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THE RESPONSE OF PLASTIC SCINTILLATORS TO HIGH-ENERGY PARTICLES

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The response of the plastic scintillator NE 102 is calculated for protons, deuterons, tritons and alpha-particles up to 160 MeV and it is shown how a linear counter may be constructed. The results of the calculation are tested experimentally for protons and deuterons.

1. Introduction

It has been customary, where linearity is important, to use sodium iodide or caesium iodide crystals as total-energy detectors for heavy charged particles. With pulsed-beam accelerators it is common to have peak counting-rates of the order of 10^7 per second and because of their long decay times inorganic scintillators are unsuitable. These counting-rates can easily be handled with plastic scintillators in conjunction with 10 nsec linear gates which have been developed for this purpose[1]).

Plastic scintillators are, however, non-linear for heavily-ionizing particles and their response is not well-known. In this paper it is shown how the low energy proton data can be used to predict accurately the response for protons and deuterons up to 150 MeV and presumably for other particles. It is further shown how, by sacrificing the first few MeV of response, a counter may be constructed which is nearly linear for particles up to any specified energy.

2. Calculations

In organic scintillators the light output for a given energy loss is less when the density of ionization is high. There are various theoretical explanations for this non-linear response. Birks[2]) has obtained the following relationship between the light output and the energy loss in a small element of the track of an ionizing particle.

$$\frac{\mathrm{d}L}{\mathrm{d}x} \propto \frac{\mathrm{d}E/\mathrm{d}x}{1 + B\,\mathrm{d}E/\mathrm{d}x}$$

where L is the light output, $\mathrm{d}E/\mathrm{d}x$ is the rate of energy loss of the particle in the scintillator and B is a constant. Wright[3]), attributing the effect to a different mechanism obtains

$$\mathrm{d}L/\mathrm{d}x \propto \log(1 + a\,\mathrm{d}E/\mathrm{d}x)$$

where "a" is a constant. These two formulae fit the experimental data equally well[4]). We have chosen for computational convenience Wright's formula.

The range-energy curve for $CH_{1.105}$, which is the composition of the plastic scintillator NE 102, was determined by interpolating between C, CH and CH_2[5]). For energies from 1 to 150 MeV it can be represented approximately by a power law of the following form:

$$\mathrm{d}E/\mathrm{d}x = 16.94\, x^{-0.448} \text{ for protons}$$
$$\mathrm{d}E/\mathrm{d}x = 23.08\, x^{-0.448} \text{ for deuterons}$$
$$\mathrm{d}E/\mathrm{d}x = 27.71\, x^{-0.448} \text{ for tritons}$$
$$\mathrm{d}E/\mathrm{d}x = 67.76\, x^{-0.448} \text{ for alpha-particles}$$

where the energy is in MeV and the range x is in g/cm^2.

The light output for protons was then obtained by integrating the relation

$$L = \int_0^x \log(1 + a\, 16.94\, x^{-0.448})\,\mathrm{d}x$$

1) G. B. B. Chaplin and A. J. Cole, Nuclear Instruments 7 (1960) 45.
2) J. B. Birks, Proc. Phys. Soc. A **64** (1951) 874.
3) G. T. Wright, Phys. Rev. **91** (1953) 1282.
4) F. D. Brooks, Progress in Nuclear Physics, Vol. **5** (Pergamon Press, 1956) 252.
5) Rich and Madey, Range-Energy Curves, UCRL 2301.

up to the range of the particle. The calculation was performed on the Harwell "Mercury" computer, to an accuracy of 0.1% of the light output for 160 MeV protons (arbitrarily normalized to unity), for several values of the parameter "*a*". The same normalization was used for the deuteron, triton and alpha-particle calculations. To determine the best value of the parameter "*a*" the calculations were compared with the known response of NE 102 to protons from 1 MeV to 14 MeV[6,7]). It was found to be 25 ± 2 mg/cm^2/MeV. Table 1 and fig. 1 show the results of the calculations for this value of the parameter.

