$n(\omega)$, 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

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

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 ω_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 ω_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.

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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.

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[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.

The gas laser operated with a CO_2-N_2-He mixture which was continuously drawn through the laser; the tube length was 3.5 m, the diameter 57 mm, and the discharge current reached 90 mA. In cw operation, the laser delivered up to 70 W. The Q-switch was a rotating mirror. The pulses had a repetition frequency of 50 - 250 Hz, a peak power on the order of 10 kW, and a duration 0.3 - 1.5 μsec. The radiation passed through a salt window into a high-pressure cell of 270 cm^3 volume, was reflected backwards by an internal spherical mirror with $f = 1.5$ cm, and focused in the center of the vessel into a circle of radius $r \simeq 4 \times 10^{-3}$. The gases were investigated at pressures p up to 25 atm.

We recorded simultaneously the waveforms of the incident pulse, of the pulse passing through the breakdown plasma, and the pulse reflected from the plasma back to the mirror, and also the visible glow of the plasma. The IR receivers were photoresistors based on gold-doped germanium, and the visible-light receiver was an FEU-52 photomultiplier. The signals were applied simultaneously to three channels of the S1-33 oscilloscope.

A typical set of oscillograms is shown in Fig. 1. The breakdown (cascade) develops rapidly, within a time not exceeding the receiver time constant (∿0.1 μsec): In xenon, the greater part of the radiation is absorbed by the plasma (up to 75%), and the reflection is not less than 7% of the incident radiation. The signal reflected from the plasma decreases with decreasing pressure and vanishes at $p < 5$ atm (only reflection from the input window remains). The absorption, reflection, and glow occur practically simultaneously, at the instant of the breakdown and at the threshold this instant is close to the instant of the peak power. The duration of the plasma glow exceeds the duration of the pulses, but it smaller by three orders of magnitude than the period between pulses.

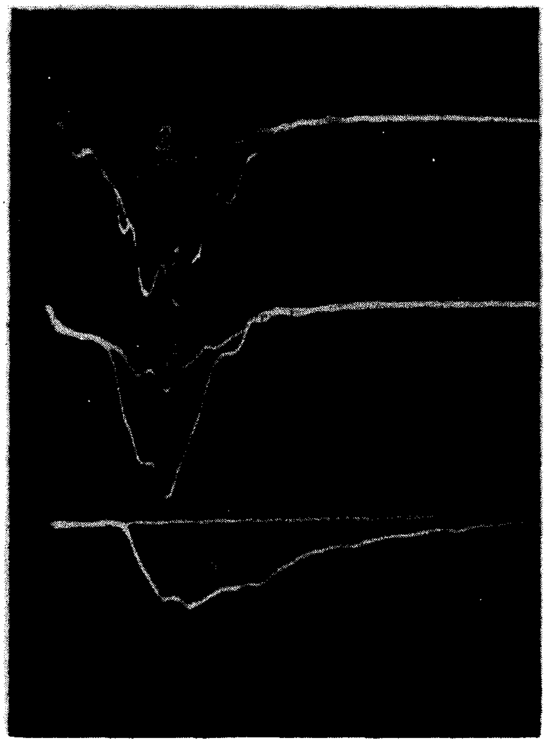

Fig. 1. Breakdown of Xe, p = 21 atm. Major division along the abscissa equals 1 μsec. Curves 1 and 2 - incident and transmitted pulses; 3 and 4 - incident and reflected pulses. with signal 3 attenuated by a factor of 30 compared with 4; 5 - pulse of plasma glow.

