the atom out of the field. The reflection of the atom at the "mirror" may be considered a result of its being expelled out of a potential field whose energy is

$$U(y)=\tfrac{1}{2}\hbar(\Delta-k_1 v_x)\ln\left[\frac{1+G(y)}{1+(\Delta-k_1 v_x)^2/\gamma^2}\right].\qquad(2)$$

It can be demonstrated from consideration of the atomic motion in field (2) that the angle of reflection of the atom is equal to the angle of incidence, which means that what we have here is the specular reflection of the atom. With the transverse atomic velocity component v_y being great enough $\{v_y>v_y^{\max}=[2U(0)/M]^{1/2}$, M being the atomic mass$\}$, the atom reaches the surface. In that case, it either adheres to the surface or is reflected from the surface. Usually reflection of atoms by surface is diffuse. Specular reflection can occur when de Broglie wavelength of atom divided by the grazing angle ψ is
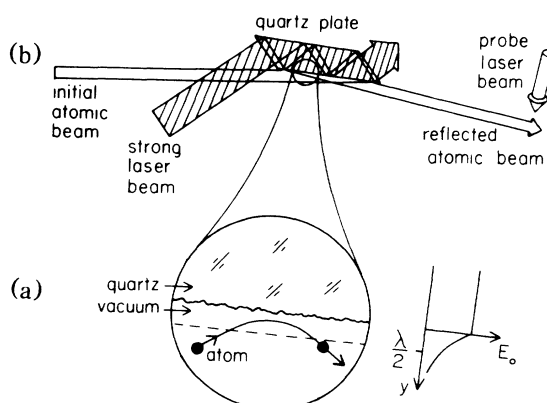

FIG. 1. (a) Principle of mirror reflection of atoms by nonuniform laser field of surface wave. (b) Schematic diagram of experimental setup.

larger than the local surface roughness.[11] For typical atomic parameters (e.g., for the sodium atom) $M = 4 \times 10^{-23}$ g, $v_x = 6 \times 10^4$ cm/s, and $\gamma/2\pi = 5$ MHz, and tunable-laser-radiation parameters $k_1 = 10^5$ cm^{-1}, $G(0) = 10^5$, and $\Delta/2\pi = +2.6$ GHz, we have $v_y^{max} = 430$ cm/s. Accordingly, for thermal atomic velocities, the maximum grazing angle $\psi_{max} = v_y^{max}/v_x = 7 \times 10^{-3}$ rad.

That the atomic reflection is quantum-state selective follows from the character of the relationship between gradient force (1) and the detuning $\Delta - k_1 v_x$. When the detuning is positive, the gradient force repels the atom from the surface and thus the specular reflection of the atom is effected. With a negative detuning, the force attracts the atom to the surface, and so diffuse reflection is observed.

Let an atom (or molecule) have several sublevels in the ground state. For atoms, these may be, for example, fine and hyperfine ground-state splitting components (and for molecules, the vibrational-rotational sublevels of the ground state). Atoms (molecules) on a sublevel for which the frequency of transition to an excited state is lower than the laser frequency are reflected from the atomic mirror. Thus, if a beam of atoms (molecules) distributed among several ground-state sublevels is incident upon the mirror, the reflected beam will contain only atoms in one and the same quantum state. Since the expression for the gradient force (1) includes the Doppler shift, the minimum distance between the lower sublevels at which the quantum-state–selective reflection will still obtain is determined by the magnitude of the Doppler broadening.

We have studied the quantum-state–selective reflection of the sodium atoms. The ground state of Na, $3S_{1/2}$, is split, because of hyperfine interaction, into two sublevels, one with the quantum number $F = 2$ and the other with $F = 1$, the distance between which is equal to 1772 MHz. According to the statistical weights of these sublevels, 62.5% of sodium atoms in a thermal beam are on the sublevel with $F = 2$ and 37.5% on that with $F = 1$. If the laser frequency ω is selected so that the condition $\omega_{20} + k_1 v_x < \omega < \omega_{10} + k_1 v_x$ (ω_{10} and ω_{20} being the frequencies of transitions from the sublevels with $F = 1$ and $F = 2$ to the excited state $3P_{3/2}$) is satisfied, the reflected beam will contain only atoms in the quantum state with $F = 2$.

