

pickups, screened against capacitive induction with grounded slotted shields.

We have thus confirmed the presence of a rapidly produced ionization aureole that anticipates the ionization front, behind the shock wave which covers a very short path during the short time of the aureole. (A microwave investigation of the ionization aureole was reported earlier [1].)

We can estimate the lower limit of the effective conductivity of the ionization in the aureole, using only the time  $\tau$  of dipole-moment variation. It is known that the time of expulsion of the external electric field from a volume with conductivity  $\sigma$  is equal to  $t \sim 1/\sigma$ . Since  $t < \tau$ , we have  $\sigma > 1/\tau$ , but  $\sigma = n_e e^2 / m v_{so}$ , where  $v_{so}$  is the frequency of electron collision with the neutral particles (in gas  $v_{so} \approx 3 \times 10^{10} \text{ sec}^{-1}$  at normal pressure). We obtain from this  $n_e > 10^{10} \text{ el/cm}^3$  at  $\tau \approx 10^{-8} \text{ sec}$ . The ionization of the gas can be due either to cascaded absorption of ultraviolet quanta or to absorption of kilovolt x-ray quanta emitted by the hot plasma of the spark. (For example, the number of kilovolt x-ray quanta whose free path in air is commensurate with the aureole dimensions is  $N_{KV} \approx N_e \epsilon e^{-\epsilon/kT_e} v_s \tau r_0 / hc \sim n_e a^3 I_1 / \epsilon$  at a total number  $N_e \sim 10^{17}$  electrons in the central plasma of the spark, a collision frequency  $v_s(kT_e) \approx 10^{15} \text{ sec}^{-1}$ , and a quantum-energy to thermal-energy ratio  $\epsilon/kT_e \approx 20$ .)

An interesting result of the experiment is also the observation of a rapidly produced intrinsic dipole moment of the spark, directed opposite to the light flux (positive charge on the side of the spark front), and apparently connected with the light pressure or with thermoelectric effects.

The polarization of the fast ionization aureole in external fields and the rapid changes in the intrinsic dipole moment of the light spark may serve as sources of bursts of radio emission in the meter band, whose intensity may be quite high because of the abrupt variation and magnitude of the dipole moment.

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#### PHOSPHORESCENCE AND BAND STRUCTURE OF RUBY

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Prolonged phosphorescence, reliably recordable 2 - 3 days after the instant of excitation, was observed in ruby crystals following high-power optical excitation (with several laser flashes of 450 Joules). This phosphorescence attenuates hyperbolically with exponent  $\approx 1$ , and its spectrum is located near the R line.

To clarify the nature and mechanism of the observed phenomenon, we investigated the initial stages of the attenuation of phosphorescence excited with light of varying intensity and wavelength. We observed that 2 - 3 seconds after cessation of the excitation, the phos-

phorescence intensity varies hyperbolically with exponent  $\approx 1$ , and that at the initial stage the time variation is even faster. Measurements of the initial brightness ( $I_0$ ) as a function of the excitation intensity ( $E$ ) have shown that  $I_0 \sim E^{2-2.5}$ . These data indicate that this is a recombination process [1], i.e., a process proceeding via the conduction band.

Measurements of the spectral dependence of the phosphorescence excitation have shown that the long-wave limit of this excitation is  $6030 \text{ \AA}$  ( $\approx 2 \text{ eV}$ ). Of course, such a quantum is insufficient to project the electron from the ground level of the chromium ion to the conduction band, so that it is natural to assume a more complex excitation process - cascade or multiphoton.