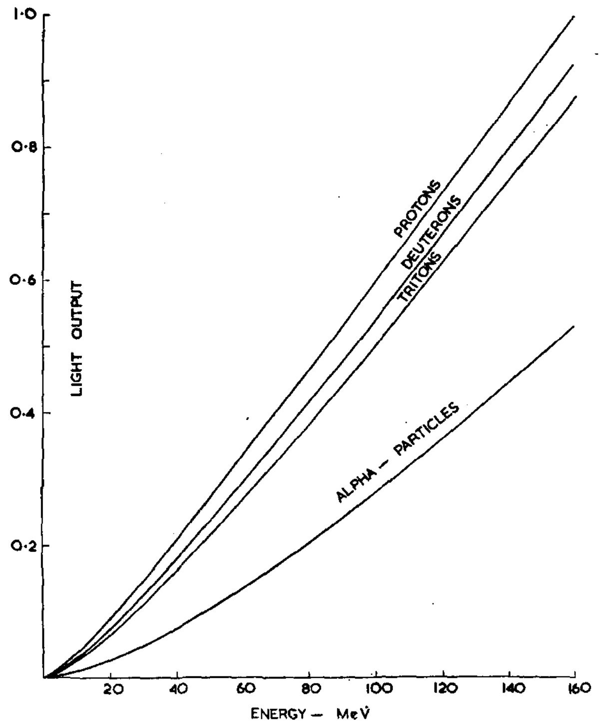

Fig. 1

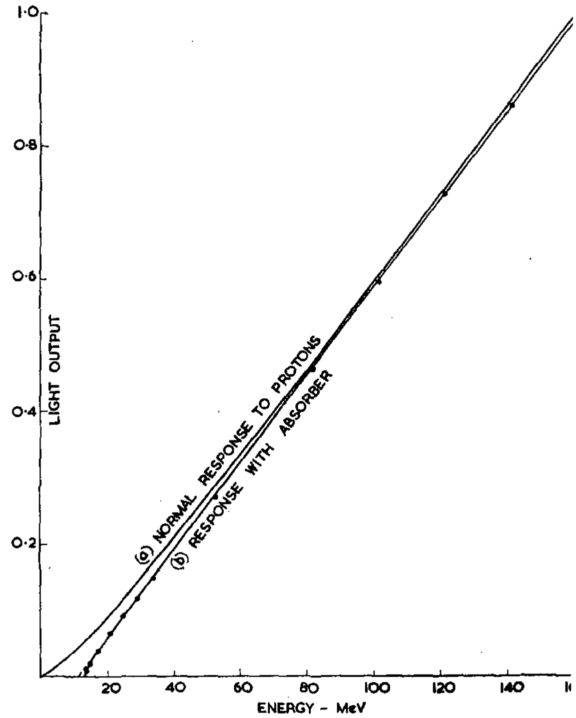

Fig. 2

Fig. 1. The calculated response of NE 102 to protons, deuterons, tritons and alpha particles. The response to a 160 MeV electron on this scale would be 1.16.

Fig. 2. (a) The response of NE 102 for protons, as in fig. 1. (b) The response when an absorber equal to the range of 13 MeV protons is placed in front of the scintillator, plotted as a function of the energy incident on the absorber. The points represent the calculated response while the straight line is the best overall fit for protons between 15 and 150 MeV.

Table 2 shows the response for 120 MeV deuterons, tritons and alpha-particles relative to that for protons of the same energy, with different values of the parameter "*a*". It will be seen that a measurement for example of the ratio L_d/L_p, where L_d and L_p are the responses for deuterons and protons, at a fixed energy will determine the value of the parameter "*a*".

To make the response more linear we introduce a thin absorber in front of the scintillator. The energy lost in the absorber by low-energy particles is greater than that lost by high-energy ones. This has the effect of straightening out the response curve but gives it an intercept on the energy axis. The thickness of absorber to give the best overall linearity depends both on the range of energies over which linearity is required and on the type of particle. For example, an absorber equal to the range of 13 MeV

[6]) H. C. Evans and E. H. Bellamy, Proc. Phys. Soc. 74 (1959) 483.
[7]) M. G. Rusbridge, Private Communication.

protons gives good overall linearity for protons from 15 MeV to 150 MeV as will be seen in fig. 2, whilst for protons between 10 MeV and 50 MeV an 8 MeV absorber is better.

TABLE 1

The calculated response of NE 102 to protons, deuterons, tritons and alpha particles. The parameter "a" is taken as 25 $mg \cdot cm^{-2} \cdot MeV^{-1}$. The light output for a 160 MeV electron on this scale would be 1.16. These results are plotted in fig. 1

Energy (MeV)	L_p	L_α	L_t	L_α
3	0.007	0.005	0.004	0.001
6	0.019	0.014	0.012	0.004
10	0.037	0.029	0.025	0.009
15	0.062	0.050	0.043	0.017
20	0.090	0.074	0.064	0.026
25	0.118	0.099	0.087	0.037
30	0.148	0.125	0.111	0.049
40	0.208	0.179	0.161	0.075
50	0.270	0.236	0.214	0.104
60	0.334	0.294	0.269	0.135
80	0.464	0.415	0.383	0.204
100	0.596	0.539	0.502	0.279
120	0.729	0.666	0.624	0.359
140	0.864	0.795	0.748	0.443
160	1.000	0.925	0.873	0.531

TABLE 2

The response of NE 102 to 120 MeV deuterons, tritons and alpha-particles given as a fraction of the response to protons of the same energy, for different values of the parameter "a"

$mg \cdot cm^{-2} \cdot MeV^{-1}$	L_α/L_p	L_t/L_p	L_α/L_p
10	0.953	0.919	0.647
15	0.936	0.893	0.577
20	0.925	0.872	0.529
25	0.914	0.856	0.492
30	0.904	0.839	0.462

3. Experimental Method

To verify these calculations the response of the plastic scintillator NE 102 has been measured for protons from 28 to 147.5 MeV and for deuterons from 46 to 120 MeV.

