

FIG. 1. Theoretical curves showing the variation of specific fluorescence  $v_s$  specific energy loss in a fluorescent scintillator.

$\gg a + bn_{10} + cn_{10}^2$ , we have

$$L_s \sim \frac{n_{10}e_2}{q_2 + e_2} \left( 1 - \frac{a + bn_{10} + cn_{10}^2}{T_1N_2 + T_1'N_2'^2} \right). \quad (5)$$

When the specific energy loss is large, i.e.,  $T_1N_2 + T_1'N_2'^2 \ll a + bn_{10} + cn_{10}^2$ , we have

$$L_s \sim \frac{n_{10}e_2}{q_2 + e_2} \frac{T_1N_2 + T_1'N_2'^2}{a + bn_{10} + cn_{10}^2} \left( 1 - \frac{T_1N_2 + T_1'N_2'^2}{a + bn_{10} + cn_{10}^2} \right). \quad (6)$$

One can easily obtain similar results for other types of fluorescent scintillators, provided suitable similar general physical considerations are adopted. For example, for substances like anthracene or NaI(Tl) crystal, which absorb and emit the irradiated energy through the same kind of molecules, we obtain instead of (4) the expression

$$L = n_{10}e_1 / (e_1 + a + bn_{10} + cn_{10}^2), \quad (7)$$

with limiting cases similar to those given by (5) and (6).

The general feature of (4) or (7) is shown in Fig. 1. The three branches A, B, and C correspond respectively to the cases where the effect of the constants  $a$  or  $b$  or  $c$  respectively predominates the quenching factor  $q_1$  as given by (3). In practical cases, it might not be easy to distinguish the cases A and B. Experimental curves like A and B have been reported<sup>1,3</sup> for organic and inorganic crystals being irradiated by electrons,  $\gamma$ -rays and heavy particles. An experimental curve like C has been reported for electrons passing through an anthracene crystal.<sup>1</sup> The theoretical curves derived above seem to be able to account for these experimental results satisfactorily.

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<sup>1</sup> Taylor, Jentschke, Remley, Eby, and Kruger, Phys. Rev. **84**, 1034 (1951).

<sup>2</sup> C. N. Chou [Phys. Rev. **87**, 903 (1952)] and the literature given there.

<sup>3</sup> R. H. Lovberg, Phys. Rev. **84**, 852 (1951).

<sup>4</sup> W. S. Koski, Phys. Rev. **82**, 230 (1951).

<sup>5</sup> W. L. Buck and R. K. Swank, Phys. Rev. **87**, 191 (1952), and private communication.

<sup>6</sup> T. Foerster, Ann. Physik **2**, 56 (1948).

## Optical Polarization in Single Crystals of Tellurium\*.<sup>†</sup>

J. J. LOFERSKI

University of Pennsylvania, Philadelphia, Pennsylvania

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THE transmission of tellurium crystals has been observed in the infrared. Because of the hexagonal nature of the lattice, the transmission was measured as a function of the polarization of the incident radiation relative to the C-axis of the crystal. Recently, Moss has reported on the transmission of tellurium films and of a bulk sample, although he does not specify whether he had a single crystal.<sup>1</sup>

The crystals were obtained from the Anaconda Sales Company, which reported that the material was at least 99.8 percent pure, although subsequent spectroscopic tests failed to indicate any impurities.<sup>2</sup> The samples were prepared for investigation by polishing them according to metallographic techniques. Their resistivity as determined by probing the surface was about 0.3 ohm-cm at room temperature, at which temperature they were in the intrinsic range. A Beckman IR2 monochromator with rock salt optics was used with a Nernst glower to provide the monochromatic radiation, which was modulated at 10 cps. The emerging beam passed through the polarizer onto a mirror which formed an image of the exit slit on the sample, and the transmitted radiation was collected by a second mirror which formed an image on the exit slit on the sample, and the transmitted radiation was collected by a second mirror which formed an image on the target of a Perkin-Elmer radiation thermocouple, whence the ac signal was fed into a suitable amplifier. The transmission polarizer consisted of a set of unsupported films of amorphous selenium, and was constructed according to the method of Elliott *et al.*<sup>3</sup>

The transmission of a typical sample is shown in Fig. 1. It is to be noted that the position of the absorption edge as well as the amount of radiation transmitted at longer  $\lambda$  depends markedly on the polarization. By observing the transmission of a number of separate samples of different thicknesses, it is possible to determine the absorption constant as a function of  $\lambda$  and to get an approximate value of the index of refraction of the crystals. Typical results are shown in Fig. 2 for a few values of  $\lambda$ . For this purpose it is necessary to assume that the fraction of radiation transmitted is given by the expression

$$I/I_0 = (1-R)^2 e^{-kx},$$

where  $I$  and  $I_0$  are the transmitted and incident radiation intensity, respectively,  $R$  is the reflection loss at a surface,  $k$  is the

