TABLE I. Pulse sizes (in the same arbitrary units as used in Fig. 1) from plastics irradiated with Co^{60} and Po sources.

Plastic scintillator	Specifications	Pulse size observed with Co^{60} source	Pulse size observed with Po source	Ratio of pulse size with Co^{60} to pulse size with Po
A1	2% anthracene in polystyrene	0.89	0.50	0.56
A2	3% anthracene in polystyrene	0.86	0.50	0.58
A3	5% anthracene in polystyrene	0.97	0.53	0.55
B2	2% *p*-terphenyl in polystyrene	1.65	0.82	0.50
C2	2% *p*-terphenyl +0.03% diphenyl-hexatriene in polystyrene	1.52	0.82	0.54
C3	4% *p*-terphenyl +0.03% diphenyl-hexatriene in polystyrene	2.05	1.05	0.51

We can make the following remarks concerning the experimental results shown in Fig. 1 and in Table I. Since it is known that in the case of small specimens being irradiated with electrons,[1] NaI(Tl) gives linear response at energy losses well beyond the range covered by the present experiment, the apparent deviation from linear response above about 4 times minimum ionization loss, as demonstrated in Fig. 1, is most probably due to the inhomogeneity of the proton beam and its straggling in passing through the copper absorbers and the geometrical arrangement adopted here. It is to be noted that the *p*-terphenyl in polystyrene plastic gives a reasonably linear response up to about 3 times minimum ionization loss, and the anthracene in polystyrene gives linear response up to at least 4 times minimum loss. The variation in concentration from 2–5 percent in the case of anthracene in polystyrene and from 2–4 percent in the case of *p*-terphenyl in polystyrene have within the experimental errors no significant effect on the saturation of these two scintillators. Also the addition of a small amount of diphenylhexatriene in the *p*-terphenyl in polystyrene did not show definite remarkable influence on the saturation effect observed. The results of Fig. 1 seem to indicate quite clearly that the plastic scintillators show less saturation than the liquid phenylcyclohexane solution. Table I shows that the results of the α-particle measurements regarding saturation support the conclusions drawn from the investigations with the mesons and protons.

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The Nature of the Saturation Effect of Fluorescent Scintillators*

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IT has been found that when a high energy particle passes through a scintillating organic crystal or liquid or a plastic scintillator, the fluorescent light output it produces is no longer proportional to its energy loss above a certain value of the loss.[1,2] The same kind of deviation from proportionality is less pronounced for scintillating inorganic crystals like NaI.[1,3] In the following we propose an interpretation of this phenomenon based on some general physical considerations. As an example, we consider first the case of plastic scintillators, for instance, polystyrene impregnated with a small amount of fluorescent substance like anthracene. For simplicity of argument, we shall consider the thickness of the scintillator unity. Let n_1 denote the number per cc, q_1 the quenching probability, and e_1 the probability of light emission of the molecules of the plastic substance excited by the passage of a high energy particle through the scintillator, and let n_2, q_2, and e_2 denote the same quantities for the excited molecules of the impregnated fluor. We shall denote the total number of molecules per cc available of the fluor as N_2 and assume that N_2 is always larger than n_1.

There is evidence that the irradiated energy is first absorbed by the molecules of the plastic substance and then transferred to the fluor.[4,5] According to recent results,[5] the mechanism of energy transfer is probably partly radiative and partly nonradiative. The probability of nonradiative transfer due to energy exchange through a sort of resonance is known to be proportional to the square of the concentration of the "dissolved" molecules.[6] One can set up for the change of n_1 and n_2 with time the following differential equations,

$$\frac{dn_1}{dt}=-T_1N_2\left(1-\frac{n_2}{N_2}\right)n_1-T_1'N_2^2\left(1-\frac{n_2}{N_2}\right)^2n_1-q_1n_1-e_1n_1, \quad (1)$$

$$\frac{dn_2}{dt}=T_1N_2\left(1-\frac{n_2}{N_2}\right)n_1+T_1'N_2^2\left(1-\frac{n_2}{N_2}\right)^2n_1-q_2n_2-e_2n_2, \quad (2)$$

where T_1 is the probability constant of the radiative transfer and T_1' that of the nonradiative transfer (assumed to be due to the above-mentioned mechanism of energy exchange). The initial condition for $t=0$, is given by $n_1=n_{10}$, where n_{10} is proportional to the energy lost by the irradiating particle. No attempt was made to find a complete solution of Eqs. (1) and (2). However, we make use of the fact mentioned above that the energy transfer from the plastic to the fluorescent molecules must be almost complete before the plastic itself emits an appreciable amount of light. Also we shall assume that $N_2\gg n_2$ for all times; then instead of (1) we solve the simplified equation,

