Response of CsI(Tl) Crystals to Energetic Particles*

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(Received August 5, 1957)

The light output of thallium-activated cesium iodide was measured as a function of bombarding energy for protons (240 kev $\leqslant E_p \leqslant$ 2550 kev), alpha particles (980 kev $\leqslant E_\alpha \leqslant$ 4920 kev), and C^{12} ions (320 kev $\leqslant E_C$ $\leqslant$ 1850 kev). The relation of the light output to the particle energy is approximately linear in these energy ranges. The light outputs for different particles of the same energy are in the ratio $p:\alpha:C^{12}=1.00:0.59:0.35$. Saturation effects account for these results. The resolution varies inversely as the square root of the light output.

THE use of scintillating substances as detectors of charged particles is well-known, and is based partly on the fact that the light output of the scintillator is a function of the particle energy and the kind of particle. The light output for a given particle increases as the particle energy increases. Also, for a given energy loss the light output is greatest for electrons, and is reduced as the particle mass increases.[1–11] Scintillating liquids, plastics, and organic crystals show saturation effects[6–8,10,12] which are revealed in a clearly nonlinear relationship between light output and particle energy. In ionic crystals, like NaI(Tl),[3,4,8,9,13–15] KI(Tl),[15] and CsI(Tl),[16] the light output is apparently a linear function of particle energy for protons. However, a nonlinear dependence has been reported[1,3,5,8,9,17] for ionic crystal detectors with alpha particles, although the deviation from linearity is small. Furthermore, the response curves for various particles, even when apparently straight lines, have not always extrapolated to the origin.[4,13,15,16,18] Little has been done to explain these effects in ionic crystals.

In order to understand scintillator behavior, it is important to acquire additional data on the effects of various particles on scintillators. This is especially true of heavy particles which accentuate any effects due to high specific energy losses.[9,10] It is also of considerable practical utility to develop detectors suitable for experimental work. Thallium-activated crystals of cesium iodide have been shown to be satisfactory for the detection of fast protons,[16] and nitrogen ions.[1] Although they give less light[16] and have a longer decay time[16] than crystals of NaI(Tl), they are nonhygroscopic and easily shaped. The present paper corroborates the earlier work on protons and discusses the light output of CsI(Tl) crystals from monoenergetic alpha particles and C^{12} ions.

Protons, accelerated in a Van de Graaff generator to energies between 650 kev and 3300 kev, entered a thin,

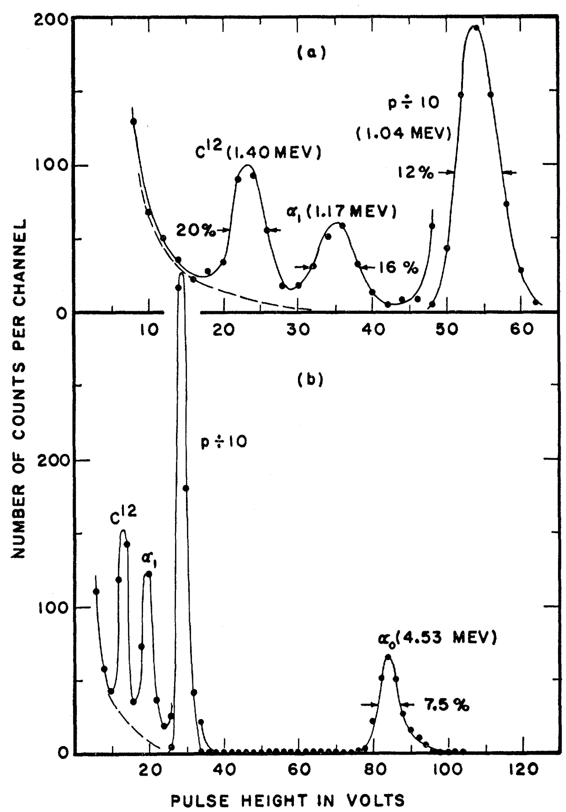

Fig. 1. Pulse-height distributions from a CsI(Tl) crystal bombarded with charged particles. The particles resulted from 1210-kev proton bombardment of N^{15} enriched nitrogen gas. Their energies are given at entrance to the crystal. The solid lines were drawn through the data points; the dashed lines show the gamma-ray background pulse-height distributions. (a) Expanded gain. (b) Compressed gain.

* Supported in part by the U. S. Atomic Energy Commission.

