Effect of radiation pressure on shape of saturated-absorption resonance of cesium vapor

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A study has been made of the effect of radiation pressure on the shape of the resonance of the saturated absorption and on the velocity distribution of cesium atoms. High-coherence injection lasers with an external resonator ($\Gamma < 1$ MHz) were used.

An optical field affects resonant atoms in two ways: It changes the internal state and also the translational motion of particles. Under the influence of the radiation-pressure force, the velocity distribution of atoms changes.[1] As a result, the nonlinear susceptibility of a gas has a component due to radiation pressure.[2] Experiments carried out to observe the radiation-pressure effect have for the most part used atomic beams.[3–5] The effect of radiation pressure on the susceptibility of an atomic gas was first observed in Ref. 6. A frequency shift of the Doppler line of the susceptibility of ytterbium vapor was detected.

In this letter we examine manifestations of radiation pressure in nonlinear intra-Doppler spectroscopy of a resonant gas. In this case the duration of the interaction of the atoms with the field is determined by the time taken by an atom to pass through the light beam: $\tau \sim a/v_T \sim 10^{-4}$–$10^{-5}$ s (a is the diameter of the light beam, and v_T is the thermal velocity of the atoms). During cyclic excitation (in a two-level model of an atom), radiation pressure should have a significant effect on the shape of the saturation resonance.

Let us assume that two fields, a saturating field $E_1\exp(ik_1x - i2\pi\Delta_1 t)$ and a probing field $E_2\exp(ik_2t - i2\pi\Delta_2 t)$, are acting on a gaseous medium. These fields are acting in the same direction. Here $E_1 \gg E_2$, $\Delta_1 = \nu_1 - \nu_0$, $\Delta_2 = \nu_2 - \nu_0$, where ν_0 is the resonant frequency.[2] The absorption coefficient for the probing light, which depends on E_1, is[2]

$$\alpha(\nu_2) = \alpha_0(\nu_2)[1 - 2G(1 + \epsilon_r\tau\delta)(1 + \delta^2)^{-2}]. \tag{1}$$

Here $G = (E_1 d/h\gamma) < 1$ is the saturation parameter, d and γ are the dipole moment and total radiation width of the atomic transition, $\alpha_0(\nu_2)$ is the equilibrium absorption coefficient, and $\delta = 2(\nu_2 - \nu_1)/\gamma$.

The nonlinear term in (1), which is independent of τ and which is of even parity in δ, stems from a redistribution of particles between the ground and excited states (a Bennett hole).

If the fields $E_1(x,t)$ and $E_2(x,t)$ do not spatially overlap but are close to each other, we find in place of (1)

$$\alpha(\nu_2)=\alpha_0(\nu_2)[1-2G\epsilon_r\tau\delta(1+\delta^2)^{-2}]. \qquad (2)$$

In the experiments we studied the effect of radiation pressure on the velocity distribution and shape of the resonances of the saturated absorption of a gas of ^{133}Cs atoms during excitation of the $6S_{1/2}$ $(F=4)$–$6P_{3/2}$ $(F'=5)$ transition ($\lambda=852.1$ nm, $\gamma=5.3$ mHz, Doppler width of 380 MHz at room temperature).

As the sources of the resonant light we used two identical external-resonator injection lasers, L1 and L2 (Ref. 7). The spectral width of the output of the lasers did not exceed 1 MHz; their output power did not exceed 3 mW. The output frequencies of L1 and L2 were stabilized with the help of confocal tunable interferometers.[7] The probing laser, L2, was used to detect structural features in the absorption spectrum of the cesium vapor. The saturating laser, L1, had a fixed output frequency near the unperturbed frequency ν_{45} of the $6S_{1/2}$ $(F=4)$–$6P_{3/2}$ $(F'=5)$ transition. The output beams from L1 and L2, with a divergence $<10^{-3}$ rad and cross-sectional areas of 0.15×0.8 cm^2 and 0.15×0.2 cm^2, respectively, were sent to a glass cell $l=3$ cm long filled with ^{133}Cs vapor. The cell was at room temperature. The angle between the laser beams was $\theta<10^{-2}$ rad. The power of the probing beam in the cell was 50 μW; the power of the saturating beam could be varied from 0 to 2 mW. To eliminate the Doppler pedestal from the saturated-absorption spectrum, we used the standard technique of synchronous detection of the signal at the frequency at which the saturating laser beam was chopped.[7] To make the interaction of the atoms with the light on the $6S_{1/2}$ $(F=4)$–$6P_{3/2}$ $(F'=5)$ transition cyclic, we used a special layout to excite the atoms, in which only transitions accompanied by a change $\Delta m=1$ in the magnetic quantum number were allowed. For this purpose, a longitudinal magnetic field $H=1$ G was produced in the cell, and the laser beams were circularly polarized in an identical way.[3–5]