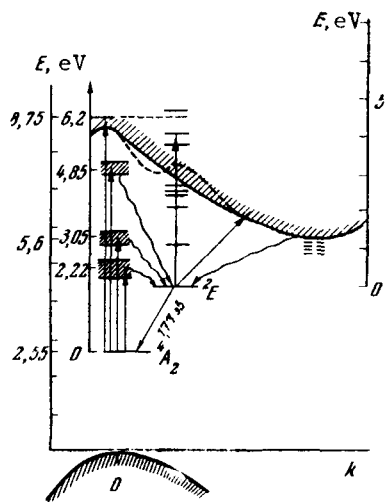
To distinguish between these two possibilities, we undertook a series of experiments in which the ruby was excited with two light pulses applied either practically simultaneously (the duration of the first pulse (pump) was 2.2 msec, that of the second (illumination) 0.8 msec; the start of the second pulse lagged behind the start of the first (by  $\tau_{\text{del}} = 0.6 \text{ msec}$ ) or in sequence ( $\tau_{\text{del}} = 2.4 \text{ msec}$ )). In the latter case the illumination pulse was applied only when the  ${}^2E$  levels were populated as a result of the pump pulse (the lifetime at the  ${}^2E$  levels, as is well known [2], is 3.6 msec).

If the excitation is a two-photon process, then the phosphorescence should acquire a non-additive intensity increment if it is excited simultaneously by the two pulses, compared with excitation by each of the pulses separately; no such increment can arise if the two pulses are sequentially applied. On the other hand, if the excitation is by cascade via the  ${}^2E$  levels, then the successive action of the pulses should result in a non-additive increment. Our investigations have shown that a non-additive increment of approximately equal magnitude is produced for both values of delay time, 2.4 and 0.6 msec. We can conclude from these results that in our case the phosphorescence is excited in cascade via the  ${}^2E$  levels.

Thus, high-power optical excitation makes it possible for the electron to go over from the ground state of the chromium atom to the conduction band by successively absorbing two light quanta. The bulk of the electrons are dumped back from the conduction band to the  ${}^2E$  levels and then go back to the ground state, producing luminescence quanta, while a smaller fraction <sup>1)</sup> settles at the local levels near the bottom of the band and then returns to the ground state slowly (the lifetime of these levels is relatively large) through the band and the  ${}^2E$  levels, emitting phosphorescence quanta.

Our data and results of earlier investigations of the absorption spectra of ruby [3] and corundum [4] allow us to propose for ruby a band structure which may be useful in explaining the optical and semiconductor processes that take place in the ruby crystal.

It is known that the absorption coefficient of corundum increases sharply in the region  $\lambda \approx 1410 \text{ \AA}$ . This increase is apparently due to direct transitions from the valence band to the conduction band, so that the corresponding energy distance between these bands can be assumed to equal  $\approx 8.75 \text{ eV}$ . However, the presence of small absorption with maximum at  $1800 \text{ \AA}$  and with a tail extending to  $\approx 2200 \text{ \AA}$  apparently indicates that the bands have a complicated structure and that indirect transitions between the bands also exist; the latter may offer



Band structure of ruby

into the conduction band: the transition is apparently indirect. We must note, to be sure, that in accordance with our scheme the red edge of phosphorescence excitation should occur at larger wavelengths ( $\approx 1.2$  eV); it is possible that it was inaccurately determined in our experiments, for since the process is patently nonlinear and indirect transitions are produced, a more exact determination of this edge calls evidently for still higher excitation intensities and higher apparatus sensitivity.

In conclusion, we are grateful to M. D. Galanin and D. T. Sviridov for interest in the work and for valuable discussions.

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1) According to our estimates, the quantum yield of the phosphorescence investigated by us does not exceed  $10^{-7}$ .

2) The levels of the chromium ions were spread along the k axis in Fig. 1 to be able to distinguish between the doublet and quadruplet systems without cluttering up the figure.

evidence of a shift of the bands in momentum space. Thus, the bands of corundum can be arranged as shown in the figure: the direct transition corresponds to 8.75 eV, while the indirect ones reach 5.6 eV. The sharp increase in the absorption coefficient of ruby in the 2000 - 2100 Å region [3] can be attributed to the direct transition of the electrons from the ground level of the chromium ion to the conduction band of the crystal, so that the position of the ground level of the chromium in the forbidden band of corundum can thus be determined (see the figure). It is then easy to locate the other chromium-ion levels, which have been calculated previously [5] 2).

Within the framework of the proposed scheme, we can readily explain why a quantum with so little energy ( $\approx 2$  eV) is capable of transferring an electron from the  ${}^2E$  level