1 M. L. Halbert, Phys. Rev. **107**, 647 (1957).
2 J. D. Seagrave, Phys. Rev. **97**, 757 (1955).
3 F. S. Eby and W. K. Jentschke, Phys. Rev. **96**, 911 (1954).
4 S. K. Allison and H. Casson, Phys. Rev. **90**, 880 (1953).
5 W. T. Link and D. Walker, Proc. Phys. Soc. (London) **A66**, 767 (1953).
6 C. N. Chou, Phys. Rev. **87**, 903, 904 (1952).
7 J. B. Birks, Phys. Rev. **84**, 364 (1951).
8 Taylor, Jentschke, Remley, Eby, and Kruger, Phys. Rev. **84**, 1034 (1951).
9 Taylor, Remley, Jentschke, and Kruger, Phys. Rev. **83**, 169 (1951).
10 Frey, Grim, Preston, and Gray, Phys. Rev. **82**, 372 (1951).
11 H. Kallmann, Phys. Rev. **78**, 621 (1950).
12 Jentschke, Eby, Taylor, Remley, and Kruger, Phys. Rev. **83**, 170 (1951).
13 J. E. Brolley and F. L. Ribe, Phys. Rev. **98**, 1112 (1955).
14 J. G. Likely and W. Franzen, Phys. Rev. **87**, 666 (1952).
15 Franzen, Peelle, and Sherr, Phys. Rev. **79**, 742 (1950).
16 Galonsky, Johnson, and Moak, Rev. Sci. Instr. **27**, 58 (1956).
17 R. H. Lovberg, Phys. Rev. **84**, 852 (1951).
18 W. E. Burcham, Proc. Phys. Soc. (London) **A70**, 309 (1957).

nitrogen gas target containing N^{15} with an enrichment of either 61% or 95%. A 1000-A thick nickel foil sealed the gas, at a pressure of about 2 mm of Hg, from the vacuum system of the accelerator. The following nuclear reactions occurred and were used as a source of protons, alpha particles, and carbon ions:

$$N^{14}+p\rightarrow N^{14}+p,$$
$$N^{15}+p\rightarrow N^{15}+p,$$
$$N^{15}+p\rightarrow C^{12}\text{ (ground state)}+\alpha_0,$$
$$N^{15}+p\rightarrow C^{12}\text{ (4.43-Mev excited state)}+\alpha_1.$$

Carbon ions and alpha particles from both of the latter reactions were used. Protons scattered from traces of hydrogenous material present in the gas were used at forward angles.

The particles from these reactions were detected with a thallium-activated cesium iodide crystal,[19] water-polished to a thickness of 0.006 in. and cemented to a Dumont 6291 photomultiplier tube with Spra-Koat.[20] The crystal was $\frac{3}{8}$ in. in diameter. Collimators restricted particles striking the crystal to a $\frac{1}{4}$-in. diameter circle in its center. No light-shield or reflector was used in these measurements.

The energies of the particles under study varied as the incident energy and the angle of observation were changed. Since the Q values for the reactions are well-known,[21] the energy variations of the reaction products helped to identify the particles. Additional identification came from noting anomalies in the particle yields at known[22] resonances for the reactions, and by comparison of the crystal's response to the reaction products and to polonium alpha particles. The particles under study passed through 3 inches of the target gas in order to get from the reaction volume to the detector. The energy loss by protons in going this distance was 10% at the lowest energy used and less than 2% for energies greater than 0.5 Mev. Corrections were made by using Weyl's data on the stopping power of gases for protons.[23] Corrections of at most 6% were made for the energy losses of alpha particles in the target gas, using the alpha-particle stopping power of air.[24] A cruder correction was made for the carbon-ion energy loss in the gas. That correction was taken as the energy loss of an alpha particle of the same velocity times the square of the ratio of the effective charges. An effective charge ratio of 1.6 was used.[25] The correction amounted to 20% at the lower energies and 8% at the higher ones.

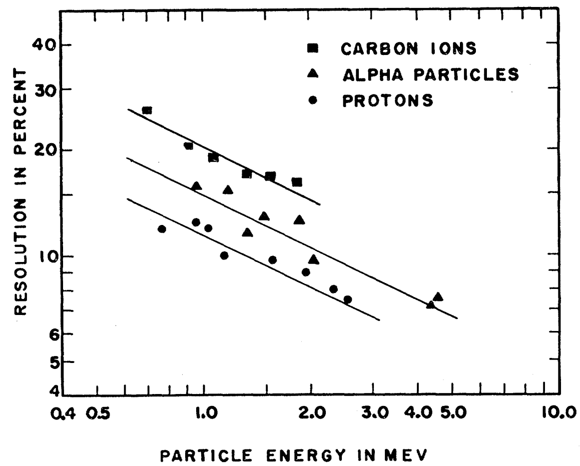

FIG. 2. Resolution *versus* particle energy for protons, alpha particles, and carbon ions. Points are experimental. Lines are drawn for resolution varying inversely as the square root of the particle energy.

The Dumont photomultiplier showed gain shifts dependent on the counting rate averaged over a several hour period. Shifts of about 3% were observed for the extremes of counting rate in the present work. To overcome such shifts, the pulse heights corresponding to one group of particles of a given energy were observed at the different counting rates and used to normalize.

Figure 1 shows the distribution of the pulse heights from the detecting system (crystal, photomultiplier tube, cathode follower, nonoverloading amplifier,[26] and ten-channel pulse-height analyzer[27]) for scattered protons, alpha particles, and C^{12} ions at a bombarding energy of 1210 kev. Pulses, from a pulse generator, fed into the cathode-follower input showed the following part of the detecting system to be linear to 0.5%. Figure 2 shows the resolution (full width of the peak at half-maximum divided by the pulse height) as a function of energy for the various ions detected. The lines were drawn to represent a resolution which varies inversely as the square root of the particle energy. Such lines are expected if the resolution depends on the statistical variation in the number of photoelectrons released at the photocathode and the pulse height is proportional to the energy loss. A plot of resolution against pulse height gives a single straight line of the same slope as that of the lines drawn in Fig. 2.