The beam of sodium atoms [Fig. 1(b)] was formed by a 400-μm-diam hole in the source and a square slit measuring 85 μm horizontally by 400 μm vertically and placed at a distance of 220 mm from the oven. The atomic mirror reflecting the atoms in a horizontal plane was at a distance of 15 mm from the slit. It was a plane-parallel plate of fused quartz 0.4 mm thick and 25 mm long into which a single-frequency laser beam was directed through a beveled side. To increase the surface area of the atomic mirror, use was made of multiple total internal reflection in the plate. The laser beam diameter

was 0.5 mm at the $1/e^2$ level. The laser power was 300 mW. The grazing angle ψ was 2×10^{-3} rad. The plate surface was finished to an accuracy of $\lambda/10$. To prevent the atoms from being deposited onto the surface, the plate was heated to around 150°C. The residual gas pressure in the vacuum chamber was no worse than 5×10^{-6} Torr.

The detection region was 330 mm distant from the slit. The atomic intensity in the beam was registered by means of a single-frequency probe laser beam which crossed the reflected atomic beam at an angle of 76° in a vertical plane. The probe laser frequency was scanned over the $3S_{1/2} \rightarrow 3P_{3/2}$ transition, which made it possible to monitor the presence in the beam of atoms on the sublevels with $F = 2$ and $F = 1$.

Figure 2 demonstrates the results of the quantum-state-selective reflection of sodium atoms at the atomic mirror. The frequency ω of the intense laser radiation is measured relative to the frequency $\omega_{20} + k_1 v_p$ of the
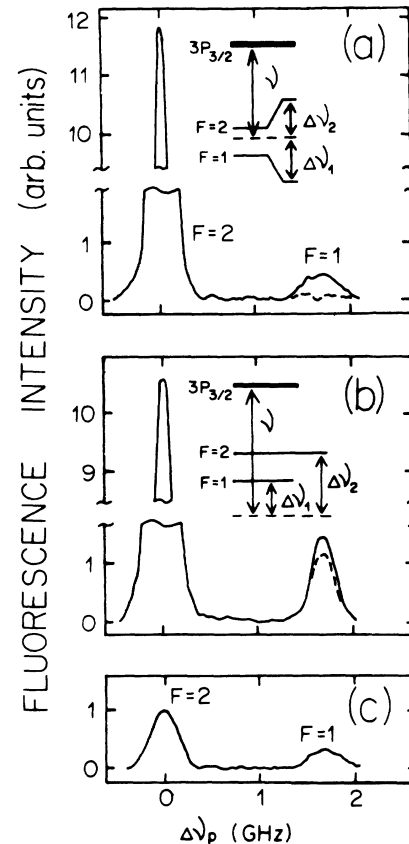
FIG. 2. Quantum-state–selective reflection of atomic sodium beam at atomic mirror. (a) Absorption spectrum of reflected atomic beam at detunings of intense laser field forming atomic mirror $[\omega_1 - (\omega_{10} + k_1 v_p)]/2\pi = -1.2$ GHz, $[\omega_2 - (\omega_{20} + k_1 v_p)]/2\pi = +0.5$ GHz ($v_p = 8.2 \times 10^4$ cm/s). (b) Same for the case $\Delta\omega_1/2\pi = +2.9$ GHz, $\Delta\omega_2/2\pi = +4.6$ GHz. (c) Same at $P_L = 0$ (scattered atoms). Dashed line, result of subtraction of background signal due to scattered atoms.

$3S_{1/2}(F=2) \rightarrow 3P_{3/2}$ transition for the atom with the most probable velocity v_p equal to 8.2×10^4 cm/s at a source temperature of $T=630$ K. Figure 2(a) corresponds to the case in which the laser frequency detuning is selected so as to be positive only with respect to the frequency of the transition $3S_{1/2}(F=2) \rightarrow 3P_{3/2}$ {$[\omega - (\omega_{20} + k_1 v_p)]/2\pi = +0.5$ GHz }. The laser frequency detuning with respect to the transition $3S_{1/2}(F=1) \rightarrow 3P_{3/2}$ is

$$\Delta\omega_1/2\pi = [\omega - (\omega_{10} + k_1 v_p)]/2\pi = -1.2 \text{ GHz}.$$