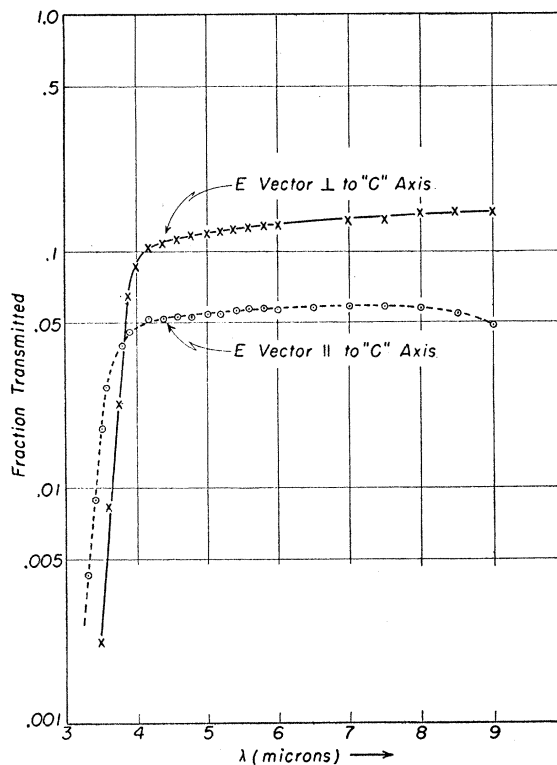


FIG. 1. Transmission of a Te crystal 0.063-cm thick, showing effect of polarizing the incident radiation.

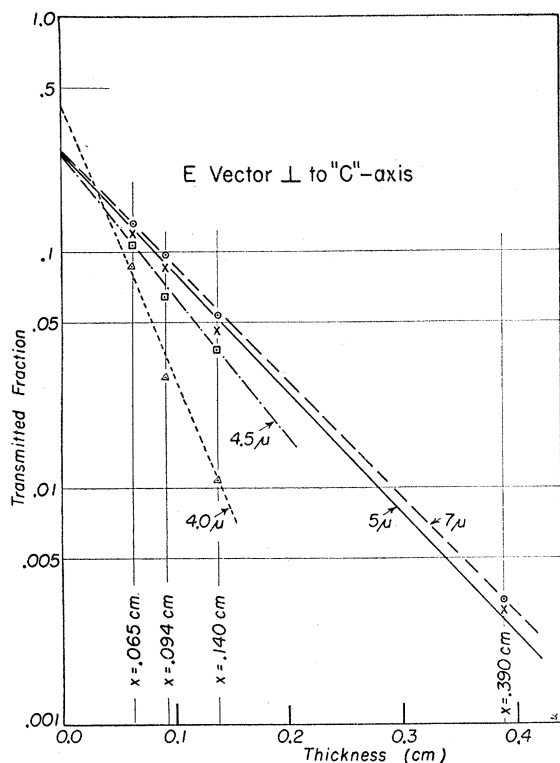


FIG. 2. Transmission of Te crystals as a function of thickness for a few values of  $\lambda$ .

absorption constant ( $\text{cm}^{-1}$ ), and  $x$  is the thickness in cm. The resulting values of  $k$  are shown in Fig. 3.

The interpretation of these results suggests first of all that the increasing absorption beyond the edge toward shorter  $\lambda$  is due to electrons making the transition from the filled to the conduction band. If we locate the absorption edge which occurs for the larger value of  $\lambda$  at  $3.6\mu$  by associating it with the gap width as deter-

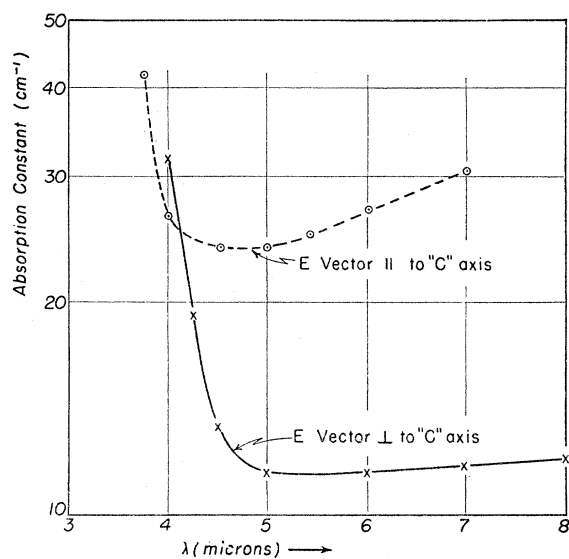


FIG. 3. Experimental values of the absorption constant of Te crystals as determined from the slopes of the lines in Fig. 2.