Figure 3 shows the pulse height as a function of particle energy. Similar results have been obtained for CsI(Tl),[1,16] KI(Tl),[15,18] and NaI(Tl).[4,8,9,15] For the energy range common to the three types of particles observed here, the ratio of pulse heights for the same energy is $p:\alpha:C^{12}=1.00:0.59:0.35$. The curves through the experimental points were calculated by using the

[19] Obtained in bulk from the Harshaw Chemical Company, Cleveland, Ohio.
[20] An acryllic plastic, General Cement Manufacturing Company, Rockford, Illinois.
[21] D. M. Van Patter and W. Whaling, Revs. Modern Phys. **26**, 402 (1954).
[22] S. Bashkin and R. R. Carlson, Phys. Rev. **106**, 261 (1957); F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
[23] P. K. Weyl, Phys. Rev. **91**, 289 (1953).
[24] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 245 (1937).
[25] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. **25**, 779 (1953); see p. 804.
[26] Beva Laboratory, Trenton, New Jersey.
[27] W. C. Johnstone, Nucleonics **11**, No. 1, 36 (1953).

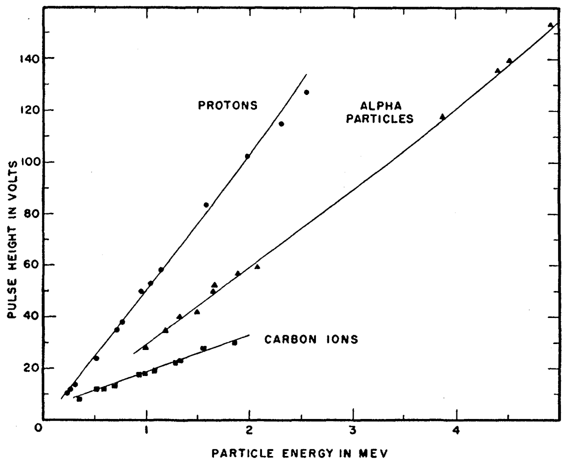

FIG. 3. Pulse-height *versus* particle energy for protons, alpha particles, and carbon ions. Points are experimental. Curves are calculated.

form of the specific light output, dL/dx, suggested by Birks[7]:

$$dL/dx = \frac{b dE/dx}{1+(1/a)(dE/dx)},$$

where dE/dx is the specific energy loss in CsI(Tl) and a and b are adjustable parameters. Pulse heights, $L(E)/b$, were obtained by numerical integration:

$$L(E)/b = \int_0^E \frac{dE}{1+(1/a)(dE/dx)}.$$

The calculated curves pass through the origin, of course, and show their largest curvature in the region of maximum specific energy loss. If a straight line approximation is used to any region of this calculated curve, it may have a positive or negative intercept on the energy axis depending on the particular energy range chosen. The fit to the present data depends only upon the shape of the specific-energy-loss curves and the relative magnitudes of these curves for the different particles. The specific-energy-loss curves for protons and alpha particles in NaI(Tl), calculated by Eby and Jentschke,[3] were used here. The specific energy loss curve for carbon ions was derived from that for alpha particles by assuming the carbon-ion specific energy loss equal to the specific energy loss of an alpha particle of the same velocity times the square of the ratio of the effective charges. The effective charge ratio was again 1.6. A value of the parameter, a, equal to 2.2 times the maximum specific energy loss of a proton was used to fit the data in Fig. 3. The absolute value of a does not enter the calculation. The parameter, b, is simply a scale factor but it is the same for all three curves.

The agreement between the calculated shapes of the response curves and the data does not mean that those shapes are necessarily correct, since straight lines match the experimental points equally well. However, the different light output for different particles is adequately explained. Moreover, by proper adjustment of the parameter, a, the response curves found by other groups for other crystals could be fitted. Within the accuracy of these calculations and for the energy range of interest, it has not been considered fruitful to include the contribution from hard scattering.[4,28]

The light output of a CsI(Tl) crystal was measured by Halbert[1] as a function of energy for nitrogen ions from 2.9 Mev to 23.8 Mev, and for alpha particles up to 5.3 Mev. The particle energy was varied with absorbing foils. His results are very similar to ours as to the near linearity of the response curves and a different light output for the different particles. He quotes in the latter connection:

$$(dL/dE)_{\text{nitrogen}}/(dL/dE)_{\text{alpha}} = \tfrac{1}{4}.$$

The energy at which this is evaluated is about 5 Mev. In the present work we found:

$$(dL/dE)_{\text{carbon}}/(dL/dE)_{\text{alpha}} = \tfrac{1}{2}$$

at an energy of 1.5 Mev. The saturation mechanism used in the above calculations can account for this difference since the alpha particle saturates less at the higher energy whereas the heavier ion saturates more.

[28] N. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **18**, 8 (1948); Phys. Rev. **59**, 270 (1941).