# Scattering of atoms by a short, standing-light-wave pulse[1)]

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The first observation of the scattering of sodium atoms by a short light pulse ($\sim 10^{-8}$ sec) of a resonance radiation due to gradient forces of a stimulated light pressure is reported. The scattering angle is of the order of 0.01 rad in a field of $\sim 10^3$ V/cm.

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The diffraction scattering of electrons by a standing light wave (the Kapitsa-Dirac effect), which has been observed in high-intensity laser fields, corresponds to scattering in the first Bragg maximum.[1,2]

The possibility of the scattering of neutral atoms and molecules by the resonance field of a standing wave was examined in Refs. 3 and 4. A unique feature of induced resonance light pressure is its multiphoton nature in comparatively weak fields. As a result of this, by restricting our study to the envelope of the Bragg peaks, the particle scattering can be described classically by means of the effective potential of the atom in the field, which was calculated in Refs. 5 and 6. A quantum theory of the scattering of atoms by a light field was developed in Refs. 7 and 8.

In our work we have investigated experimentally the scattering efficiency of Na atoms by a standing light wave. The large value of the gradient forces makes it possible to use short light pulses with $\tau \lesssim 10^{-8}$ sec. Since in this case the parameter $\gamma\tau < 1$ ($\gamma$ is the frequency of the spontaneous transitions), the spontaneous radiation is unable to change the phase (sign) of the dipole moment of the atom during the pulse, and the gradient-force fluctuations are missing. The scattering of atoms in this case is coherent.[9]

The other limiting case–large $\gamma\tau$ ($\sim$10)–was recently observed in Ref. 10, where the scattering of a beam of Na atoms was investigated in the steady-state regime. Here, however, the fluctuations of the gradient force play a significant role and the motion of atoms becomes partially diffusive.[11,12]

The schematic of the experiment is shown in Fig. 1. A narrow, flat beam of sodium atoms (divergence of $\sim 5 \times 10^{-4}$ rad) with a density of $\sim 10^8$ cm$^{-3}$ interacts with a standing-wave field, which is formed due to the reflection from a mirror of laser radiation, that propagates perpendicularly to the atomic beam. A special detector, whose action is based on the surface-ionization effect, was used to record the atomic beam. The sodium ions are ionized at the heated surface of a tungsten-rhenium wire ($\phi = 125$ $\mu$m) that was stretched in the plane of the flat beam, are accelerated in the field of a plane capacitor, and strike a secondary-electron multiplier

  

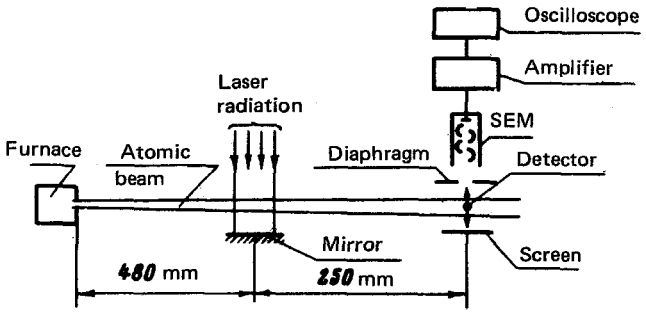


FIG. 1. Schematic of the experimental setup.

(SEM). A micrometer mechanism is provided for moving the detector in a direction perpendicular to the direction of beam motion. The size of the atomic beam in the region of interaction with the field is $0.36 \times 11$ mm$^2$.

A tunable-dye (Rhodamine 6G) laser was used as the radiation source. The laser operated in the longitudinal mode, the radiation-pulse duration was $t = 8 \times 10^{-9}$ sec, and the width of the emission line was $5 \times 10^{-2}$ Å. The resonance detuning was measured and monitored by means of a spectrograph (1.5 Å/mm dispersion in the ~600-nm wavelength region). The resonance detuning was checked at each laser pulse.

The standing-wave field was formed with the aid of a mirror at a distance of 7 mm from the plane of the beam of sodium atoms. At the indicated line width of the radiation the coherence length was several times greater than the distance from the mirror to the atomic beam. The diameter of the radiation beam in the region where it intersects the atomic beam was ~1 cm.