Figure 1 shows the intra-Doppler resonance of the saturated absorption, which was detected against a zero background while the output frequency of L1 was tuned to a point 50 MHz above the transition frequency ν_{45}. The power of the saturating beam was 2 mW, and its cross-sectional area 0.1 cm^2. The probing beam was superimposed on the center of the saturating light beam. The transmission of the probing beam at the frequency ν_{45} in the cell without the saturating beam was 40%. The unit of measure in Figs. 1 and 2 corresponds to a 1% change in the transmission of the probing beam. The asymmetry of the nonlinear resonance (Fig. 1) is a consequence of the effect of the radiation pressure on the atoms. The radiation pressure distorts the shape of the resonance and shifts its crest. The shape of the intra-Doppler resonance of the saturated absorption can be described qualitatively by expression (1) with $G\approx1$ and $\epsilon_r\tau\approx1$, since we have $T=[1-\alpha(\nu)l]$.

We are interested in singling out the nonlinear increment in the absorption coefficient which stems from the change in translational degrees of freedom alone. To detect this nonlinear resonance, we introduced a spatial separation of 2 mm between the saturating and probing beams. Otherwise, the experimental conditions were unchanged. The peak and valley in Fig. 2 are associated with a displacement of a group of atoms in the vicinity of $\delta\sim1$ into the high-frequency region under the influence of

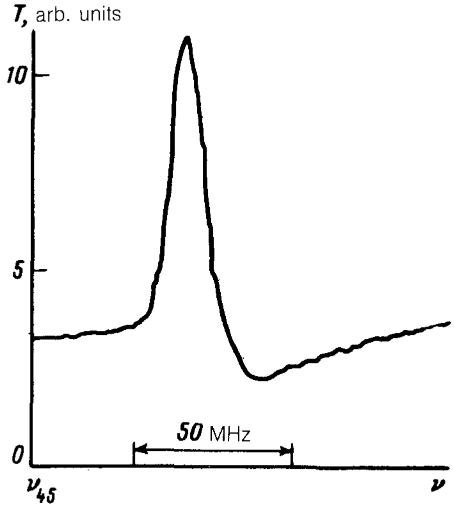

FIG. 1.

the radiation-pressure force. With $G \approx 1$ and $a = 0.8$ cm, $\sim 10^3$ reradiation events occur over the time taken by an atom to pass through the light beam, and the radiation-pressure force increases the longitudinal component of the velocity of these atoms by an amount $\delta v \sim \gamma c/v \sim 2$ m/s. The overall shape of resonances of this type and the dependence of their amplitude on the power and transverse dimension of the saturating laser beam provide qualitative confirmation of expression (2). Note, how-

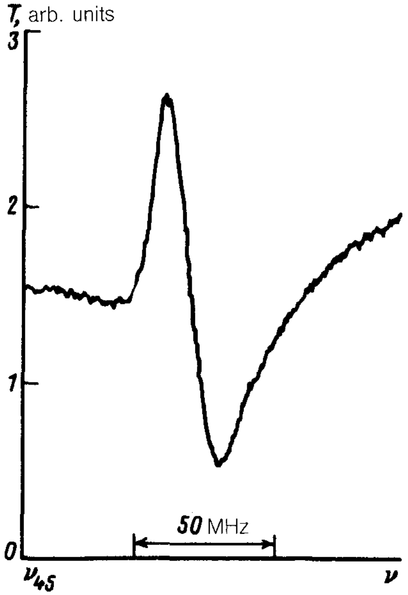

FIG. 2.

ever, that expression (2) is of odd parity in the frequency deviation; the widths of the peak and of the valley should be the same. The resonance in Fig. 2, which corresponds to a minimum of the transmission of light, has a width which is roughly twice that of the resonance corresponding to the transmission maximum. Apparently one reason for the discrepancy between the theoretical and experimental data is the circumstance that the calculation was carried out by perturbation theory ($G < 1$, $\epsilon_r \tau < 1$, $\alpha l < 1$).[2]

In summary, radiation-pressure effects in a gas change the shape of nonlinear resonances. The parity of the resonances with respect to the frequency deviation changes. The nonlinear response depends on the diameter of the light beam. Finally, the interaction of light beams may be nonlocal because of a change which occurs in the velocity distribution of the atoms which have passed through the light beam. All these circumstances may prove important in high-resolution nonlinear spectroscopy.

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