Dispersion properties of the scattering of sodium atoms in a strong field of short counterpropagating laser pulses

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Experimental results on the scattering of a beam of sodium atoms in a strong field of short counterpropagating pulses of resonant laser light are presented. The scattering amplitude oscillates nonmonotonically with frequencies of the order of 10 GHz as a function of the detuning from resonance. In general, the scattering diagram is asymmetric relative to the direction of propagation of the undisturbed beam, and the sign of the asymmetry is an oscillating function of the detuning.

We present new results of an experimental study of the scattering of sodium atoms in the field of two counterpropagating pulses of resonant laser light. This work is a continuation of our preceding investigations of scattering of sodium atoms by stimulated light pressure in pulsed fields.[1] An improvement of the experimental apparatus enabled us to investigate in detail the dispersion properties of the scattering efficiency over a wide range of angles. As a result, we were able to observe previously unknown features of the dispersion dependence of the scattering process, which, in particular, do not fit the simple description of scattering of resonance atoms in gradient fields of the standing-light-wave type.[2]

The experimental arrangement—described in detail in Ref. 1—is shown in Fig. 1. A ribbon beam of thermal sodium atoms with small divergence ($\sim 5\times 10^{-4}$ rad), density $\sim 10^8$ cm^{-3}, and dimensions of 2×10^{-2} cm$\times$1.1 cm was irradiated at right angles with a short pulse ($\tau \sim 10^{-8}$ sec) from a single-frequency (linewidth $\sim$0.4 GHz) rhodamine-C dye laser. A light beam, propagating opposite to the incident beam, was produced with the help of a mirror installed 7 mm from the plane of the atomic beam. The transverse intensity distribution of the light beam had a smooth bell shape with maximum field strength of up to 4×10^3 V/cm. The diameter of the light beam was $\sim$4 cm. The frequency of the laser was tuned near the frequency of the D_2 line of the sodium atom (the transition $3S_{1/2}$–$3P_{3/2}$). The atom detector was installed 25 cm from the interaction region and could be moved across the atomic beam with an accuracy of $\sim 2\times 10^{-3}$ cm. A surface-ionization detector was employed. The sensitive element of the detector consisted of a thin ($\sim 10^{-2}$ cm in diameter) tungsten–rhenium filament. The principle of operation and the construction of the detector are described in detail in Ref. 1.

As a result of the pulsed irradiation, on entering the field region the beam propagating toward the detector expands due to the transverse velocities (i.e., along the

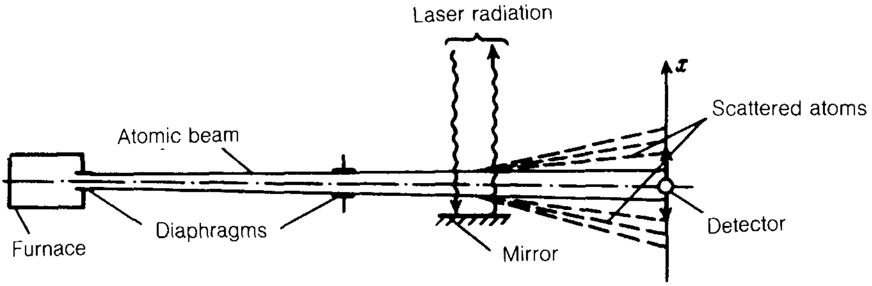

FIG. 1. Experimental arrangement. *1*—Furnace, *2*—diaphragms, *3*—atomic beam, *4*—mirror, *5*—scattered atoms, *6*—detector.

direction of propagation of the counterpropagating laser beams) acquired by the atoms. The detector measures the particle flux as a function of time at a fixed coordinate x. The duration of the signal at the detector is related to the Maxwellian distribution of atoms over longitudinal velocities. All curves of the scattering amplitude were subsequently constructed for atoms arriving at the detector at the same time, i.e., atoms having the same longitudinal velocity.

The scattering diagram of sodium atoms (the scattering amplitude A_i as a function of the distance from the center of the atomic beam), measured with the laser frequency tuned to the center of the D_2 line of sodium, in a field $E_{\max} \simeq 5 \times 10^3$ V/cm is presented in Fig. 2. No measurements were performed within the region occupied by the stationary beam. Two scales are given on the abscissa: The transverse coordinate, measured in units of the atomic-beam width $a = 2 \times 10^{-2}$ cm, is given in one scale and the transverse momentum P_x of an atom, measured in units of the photon momentum $\hbar k$, is plotted along the second scale.

In the experiment the scattering of atoms at angles up to 1.2×10^{-2} rad was recorded. This corresponds to transverse velocity of an atom ~ 460 cm/sec, i.e., momentum of 170 $\hbar k$. We note that the scattering occurs only in the presence of two counterpropagating beams. When one beam is removed, there is no scattering at all. Thus an atom acquires transverse momentum due to reradiation of photons from one wave into the oppositely traveling wave. Approximately one hundred such photon rescattering events occur over an interaction time of $\sim 10^{-8}$ sec; i.e., the rate of the process is $\sim 10^{10}$ 1/sec. This corresponds to a frequency $\sim dE/\hbar$ of induced transitions in the atom (d is the dipole moment of the resonance transition) in the fields realized in the experiment. It can therefore be asserted that the observed strong scattering of sodium atoms in a pulsed field of two counterpropagating laser beams is due to the force associated with the induced transitions in the atom.