From the classical point of view, the scattering can be represented as follows. The induced transitions lead to the formation of an effective atomic potential, which has the form $U = dE \cos kx$ under resonance conditions (if we abstract from the finite width of the radiation line). Since the transverse dimension of the atomic beam is much greater than the light wavelength, one half of the atoms are scattered by positive gradients of this potential and one half are scattered by negative gradients; this results in a symmetrical scattering diagram.

As a result of pulsed irradiation of the sodium atomic beam, some of the atoms that enter the region of interaction with the standing-wave field acquire a transverse velocity because of the induced light pressure. The irradiated portion of the beam is broadened as it moves toward the detector. As a result, the number of atoms at the center of the beam decreases in a step-like manner, while the number of atoms in the wings increases.

The experiment was carried out in a linearly polarized field with an intensity of $\sim 2 \times 10^3$ V/cm at the rest of the standing wave. The field broadening $dE/\hbar = 3.3 \times 10^{10}$ sec$^{-1}$ ($6 \times 10^{-3}$ nm) in this field was of the order of the width of the laser line $\Gamma = 2.6 \times 10^{10}$ sec$^{-1}$ ($5 \times 10^{-3}$ nm). Figure 2 shows the dependence of the number of scattered particles on the coordinate of the detector for a precise resonance. The dimensions of the atomic beam are denoted by the shaded region. The signal

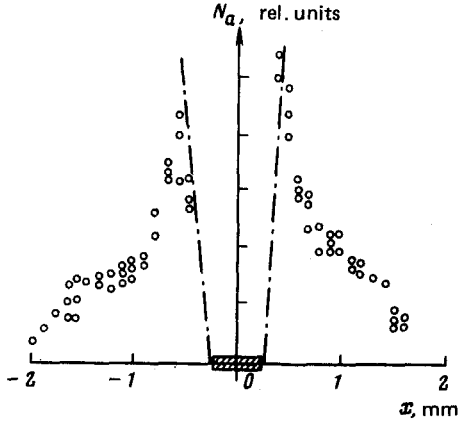


FIG. 2. Distribution of the scattered particles in the transverse plane of the Na atomic beam.

corresponding to the scattered particles was measured reliably in the wings of the atomic beam. The measurements in the central region of the beam were difficult to carry out because of the signal instability and therefore are not shown in the diagram. The dot-dash lines denote the boundaries of the abrupt amplitude spike due to the change in signal polarity. The characteristic scattering angle was $\theta \sim 4 \times 10^{-3}$ rad, so that the angular divergence of the irradiated beam was $2\theta \sim 8 \times 10^{-3}$ rad, which is more than an order of magnitude greater than the original divergence. This is consistent with the simple estimates of the predicted scattering angle,

$$\theta = \frac{v_\perp}{v_\parallel} \sim \frac{dE}{Mv_\parallel} kt, \tag{1}$$

where $v_\parallel$ is the thermal velocity of atoms in the beam and $v_\perp$ is the transverse velocity acquired by a particle due to the action of the gradient force during the operation of the pulse. Equation (1) corresponds to an approximation of the transverse displacement of atoms during the irradiation, which is small compared to the wavelength. This condition is satisfied when $\Omega t < 1$, where $\Omega = k\sqrt{v/M}$ is the characteristic oscillation frequency of the atom in the potential $U(x)$.

For $E = 10^3$ V/cm, $v_\parallel = 6 \times 10^4$ cm/sec, and $t = 8 \times 10^{-9}$ sec this gives $\Omega t \sim 0.5$ and a scattering angle $\theta = 6 \times 10^{-3}$ rad. This angle agrees in order of magnitude with the angle measured experimentally. From a quantum viewpoint, a deviation from this angle means that the atom was stimulated to re-emit about 200 photons from one wave to the bucking traveling wave.

In conclusion, we note that the scattering of neutral atoms measured experimentally occurs due to the action of only the force of stimulated light pressure. It was shown that atoms can be deflected by a large angle by a short light pulse. The pulse energy in this experiment was very small ($< 10^{-5}$ J). Therefore, the scattering angles can be increased considerably by using higher pulse energies.

Pulsed scattering has several advantages over steady-state scattering from the viewpoint of possible applications. Unfocused light beams can be used to scatter

atoms; this increases the range of interaction of the atoms with the field. It is important to emphasize that the resonant selective nature of the scattering of atoms is preserved in a strong field.[3,4]

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