instant of time

$$t = t_0' + t_0 + T_3 - T_1 \qquad (8)$$

in the direction (Fig. b)

$$\vec{k} = \vec{k}_3 + \vec{k}_2 - \vec{k}_1 \qquad (9)$$

and in place of (5) we have the relation $\Phi = \Phi_3 + \Phi_2 - \Phi_1$.

We emphasize that the essential feature of the last two effects is that they can be realized when condition (4) is not satisfied and consequently there is no "photon echo" effect. This is demonstrated in the figure.

We see that the first and second pulses produce a coherent state of ions in crystals; this state is in sharp disagreement with the spatial coherence of the light field, inasmuch as the wave vector of the field does not coincide in magnitude with the vector $2\vec{k}_2 - \vec{k}_1$ (dashed lines). However, application of the third pulse in a definite direction, as shown in the figure, restores the spatial synchronism between the coherent state of the system of the ions and the radiation field (conditions (7) and (9) are satisfied). In both cases, the coherence is maintained over the entire length of the crystal, and by varying the direction of the second and third exciting pulses it is possible to attain any direction for the succeeding coherent radiation. To calculate the total radiation energy $\mathcal{E}$ it is necessary to solve the electrodynamic problem. It can be shown that $\mathcal{E} \sim (\lambda n\ell)^2 S\mathcal{E}_0 \sim N^2(\lambda^2/S)\mathcal{E}_0$, where S - the smaller of the cross sections of the pulse beam or the crystal, n - concentration of the sample ions taking part in the process ($N = nS\ell$), and $\mathcal{E}_0 = \hbar\omega W_\tau$ is the energy of the incoherent radiation from one ion in the time τ (W - transition probability).

The author is grateful to A. M. Afanas'ev, Yu. A. Bykovskii, A. N. Oraevskii, and V. I. Perel' for useful discussions.

[1] U. Kh. Kopvillem and V. R. Nagibarov, Fiz. met. i metalloved. 15, 313 (1963).
[2] N. A. Kurnit, I. D. Abella, and S. R. Hartmann, Phys. Rev. Lett. 13, 567 (1964).
[3] I. D. Abella, N. A. Kurnit, and S. R. Hartmann, Phys. Rev. 141, 391 (1966).
[4] A. N. Oraevskii, Usp. Fiz. Nauk 91, 181 (1967) [Sov. Phys.-Usp. 10, 45 (1967)].

NARROWING OF THE DOPPLER WIDTH IN A STANDING LIGHT WAVE

V. S. Letokhov
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 20 February 1968
ZhETF Pis'ma 7, No. 9, 348-351 (5 May 1968)

1. The absorption or emission lines of a low-pressure gas have, in the case of a small radiation width, a Doppler contour determined by the particle velocity distribution. The purpose of the present paper is to show that an intense standing light wave is capable of changing the velocity distribution of the atoms in such a way that an exceptionally narrow peak is produced in the center of the Doppler line when absorption or emission is observed strictly in the direction of the axis of the light wave. Physically this phenomenon is due to "dragging," between the antinodes or nodes of the standing wave, of those atoms which move almost parallel to the wave front. This new effect is of interest for spectroscopy within

the Doppler contour with exceedingly large resolving power and strong-current stabilization of laser frequency.

2. The electrons (free or bound) in a high-frequency electromagnetic field are acted upon by the force of the mean squared electric field [1,2]. It is determined by the striction force [3] acting on the atom (molecule):

$$f = \frac{1}{2}\kappa_\omega \operatorname{grad}(E^2)_{av} \tag{1}$$

where κ_ω is the polarizability of the atom at the frequency ω of the external field, determined by the refractive index n_ω of the gas ($\kappa_\omega = (n_\omega - 1)/2\pi N$, N - gas particle density).

In the case of a plane standing wave $E_0 \sin kz \sin \omega t$, the striction force is a periodic function of z:

$$f = \frac{1}{4}\kappa_\omega E_0^2 k \sin 2kz. \tag{2}$$

The moving atoms are either drawn into the antinodes of the standing wave (when $\kappa_\omega < 0$) or are pushed out of them (when $\kappa_\omega > 0$). The change of z - the coordinate of the atom - is described by the equation

$$\ddot{z} = \frac{1}{4M}\kappa_\omega E_0^2 k \sin 2kz, \tag{3}$$

which is similar to the equation of pendulum oscillations (M - mass of atom).

It is easy to show that the atoms having in the z direction an initial velocity lower than a certain critical value, given by the relation

$$v_{cr} = E_0\sqrt{\frac{|\kappa_\omega|}{2M}}, \tag{4}$$

will experience not free motion but oscillations in the z direction, with an amplitude not exceeding $\lambda/4$ (λ - wavelength of the light wave). The quantity v_{cr}, at intensities of several kW/cm^2, is smaller by several orders of magnitude than the average thermal velocity of the atoms $v_0 = \sqrt{2kT/M}$. Therefore such "dragging" between the antinodes (or nodes) of the wave will take place only for atoms moving at small angles φ to the wave surface (Fig. 1):

$$|\phi| < \phi_{cr} = \frac{v_{cr}}{v_0} = E_0\sqrt{\frac{|\kappa_\omega|}{4kT}}. \tag{5}$$

Atoms moving at angles $\varphi > \varphi_{cr}$ will cross the standing light wave freely, but the z-component of their velocity is modulated by oscillations with amplitude v_{cr}.