The most reliable measurements of the threshold intensity has been made for xenon (Fig. 2). The energy of the incident pulse was measured with a special calorimeter, and the pulses were attenuated with calibrated attenuators made of polyethylene film. The threshold was taken to be the start of the appearance of the widely spaced visible flashes. Figure 3 shows the results for other gases. Unlike Xe, the threshold of He increases noticeably with increasing purity of the gas. The sparks in Ar, He, and Ne glow for a longer time than in Xe, and the absorption and reflection of the pulses is smaller. The latter is apparently due to the fact that in He and Ne an appreciable role is played by ionization of the impurities by transfer of excitations from the atoms of the main gas (the Penning effect). The electron density in the visible breakdown is low in this case. In Xe, on the other hand, the atoms of the main gas are ionized, and at high pressures the electron density at $\lambda = 10.6$ μ the critical value 1.13×10^{19} cm^{-3}. The question of the mechanism of the appearance of the priming electrons still remains open.

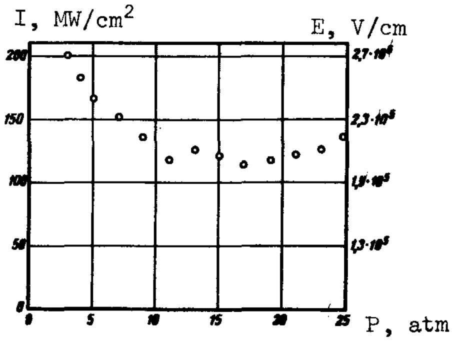

Fig. 2. Xenon breakdown threshold.

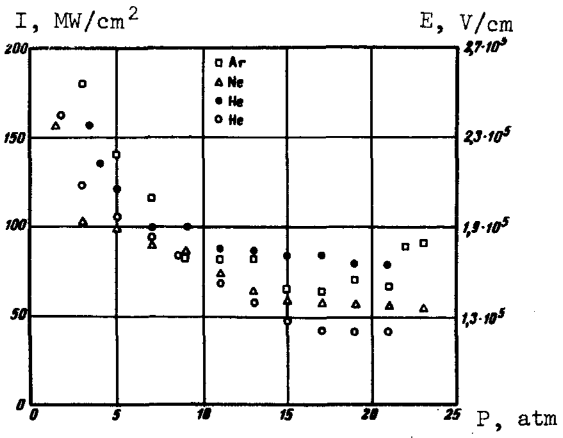

Fig. 3. Thresholds in Ar, Ne, and He. The dark circles correspond to helium of higher purity. The low experimental accuracy and the influence of the impurities do not make it possible to guarantee the correctness of the ratios of the thresholds in the different gases.

The measured thresholds can be explained by suing the concepts of cascade ionization. Under the influence of the field, the electron acquires energy at the rate

$$d\epsilon/dt = e^2 E^2 \nu_m / m\omega^2 + \nu_m^2 ; \qquad \mathcal{J} = cE^2/4\pi ,$$

where ω and $\mathcal{J}$ are the frequency and intensity of the light, and $\nu_m(\varepsilon)$ is the frequency of the electron-atom collisions. The development of the cascade is hindered by elastic and inelastic energy loss and by the diffusion drift of the electrons from the range of action of the field; the corresponding effective energy-loss rates are

$$d\epsilon/dt\,|_e = \frac{2m}{M}\epsilon\nu_m ; \quad |d\epsilon/dt|^* = \frac{\epsilon^*}{\tau^*}\,\frac{I-\epsilon^*}{I} ; \quad |d\epsilon/dt|_d = \frac{\epsilon}{\tau_d} ,$$

where M is the atom mass, ε^* and I are the excitation and ionization potentials, $1/\tau^*$ is the frequency of the excitations, $\tau_d = \Lambda^2/D$ is the characteristic diffusion time, D is the diffusion coefficient, and $\Lambda = \tau/\pi$. Roughly speaking, the cascade develops if the rate of energy acquisition exceeds the overall loss rate. The characteristic times of the processes $I|-d\varepsilon/dt|^{-1}$ are so much shorter than the pulse duration, that for the development of the cascade it suffices to have only a slight excess of ionization over the loss. Consequently, the threshold corresponds to a stationary electron density, just as in the microwave breakdown [1], in contrast to the case of short-duration pulses of ruby and neodymium lasers [4].