The scintillator was a cylindrical block of NE 102, 3 inches in diameter and 7 inches long. It was coupled to an E.M.I. 9531 B photomultiplier through a perspex light guide 3 inches in diameter and $1\frac{1}{2}$ inches long. This light guide was found to be necessary to avoid non-uniform light collection from points near the photocathode. The protons entered the scintillator parallel to the axis through a 0.002 inch aluminium foil.

The absorber was a 0.050 inch thick NE 102 scintillator used as a dE/dx counter, and, including windows, the total thickness of material before the total-energy counter was sufficient to stop 13 MeV protons. A pulse from the dE/dx counter was used to open a fast linear gate; the output of the total-energy counter was passed through this gate and displayed on a multichannel pulse-height analyser.

For the proton measurements a low-intensity beam from the Harwell 110 inch synchrocyclotron was used. A range measurement gave the mean energy as 147.5 MeV and the energy spread as 3 MeV full-width at half-height. The pulse height spectrum from the counter was symmetrical with a width at half-height of 3%. As the proton energy spread was 2% the resolution of the counter for 147.5 MeV protons must therefore be about 2%. Other proton energies were obtained by placing aluminium absorbers in front of the dE/dx counter.

For the deuteron measurements a CD_2 target was bombarded with the normal 153 MeV proton beam. The energy spread of this beam was 7.0 MeV. Recoil deuterons were detected at angles of 20° and 35° to the incident beam, and to establish their identity coincidences were required between the dE/dx counter and a second dE/dx counter placed at the appropriate angle to detect the scattered protons. Two further measurements were made at 35° by slowing down the recoil deuterons with aluminium absorbers.

The linearity of the gate and associated amplifiers was tested with pulses from a mercury-switch pulse generator fed through a calibrated variable attenuator. The output measured on the multichannel pulse-height analyser was linear within $\frac{1}{2}$% of the maximum signal. The pulses were taken from the anode of the photomultiplier at a maximum level of 2 mA into 100 ohm load. To check that the photomultiplier was not saturating, its gain was reduced by a factor of ten. The linearity was not affected.

The results are shown in fig. 3 together with the calculated responses normalized to the 147.5 MeV proton measurement. The large errors on the deuteron measurements are principally due to uncertainties in the energy of the proton beam, the angular spread of the counters and the low counting rate.

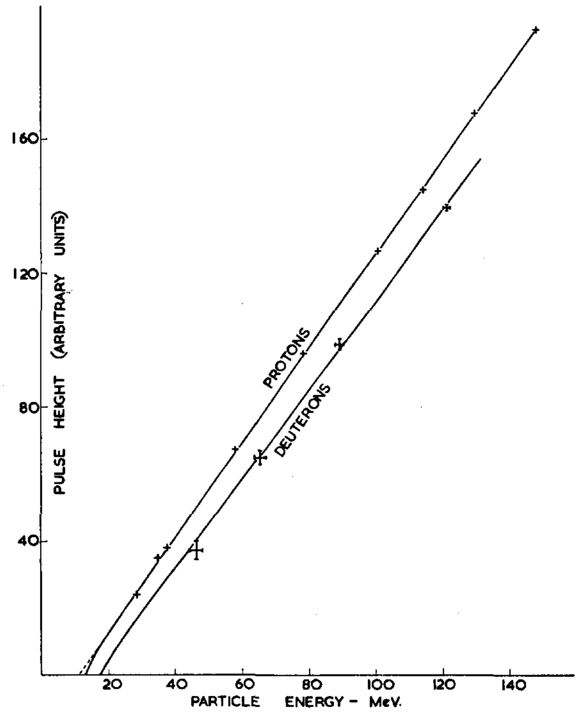

Fig. 3. Experimental results for protons and deuterons using the 13 MeV absorber. The lines represent the calculated response normalized to the 147.5 MeV proton measurement.

4. Conclusions

The proton measurements all fall within 1% of the calculated response showing that the low-energy proton calibration can be extended to higher energies by means of Wright's formula. The ratio of pulse-heights for protons and deuterons losing 120 MeV in the scintillator is 0.907 ± 0.01 giving an independent value of 28 ± 5 mg/cm^2/MeV for the parameter "a". This is in good agreement with the value $a =$ 25 mg/cm^2/MeV used in the calculations and hence we may further predict that the response for tritons and alpha-particles will be close to the values given in table 1.

Acknowledgements

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