Tangen's tentative theory that the increased yield at higher energies was due to the increase in nonresonant radiation is not compatible with more recent work of Fowler, Lauritsen, and Lauritsen,[3] who found a $Be^9(p,\gamma)B^{10}$ resonance at 998 kev. This could be fitted closely to the Breit-Wigner formula even at the "tails," showing that nonresonant radiation at these energies was small. It follows that it must be even smaller in the energy range 400–500 kev.

In order to investigate this problem further, yield curves for thin targets of thickness in energy units between five and ten kev have been obtained. A typical curve is shown in Fig. 1. The efficiency of γ-detection has been increased by using a scintillation counter, and the targets were heated to 200°C and cold trapped. This has been found to be effective in eliminating carbon contamination.[1] The thin target yield curves were reproducible and had maxima at 341.8±2.0 kev and 485.0±3 kev. The rather large uncertainty was due to the great width of the resonances and consequent difficulty in determining precisely the points of maximum yield on the experimental curves.

The yield curve is thought to be due to two broad resonances incompletely resolved. Symmetrical curves obeying the Breit-Wigner formula and having maxima at 336.0±2 kev and 492.0±3 kev could be fitted closely to the experimental curve. The half-widths were 175±5 kev and 110±5 kev, respectively.

This corresponds to excited levels in the B^{10} nucleus at 6.79(1) Mev and 6.93(5) Mev, respectively. The figures in brackets lose their significance as absolute values because of the uncertainty in the Q value for the reaction (6.49 Mev).

Yield curves for this reaction have also been observed previously by Curran, Dee, and Petryilka.[4] They observed a highly asymmetric peak at about 350 kev and another at about 480 kev which they attributed to carbon contamination of the target. Tangen's value for the experimental peak was 330±10 kev. This was reduced to 310±10 kev by his corrections for the 150-kev resonance and the assumed increase in nonresonant radiation.

Thomas, Rubin, Fowler, and Lauritsen have investigated the $Be^9(p,d)Be^8$ and $Be^9(p,\alpha)Li^6$ yield curves. They observed resonant peaks at about 330 kev and 470 kev for the former reaction, and at 330 kev only for the latter. If it is assumed that the higher energy peak can be identified with the one observed in the present work, this would indicate that while the B^{10} level at 6.79(1) Mev is unstable both to α-particle and deuteron emission, α-particle emission is forbidden from the 6.93(5)-Mev level.

Walker[6] has observed γ-rays of energy 6.71 Mev from this reaction. The energy resolution of his spectrometer[7] was too low to separate γ-rays from the two levels suggested by the present work. Other investigations on the energy levels of this B^{10} nucleus have been reviewed by Hornyak *et al.*[8]

The author wishes to thank A. J. Salmon for his assistance in the design and operation of the scintillation counter.

He is also indebted to Dr. T. E. Allibone for permission to publish this letter.

[1] S. E. Hunt (to be published).
[2] R. Tangen, Kgl. Norske Videnskab. Selskabs, Skrifter, No. 1 (1946).
[3] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948); W. A. Fowler and C. C. Lauritsen, Phys. Rev. **76**, 314 (1949).
[4] Curran, Dee, and Petryilka, Proc. Roy. Soc. (London) **169**, 269 (1939).
[5] Thomas, Rubin, Fowler, and Lauritsen, Phys. Rev. **75**, 1612 (1949).
[6] R. L. Walker, Phys. Rev. **79**, 172 (1950).
[7] R. L. Walker and B. D. McDaniel, Phys. Rev. **74**, 315 (1948).
[8] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).