mined by conductivity measurements, i.e.,  $0.34 \text{ eV}$ ,<sup>4</sup> the criterion so established places the second edge at  $3.3\mu$ . This is an arbitrary method of locating the edge, since the values as determined by absorption and conductivity can be expected to agree only at low temperatures. Secondly, as in germanium and silicon,<sup>5</sup> the value of  $k$  as determined by assuming only free carrier absorption beyond the edge toward longer  $\lambda$  is smaller by a factor of  $10^3$  than the experimental values. Finally, the index of refraction,  $n$ , as computed from the expression

$$R = (n-1)^2 / (n+1)^2,$$

is about  $5.3 \pm 0.2$  at  $6\mu$ , which is somewhat larger than the value found by Moss in tellurium films. It was impossible to detect any difference in the values of  $n$  for the two directions of polarization by this method. Preliminary measurements on prisms of crystalline tellurium yield values of  $n$  of this same magnitude.

\* Preliminary reports of this work were presented at the meetings of the American Physical Society on June 15, 1951 and March 21, 1952 [Phys. Rev. **83**, 876 (1951) and **86**, 652 (1952)].

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<sup>1</sup> T. S. Moss, Proc. Phys. Soc. (London) **B65**, 62 (1952).

<sup>2</sup> We wish to acknowledge the help of Dr. W. Scanlon, Naval Ordnance Laboratory, White Oaks, Maryland, who arranged for the analysis.

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<sup>4</sup> V. E. Bottom, Science **115**, 570 (1952); T. Fukuroi, Sci. Repts. Research Inst. Tohoku Univ. **A3**, 175 (1951).

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### Enhancement of the *F*- and *V*-Bands in Sodium Chloride Containing Calcium

H. W. ETZEL

Crystal Branch, Metallurgy Division, Naval Research Laboratory, Washington, D. C.

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IT has been observed by Hummel<sup>1</sup> that the introduction of calcium as an impurity in KCl results in a  $\gamma$ -ray induced *F*-band absorption which is much greater than one observes for the "pure" alkali halide. Curves B, C, D, and E in Fig. 1 show this enhancement in x-rayed NaCl single crystals grown by the Kypoulos method, which contain, respectively, 1, 5, 10, and  $50 \times 10^{-2}$  mol percent calcium added to the melt. Approximately one-tenth of the calcium concentration in the melt is present in the crystals. In the same figure is shown the *F*-band absorption for "pure" NaCl, curve A, and for two crystals, curves F and G, which contain additions of divalent cadmium rather than divalent calcium. To insure uniform coloration the crystals were cleaved to less than 0.36 mm in thickness. All crystals were x-rayed using molybdenum radiation at 40 kvp and 20 ma for one hour. After the first half-hour the crystals were rotated through  $180^\circ$ , and the second face was placed nearest the x-ray tube. The absorption measurements were made using a Beckman Model DU Quartz Spectrophotometer. All experimental work was carried out at room temperature.

It is interesting to note that the introduction of  $\text{Cd}^{++}$  to the lattice, and subsequent x-raying, do not produce the same striking enhancement of the *F*-band as does the incorporation of  $\text{Ca}^{++}$ . A difference in the behavior of  $\text{Ca}^{++}$  and  $\text{Cd}^{++}$  as impurities in NaCl is also observed in the work of Etzel and Maurer<sup>2</sup> and Bean and Maurer.<sup>3</sup> The former investigators found that in the neighborhood of  $400^\circ\text{C}$  the crystal shown in Fig. 1, curve F, has about one-third of the positive ion vacancies introduced by the  $\text{Cd}^{++}$  associated with this ion. At room temperature it is then likely that this association is complete. In contrast to this, Bean and Maurer find that no observable association occurs between the  $\text{Ca}^{++}$  and the positive ion vacancies.

The following mechanism is suggested to explain the enhancement of the *F*-band in the alkali halides containing ions of rare gas electronic structure as divalent impurities. When a  $\text{Ca}^{++}$ , for instance, is added to the NaCl lattice, one positive ion vacancy is also added to the lattice, at least to a first approximation. This occurs in order to maintain electrical neutrality within the crystal