relaxation curves, which depends on the relations between $T_{12}^{\dagger}$ and $T_1$, may greatly distort the temperature and concentration dependences of the SLR. Our measurements in $Ca_5(PO_4)_3F:Nd^{3+}$ show that these dependences actually change when the cross relaxation is "quenched." Detailed results will be published later.


[1] A.A. Manenkov and A.M. Prokhorov, Zh. Eksp. Teor. Fiz. 42, 75 (1962) [Sov. Phys.-JETP 15, 54 (1962)]; N.V. Karlov and A.A. Manenkov, Kvantovye usiliteli (Quantum Amplifiers), M., 1966.

[2] L.L. Luishvili, M.D. Zviadadze, and G.R. Khutsishvili, Zh. Eksp. Teor. Fiz. 56, 290 (1969) [Sov. Phys.-JETP 29, 159 (1969)].

[3] N.A. Efremov and M.A. Kozhushner, ibid. 57, 534 (1969) [30, 293 (1970)].

[4] D.M. Daraseliya, G.V. Maksimova, and A.A. Manenkov, ZhETF Pis. Red. 10, 361 (1969) [JETP Lett. 10, 229 (1969)].

[5] P. L. Scott and C.D. Jeffries, Phys. Rev. 127, 32 (1962).


## FOUR-PHOTON SCATTERING IN A RESONANT MEDIUM


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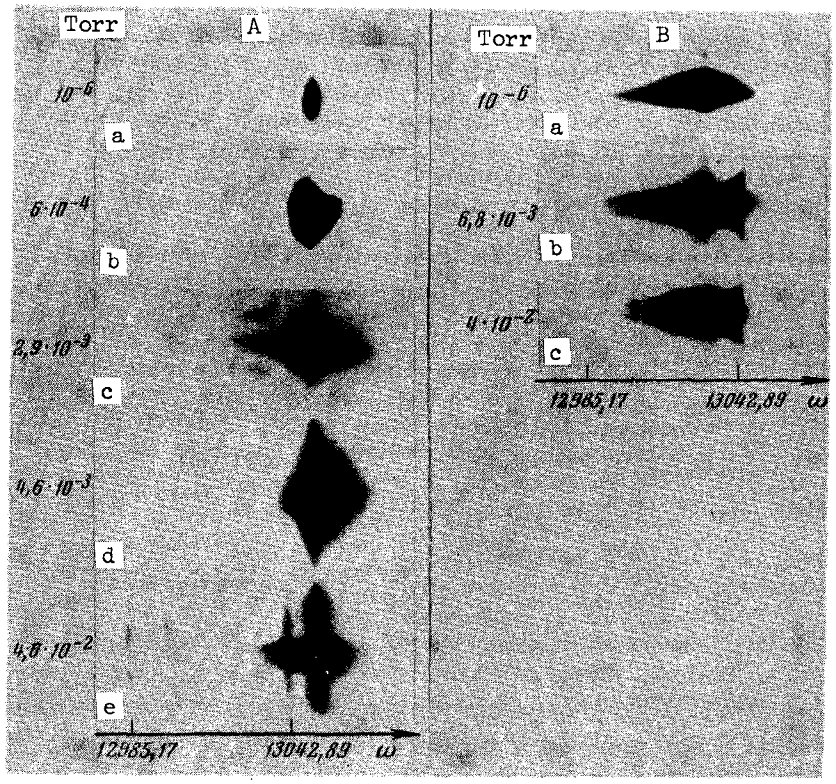
Several recent papers are devoted to spontaneous multiphoton processes, namely parametric luminescence and four-photon scattering [see [1], where other papers are cited]. Parametric luminescence is relatively easy to observe, whereas four-photon scattering under nonresonant conditions turns out to be a very weak effect. We report here observation of a very strong change of the angular and spectral distributions of powerful nonmonochromatic radiation passing through a resonant medium (potassium vapor); this radiation is interpreted as a consequence of four-photon scattering.

In our setup, a giant ruby-laser pulse (~50 MW) excited SRS in nitrobenzene (or α-chloronaphthalene). The SRS radiation, filtered out of the laser light, passed through a cell with potassium vapor and was registered with a DFS-8 spectrograph (grating with 1200 lines/mm), the slit of which was in the focal plane of the condenser. The photographic plate therefore recorded the angular distribution (along the height of the slit) and the frequency distribution of the light emerging from the potassium-filled cell).

When SRS in nitrobenzene was used (the width of the SRS spectrum is about 4 $cm^{-1}$ and is shifted by 12 $cm^{-1}$ toward the short-wave side away from the potassium resonance line $\lambda$ = 7665 Å, $\omega_0$ = 13042.9 $cm^{-1}$), the following phenomena were observed: At low vapor pressures ($p \lesssim 5 \times 10^{-4}$ Torr), slight diffusion of the radiation in frequency and in angle is observed (Figs. 1Aa, b). Characteristic "whiskers" (Fig. 1Ac) appear at frequencies lower than $\omega_0$ in the interval $5 \times 10^{-4}$ Torr $\lesssim p \lesssim 5 \times 10^{-2}$ Torr. The angle distance between the "whiskers" increases with pressure (the square of the angle depends linearly on p). At the same time, the diffusion (in terms of $\theta$ and $\omega$) increases simultaneously in the region of the initial SRS spectrum. At $p \gtrsim 0.1$ Torr, the "whiskers" leave the field of view (which is determined by the height of the spectrograph slit), and only additional broadening of the frequency-angle diagram a is observed in the region of the SRS spectrum (Fig. 1Ae). In the latter case, radiation appears also in the region of both resonance lines (7665/99 Å), shifted by 1 - 2 $cm^{-1}$ toward longer wavelengths from the atomic frequencies, with predominant concentration at $\theta \neq 0$ (Fig. 1Ae).