In that case, it is only the atoms on the sublevel with $F=2$ that are being reflected. The presence of a small number of atoms on the sublevel with $F=1$ is explained by the fact that the sodium atoms which are being scattered on the residual gas molecules reach the detection region without being reflected at the mirror [Fig. 2(c), no intense laser field]. The subtraction of the signal due to the scattered atoms [dashed line in Fig. 2(a)] shows that there are no (accurate to within measurement error) reflected atoms on the sublevel with $F=1$. If the detuning of the laser frequency is positive with respect to the frequencies of both transitions ($\Delta\omega_1/2\pi = +2.9$ GHz, $\Delta\omega_2/2\pi = +4.6$ GHz), the reflected atomic beam contains both the atoms on the sublevel with $F=2$ and those on the sublevel with $F=1$ [Fig. 2(b)]. Note that here, too, the reflection coefficient of the atoms in the state with $F=2$ is greater than that of the atoms in the state with $F=1$. This is explained by the fact that the cross section of the transition[12] $3S_{1/2}(F=2) \rightarrow 3P_{3/2}$ (and, accordingly, the saturation parameter G and the maximum transverse atomic velocity component v_y^{max}) exceeds the respective parameters of the $3S_{1/2}(F=1) \rightarrow 3P_{3/2}$ transition. For this reason, the reflected atoms in the state with $F=2$ can have a higher longitudinal velocity than those in the state with $F=1$. Accordingly, the integral (over the velocity distribution) reflection coefficient $R_{F=2}$ of the atoms on the sublevel with $F=2$ is greater than $R_{F=1}$.

To obtain quantitative data on the selective reflection, account must be taken of the optical pumping of the atoms giving rise to their redistribution among the ground-state sublevels. Such a pumping can be caused, first, by the laser light at the point of intersection of the atomic and laser beams before the atoms reach the mirror [Fig. 1(b)]; second, by the laser light scattered on the surface microirregularities in the plate in the course of multiple internal reflection; and third, by the surface wave interacting directly with the atoms.

The effect of optical pumping was taken into consideration as follows. Because of scattering on the residual gas molecules some atoms flew near the mirror and entered a registration region. These atoms were used to take account of optical pumping. With the laser beam brought out of the plate forming the atomic mirror, we switched the laser on and off and registered the resulting

changes in the signals from these atoms on the sublevels with $F=2$ and $F=1$ to measure the redistribution of the atoms between the sublevels due to the first cause of optical pumping. Then we again directed the laser beam into the plate, but made the grazing angle equal to zero (no atomic reflection), and switched the laser on and off once more to measure the total effect of the first two causes of optical pumping.

Figure 3 presents the ratio between the reflection coefficients of the atoms on the sublevels with $F=2$ and $F=1$ (reflection selectivity) as a function of the detuning of the intense laser radiation frequency relative to the frequency of the $3S_{1/2}(F=2) \rightarrow 3P_{3/2}$ transition of the atom with the most probable velocity in the beam. The reflection coefficient of the atoms in the state with $F=2$ $(F=1)$ was found as the ratio of the number of reflected atoms to the number of the atoms in the state with $F=2$ $(F=1)$ incident upon the mirror. The reflection coefficients were calculated including the effect of redistribution of the atoms between the sublevels due to optical pumping.

It is evident from Fig. 3 that there is an interval of detunings of the laser frequency relative to the atomic transition frequency wherein the reflection selectivity reaches a sufficiently high value. The maximum experimentally measured reflection selectivity is 10^2. In our case, it was determined by the noise of the registration system. It can also be seen from Fig. 3 that the characteristic frequency interval within which selective reflection is observed amounts to a few gigahertz and coincides with the frequency interval wherein the gradient force of the surface wave of the atomic mirror acts effectively on the atoms.

In conclusion, it should be noted that such a quantum-state–selective reflection can be expected in the case of molecules as well. This will offer us the unique possibilities of preparing and spectroscopically analyzing
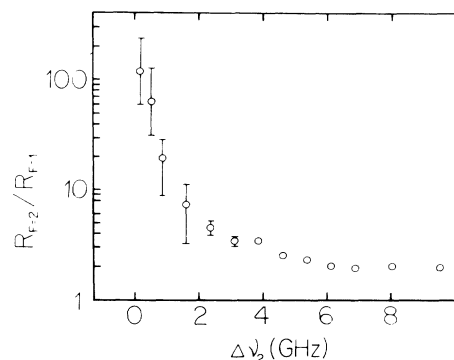

FIG. 3. Selectivity of reflection of sodium atoms on sublevels with $F=2$ and $F=1$ (ratio between reflection coefficients $R_{F=2}/R_{F=1}$) as a function of laser frequency detuning relative to $3S_{1/2}(F=2) \rightarrow 3P_{3/2}$ transition frequency of atoms with the most probable velocity $v_p = 8.2 \times 10^4$ cm/s in the beam.

beams of molecules in one and the same vibrational state which can be changed by varying the frequency of the reflecting laser radiation.

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