Let us consider specifically Xe. On the basis of the data on the cross sections, we choose $\nu_m = 9 \times 10^{12} p_{atm}$ sec^{-1}, $D = 610 p_{atm}^{-1}$ cm^2/sec, and $1/\tau^* = 3.1 \times 10^{10} p_{atm}$ sec^{-1} (at $9 < \varepsilon < 13$ eV). The elastic losses in the heavy Xe are always negligible, and at our values of p and $\Lambda = 1.3 \times 10^{-3}$ the inelastic losses are much more important than diffusion. Equating the rates of acquisition of energy and of the elastic losses, in accord with the stationarity conditions, we obtain immediately $\mathcal{J} \approx 500$ MW/cm^2, which agrees in order of magnitude with the measured thresholds.

It is more correct, of course, to start from the kinetic equation for the electron energy distribution $n(\varepsilon,t)$. Any detailed analysis would lead to extremely cumbersome calculations and to complicated formulas [1]. We introduce simplifications in the spirit of the theory of [4], but we improve on [4]. We omit the elastic-loss term and assume that ν_m, D, and τ^* are independent of ε (with $\varepsilon < \varepsilon^*$); when $\varepsilon < \varepsilon^*$ we have $1/\tau^* \equiv 0$. We assume that the electrons that have attained the energy I ionize the atoms instantaneously, i.e., $n(I) = 0$. We subject the flux along the energy axis $j(\varepsilon)$ to the multiplication condition $j(0) = 2j(I)$. In addition, n and j are continuous when $\varepsilon = \varepsilon^*$. Then the equation can be solved in elementary fashion and the stationarity condition $\partial n/\partial t = 0$ leads to a simple transcendental equation for the dimensionless threshold field $Z = Z(\xi, b)$, where $\xi = (\tau_d/\tau^*)^{1/2}$ and $b = (1/\varepsilon^*)^{1/2} \simeq 1.2$. The practically universal function $Z(\xi)$ increases monotonically ($Z(0) = 0.55$, $Z(3) = 0.75$, $Z(5) = 0.95$, $Z(10) = 1.56$) and approaches the asymptotic value $Z = 0.145\xi$ when $\xi > 10$. In our case $\xi = 9p_{atm}$.

The threshold intensity is equal to

$$\mathcal{J} = \frac{3}{2}\,\varepsilon^*\,\frac{mc}{\pi e^2}\,\frac{D\nu_m}{\Lambda^2}\left(1 + \frac{\omega^2}{\nu_m^2}\right) Z^2(\xi)\,.$$

This formula yields $\mathcal{J} \simeq 200 - 250$ MW/cm^2 at $p \simeq 2 - 20$ atm, which is closer to the experimental values, although the minimum of $\mathcal{J}$ turns is displaced, being at $p \simeq 5$ atm in place of the experimental 15 atm. It is remarkable that this simple and compact formula describes well the experimental data [1] on microwave breakdown of xenon in the range of p from 10^{-2} to 10^2 mm Hg.

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EXPERIMENTAL INVESTIGATIONS OF AN ULTRAHIGH ENERGY PARTICLE DETECTOR USING TRANSITION X-RADIATION

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It was shown in [1] that the intensity of the transition radiation of high-energy particles is directed mainly forward and is concentrated in the x-ray band. If the radiation is registered in a definite frequency interval, then the radiation intensity has a strong dependence on the particle energy.

It was shown in [2] that if we register the radiation also in a definite angle interval $0 - \theta$, then the dependence on the particle energy becomes even stronger.

Indeed, it can be shown that if $\sigma/\omega^2 \ll (mc^2/E)^2$ and $\theta^2 \ll (mc^2/E)^2$, then the radiation intensity is

$$\frac{dW}{d\omega} \approx \frac{e^2}{2\pi c}\,\frac{\sigma_2}{\omega^4}\,\theta^4 (E/mc^2)^8,$$

where σ is the square of the plasma frequency.