Saturation Effect of Plastic Scintillators*

C. N. Chou
Department of Physics, University of Chicago, Chicago, Illinois
(Received June 23, 1952)

IT is known that for high energy losses the light output from a scintillating fluor is not proportional to the energy loss of the irradiating particle passing through it in the cases of organic crystals[1–7] and liquids,[8] and to a smaller extent, in the case of inorganic crystals.[9] Recently we made some measurements of this saturation effect in plastic scintillators and in phenylcyclohexane solution and in a NaI crystal making use of the negative pion beam and the outside proton beam of the Chicago cyclotron. The plastic samples were wrapped with 0.076-mm thick aluminum foil except for the end attached to a 5819 photomultiplier. Two scintillators were placed parallel to each other and perpendicular to the direction of the beam used. The output pulse of one phototube triggered the sweep of a synchroscope whose vertical plates were connected to the output of the second tube. The output pulse of the second tube was (a) observed visually and (b) recorded photographically with a specially designed camera. The two sets (a) and (b) of observations agreed within experimental errors. Absorbers of copper plates were placed between the scintillators to obtain particles of various energies. Calibration readings with Compton electrons of minimum ionization from the 1.3-Mev γ-rays of a Co^{60} source were intermittently made during the run. Figure 1 shows the variation of the light output from the scintillators *vs* energy loss. The phenylcyclohexane solution (containing 0.3 percent p-terphenyl and 0.001 percent diphenylhexatriene) was 3.4 cm in diameter and 3.4 cm in length. The NaI (Tl activated) crystal was 1.25-in. high, 2.25-in. wide and 0.5 in. in thickness. All the plastic samples were 1-in. square and 5-mm thick. The path length of the mesons and protons through the plastics was 0.5 mm. The specifications of the various plastics and the results obtained with the Co^{60} source and with the 5.3-Mev α-particles from a Po source are given in Table I.

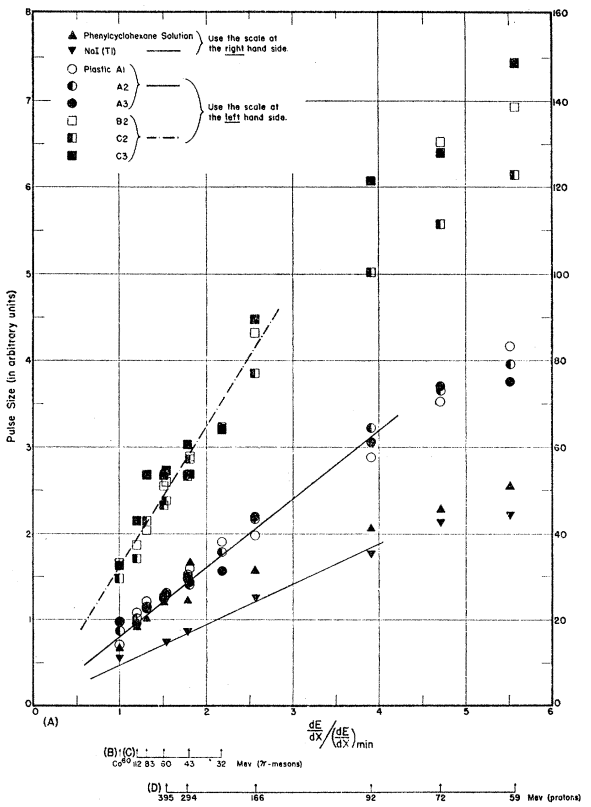

FIG. 1. Variation of light output from the scintillators with energy loss. The ordinate gives the pulse size (in arbitrary units) which is proportional to the light output. The abscissa gives the energy loss in the scintillators. The scale in row (A) represents the energy loss in units of the loss at minimum ionization. (B) refers to measurements with a Co^{60} source. Row (C) gives the energies of the pions in Mev corresponding to the energy losses represented in (A) and the scale in row (D) shows the proton energies corresponding to (A).

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.

The author wishes to express his sincere thanks to Professor Marcel Schein for the cordial hospitality in the Cosmic Ray Laboratory and for numerous valuable discussions and to Professor H. L. Anderson and the cyclotron group for facilities concerning the cyclotron measurements. He also thanks Theodore Bowen for his generous help in connection with the cyclotron measurements.

* Assisted by the joint program of the ONR and AEC.

[1] R. Hofstadter, Nucleonics **6**, 70 (1950).
[2] J. I. Hopkins, Phys. Rev. **77**, 406 (1950).
[3] J. B. Birks, Proc. Phys. Soc. (London) **A63**, 1294 (1950).
[4] W. J. Ramler and W. S. Freedman, Rev. Sci. Instr. **21**, 784 (1950).
[5] Franzen, Peelle, and Sherr, Phys. Rev. **79**, 742 (1950).
[6] Frey, Grim, Preston, and Gray, Phys. Rev. **82**, 372 (1951).
[7] Taylor, Jentschke, Remley, Eby, and Kruger, Phys. Rev. **84**, 1034 (1951).
[8] M. Furst and H. Kallman, Phys. Rev. **85**, 816 (1952).
[9] R. H. Lovberg, Phys. Rev. **84**, 852 (1951).

The Nature of the Saturation Effect of Fluorescent Scintillators*

C. N. CHOU
Department of Physics, University of Chicago, Chicago, Illinois
(Received June 23, 1952)

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., $T_1N_2+T_1'N_2^2$