Frequency-angle diffusion of SRS radiation of nitrobenzene (A) and of α-chloronaphthalene (B) vs. the potassium vapor pressure.

The foregoing effects[1)] are interpreted as the result of the four-photon scattering $\omega_1, \omega_2 \to \omega_3, \omega_4$, the probability of which is maximal of the following conditions are satisfied:

$$\omega_1 + \omega_2 = \omega_3 + \omega_4; \qquad \mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3 + \mathbf{k}_4 \, . \tag{1}$$

Under our conditions $|\omega_j - \omega_j'|/\omega_j < 10^{-3}$, $|n(\omega_j) - 1| << 1$, and formulas (1) yield the following connections, for the angles $\theta_{12}$ and $\theta_{34}$, between the wave vectors of the "parent" photons ($\vec{k}_1, \vec{k}_2$) and the "offspring" photons ($\vec{k}_3, \vec{k}_4$):

$$\theta_{34}^2 = \theta_{12}^2 + \Delta n; \qquad \Delta n = n_3 + n_4 - n_1 - n_2;$$

$$n_l \equiv n(\omega_l) = 1 + \frac{b}{\omega_0 - \omega_l}; \qquad b = \frac{\pi N e^2}{m\omega_0} f \, . \tag{2}$$

The form of the "whiskers" and their angle position calculated from (2) as well as the linear dependence on the pressure for $\theta_{34}^2$, are in good agreement with experiment.

The cruciform shape of the frequency-angle diagram in the region of the SRS spectrum (Fig. 1Ae) is connected with the sign of the curvature of the function

[1)]Observation of the broadening of the spectrum was reported in [2], but since no angle measurements were made, it is difficult to state whether the same or a different phenomenon was observed in [2].

$n(\omega)$, namely, it is easy to show that when $\omega_0 < \omega_1 < \omega_{3,4} < \omega_2$ we have $\Delta n > 0$, and angle diffusion is possible in accordance with (2) (with practically no change in frequency); on the other hand, if $\omega_0 < \omega_3 < \omega_{1,2} < \omega_4$, then $\Delta n < 0$ and $\theta_{34}^2 < \theta_{12}^2$, i.e., the change of frequency with departure from the region from the initial spectrum is not accompanied by angle diffusion.

It is possible that under our conditions an important role is played not only (and possibly not so much) by phase synchronism, but by group synchronism. The group velocity for $n(\omega)$ as given by (2) is

$$u = c\left[\frac{d(\omega n)}{d\omega}\right]^{-1} = \frac{c}{1 + \frac{b}{\omega_0 - \omega}\,\frac{\omega_0}{\omega_0 - \omega}}. \qquad (3)$$

The quantity u in the interval of $|\omega_0 - \omega|$ from 1 to 12 $cm^{-1}$ changes from c/30 to c/1.2 ($p = 5 \times 10^{-2}$ Torr), i.e., very strongly, and violation of group synchronism may turn out to be decisive at a large frequency difference $\omega_j - \omega_j'$.

Analogous effects were observed from the case of SRS of a laser pulse in α-chloronaphthalene. In this case the SRS spectrum is shifted away from $\omega_0$ towards lower frequencies (by approximately 18 $cm^{-1}$( and has a large width, so that its wing overlap both resonant lines of potassium, λ = 7665/99 Å (Fig. 1Ba). At pressures $p \approx 10^{-4} - 10^{-3}$ Torr, "whiskers" are likewise produced (Figs. 1Bb, c) in a region of frequencies lower than $\omega_0$, where $n - 1 > 0$ and it is possible to have $\theta_{34}^2 > \theta_{12}^2$. When both the laser emission and the SRS of α-chloronaphthalene pass through the cell with potassium simultaneously, the "whiskers" remain and a band of two-quantum absorption, connected with the atomic transition 4S → 4D, is observed (Fig. 1Bc).

We note in conclusion that the predominant emission of red lines at nonzero angles (Fig. 1Ae) and their shift towards lower frequencies (relative to the frequencies of the atomic transitions) points to a possible role of coherent processes. However, we have no satisfactory hypothesis at present concerning the mechanism of formation of these lines.

[1] D.N. Klyshko, Zh. Eksp. Teor. Fiz. 55, 1006 (1968) [Sov. Phys.-JETP 28, 522 (1969)].
[2] M.E. Movsesyan and V.M Arutyunyan, Paper at First Vavilov Conference on Nonlinear Optics, Novosibirsk, June 1969.

## GAS BREAKDOWN UNDER THE INFLUENCE OF LONG-WAVE INFRARED RADIATION OF A $CO_2$ LASER

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Breakdown of gases in the microwave [1] and optical [2] bands has been investigated in considerable detail. We have studied for the first time breakdown produced by radiation in the intermediate region of the spectrum, namely pluses from a $CO_2$ laser with λ = 10.6 μ[1]. The glow of the gas in the breakdown region was continuous, since the breakdown frequency exceeded 10 Hz.

[1]In each of the references [5, 6] it is merely stated that breakdown was observed in gases under the influence of infrared radiation with λ = 10.6 μ, but neither quantitative or qualitative data are given.