Two plots of the scattering amplitude of sodium atoms as a function of the detuning from resonance are presented in Fig. 3. The scattering amplitudes were measured at a distance of four atomic-beam widths (8×10^{-2} cm) symmetrically on both sides of the atomic beam. The measurements of the dispersion dependence of the

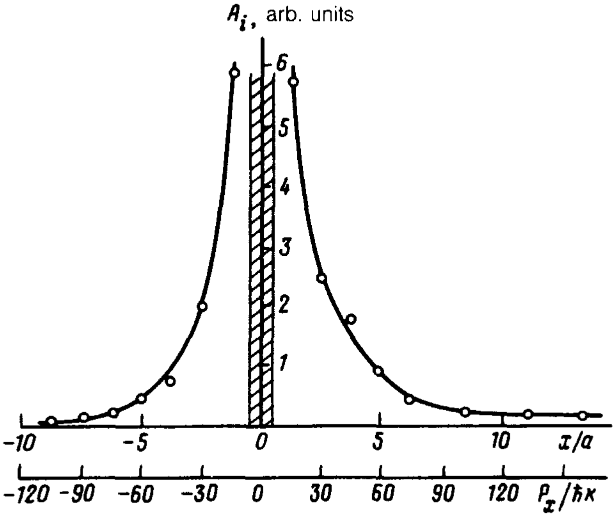

FIG. 2. Scattering diagram for sodium atoms. The hatching marks the region occupied by the stationary beam. The diagram is constructed for $\Delta=0$.

scattering efficiency exhibited two previously unknown phenomena. The first phenomenon consists of the fact that the scattering amplitude is a strongly nonmonotonic function of the frequency and oscillates with a frequency ~10 GHz. This structure lies within the field-induced broadening $(\sim 2dE/h)$, which under the conditions of our

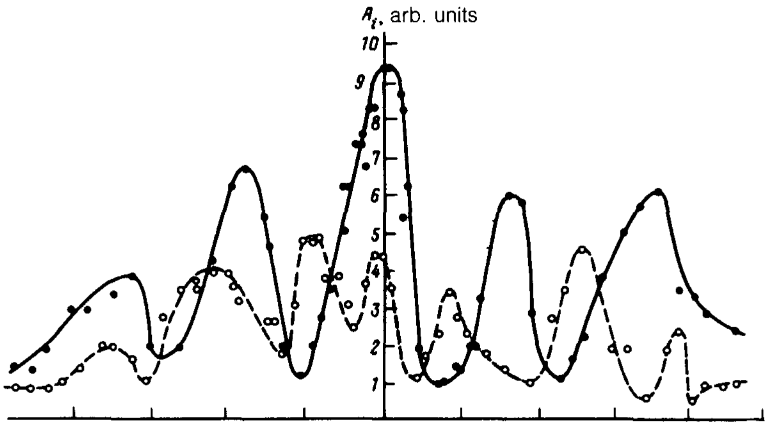

FIG. 3. Scattering amplitudes A_i of sodium atoms as a function of the detuning from resonance. The scattering amplitudes were measured at a distance equal to four atomic-beam widths ($4a=8\times10^{-2}$ cm) symmetrically on both sides of beam center. Solid line—$x=4a$ in the direction of the reflecting mirror; dashed line—$x=-4a$.

experiment is of the order of ±40 GHz. The second phenomenon consists of the fact that the scattering pattern is asymmetric with respect to the center of the atomic beam. Moreover, the asymmetry is an oscillating function of the detuning from resonance. In other words, atoms are scattered predominantly in one or another direction, depending on the frequency of the radiation.

The existing simple models describing the interaction of resonance atoms with the field of two counterpropagating beams, forming a standing wave, give a symmetric scattering pattern and monotonic dispersion with a characteristic field-induced width.[2,3] Other models[2-6] give a more complicated scattering pattern, but they employ light fields with special space–time structure, which does not correspond to the conditions of the present experiment.

The observed features—oscillatory dispersion within the field-induced broadening and scattering asymmetry—apparently indicate that there is a complicated correlation between the induced rescattering of the photons by the atoms between the two oppositely traveling waves. However, we cannot yet explain the mechanism of these correlations.

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[1] V. A. Grinchuk, E. F. Kuzin, M. L. Nagaeva *et al.*, JOSA B **2**, 1805 (1985).
[2] A. P. Kazantsev, Usp. Fiz. Nauk **124**, 113 (1978) [Sov. Phys. Usp. **21**, 58 (1978)].
[3] A. P. Kazantsev, G. I. Surdutovich, and V. P. Yakovlev, *Mechanical Action of Light on Atoms*, World Scientific, 1990.
[4] A. P. Kazantsev and I. V. Krasnov, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 264 (1987) [JETP Lett. **46**, 332 (1987)].
[5] A. P. Kazantsev and I. V. Krasnov, JOSA B **6**, 2140 (1989).
[6] V. S. Voitsekhovich, M. V. Danileiko, A. M. Negriiko *et al.*, Zh. Eksp. Teor. Fiz. **99**, 393 (1991) [Sov. Phys. JETP. **72**, 219 (1991)].

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