$$dn_1/dt=-T_1N_2n_1-T_1'N_2^2n_1-q_1n_1,$$

and obtain the solution

$$n_1=n_{10}\exp[-(T_1N_2+T_1'N_2^2+q_1)t].$$

Similarly we shall solve (2) with its first two terms at the right-hand side omitted, and obtain

$$n_2=n_{20}\exp[-(q_2+e_2)t],$$

where n_{20} is the initial value of n_2, and is given approximately by

$$n_{20}\sim\int_0^\infty(T_1N_2+T_1'N_2^2)n_1dt=\frac{n_{10}(T_1N_2+T_1'N_2^2)}{T_1N_2+T_1'N_2^2+q_1}.$$

The light output observed should be given by

$$L=\int_0^\infty e_2n_2dt=\frac{e_2}{q_2+e_2}\frac{n_{10}(T_1N_2+T_1'N_2^2)}{T_1N_2+T_1'N_2^2+q_1}.$$

We further make the plausible assumption that

$$q_1=a+bn_{10}+cn_{10}^2, \quad (3)$$

(where a, b, and c are constants), to take into account the variation of the quenching effect with the various modes and degrees of excitations which in turn depend upon the initial energy loss of the irradiating particle. Then we obtain for the light output

$$L=\frac{n_{10}e_2}{q_2+e_2}\frac{T_1N_2+T_1'N_2^2}{T_1N_2+T_1'N_2^2+a+bn_{10}+cn_{10}^2}. \quad (4)$$

When the specific energy loss is small, i.e., $T_1N_2+T_1'N_2^2$

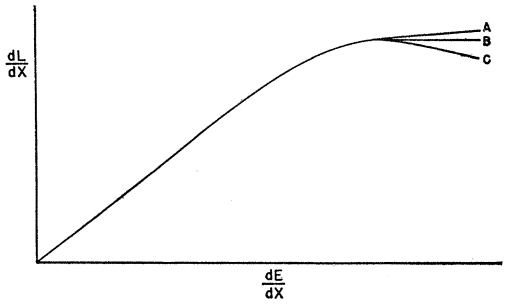

FIG. 1. Theoretical curves showing the variation of specific fluorescence *vs* specific energy loss in a fluorescent scintillator.

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

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

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[1,3] for organic and inorganic crystals being irradiated by electrons, γ-rays and heavy particles. An experimental curve like C has been reported for electrons passing through an anthracene crystal.[1] The theoretical curves derived above seem to be able to account for these experimental results satisfactorily.

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Optical Polarization in Single Crystals of Tellurium*,†

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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.[1]

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.[2] 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.*[3]

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 λ 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 λ 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 λ. For this purpose it is necessary to assume that the fraction of radiation transmitted is given by the expression

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

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

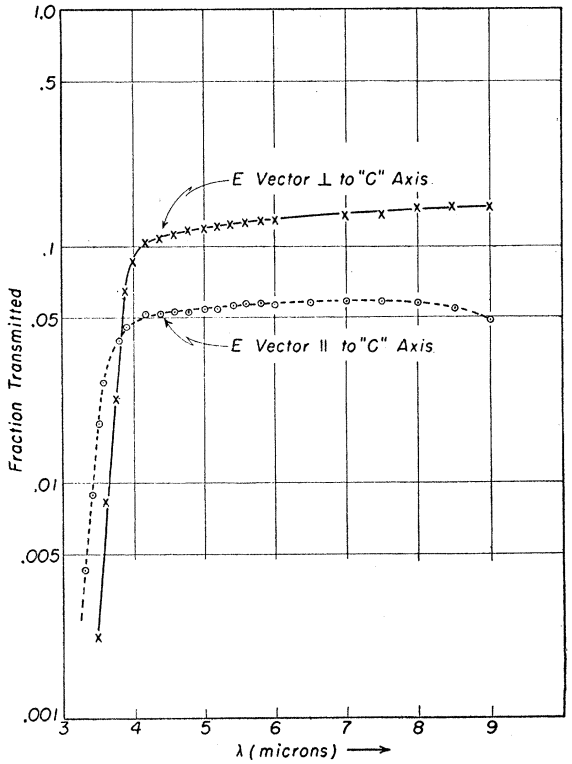

FIG. 1. Transmission of a Te crystal 0.063-cm thick, showing effect of polarizing the incident radiation.