3. When emission (absorption) of the atoms is observed in the z direction at wavelengths $\lambda' \gg \lambda$", the "dragged" atoms, which under ordinary conditions have a Doppler width $\Delta\omega_0' = 2(v_{cr}/c)\omega'$, do not experience Doppler broadening. When the atom position oscillates,

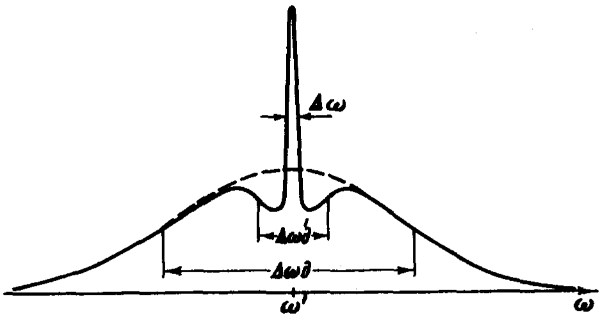

Fig. 1. Trajectory of motion of the "dragged atoms" in the standing light wave.

the emission (absorption) frequency is frequency-modulated. The relative intensity of the central unshifted component is proportional to $J_0(\lambda/\lambda')$, and the intensity of the n-th side component is proportional to $J_n(\lambda/\lambda')$, where J_n is a Bessel function of order n. When $\lambda' \gg \lambda$ the intensity of the side components is negligibly small. As a result, a narrow line is produced at the center of the Doppler line (Fig. 2), with a width determined by the time of motion of the "dragged" atoms in the standing wave, τ. If the gas pressure is sufficiently low and the radiation width of the transition sufficiently small, the time τ is determined by the time-of-flight of the atoms through a beam of diameter a. To obtain the narrow component it is necessary to satisfy the condition

$$a \gg d_{cr} = \frac{\lambda}{2\phi_{cr}}. \tag{6}$$

Then the width of the narrow component is determined by the relation

$$\Delta\omega = \frac{2}{\tau} = \frac{2v_0}{a}. \tag{7}$$

4. Assume that the frequency of the light wave lies outside the resonances and absorption bands of the atoms, and that the polarizability is $\kappa_\omega \simeq 10^{-23}$ cm^3, corresponding to a refractive index $n_\omega - 1 \simeq 2 \times 10^{-3}$ atm^{-1}. At a standing-wave power $P = c(F_0^2/16\pi) = 10^5$ W/cm^2, $\lambda = 1\ \mu$, and T = 300°K, the critical angle is $\varphi_{cr} \simeq 3 \times 10^{-4}$ rad and $d_{cr} \simeq 1.7$ mm. In this case the condition (6) cannot be completely satisfied. For example, at a beam diameter a = 1 cm and a pressure $\lesssim 10^{-4}$ Torr (to eliminate collisions) we can obtain a narrow component of

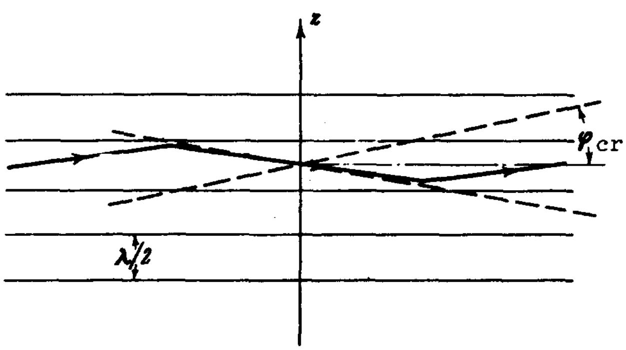

Fig. 2. Absorption (emission) line shape of an atom in the direction of the z axis in the presence of a standing light wave (dashed curve - Doppler line shape in the absence of a wave).

width $\Delta\omega \simeq 3 \times 10^4$ Hz on lines with $\lambda' \gg 1\ \mu$. $|\kappa_\omega|$ increases sharply in the resonance region, but it can be shown that the condition for "dragging" of the atoms coincides with the condition for strong saturation of κ_ω by the field. The strong saturation leads to a broadening of the homogeneous line [4], making it difficult for the effect to occur in the resonance region.

5. The narrow component can be observed in both absorption and emission. By scanning the frequency ω' of the monochromatic wave, directed strictly along the intense standing wave, it is possible to obtain the shape of the absorption line. If the absorption line consists of a number of lines, then the narrow component appears at the center of each line. The resolution of such a method is $R = (\omega'/\Delta\omega) \simeq 10^9 - 10^{11}$. In spontaneous or stimulated emission of atoms in the direction of the standing wave there should also arise one or several narrow components corresponding to the line structure.

In conclusion, the author is deeply grateful to Academician N. G. Basov and Doctor of Physical and Mathematical Sciences, O. N. Krokhin for support and valuable discussions.

[1] A. B. Gaponov and M. A. Miller, Zh. Eksp. Teor. Fiz. 34, 242 (1958) [Sov. Phys.-JETP 7, 168 (1958)].
[2] G. A. Askar'yan, ibid. 42, 1567 (1962) [15, 1088 (1962)].
[3] L. D. Landau and E. M. Lifshitz, Elektrodinamika sploshnykh sred, Gostekhizdat, 1957 [Fluid Mechanics, Addison-Wesely, 1959].
[4] R. Karplus and J. Schwinger, Phys. Rev. 73, 1020 (1948).

ERRATUM

Article by V. S. Letokhov, Vol. 7, No. 9, p. 272

The figures on p. 274 should be interchanged, but the figure captions should remain in place.