Scintillation Response of CsI(Tl) Crystals to Fission Fragments and Energy *vs* Range in Various Materials for Light and Heavy Fission Fragments

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A thin CsI(Tl) crystal was used as the phosphor of a scintillation detector of fission fragments. Light and heavy fragments from pile neutron fission of U^{235} were magnetically separated and scintillation pulse heights in CsI(Tl) crystals determined as a function of range in various gases and metals. The relationship between pulse height and fragment energy was found to be linear. Specific fluorescence of fission fragments in the crystal increases monotonically with specific energy loss. Energy *vs* range curves were obtained for median-mass light and heavy fragments in H_2, He, air, A, Al, Ni, and Au.

INTRODUCTION

WHILE there have been a considerable number of measurements of total ranges of fission fragments in various materials,[1–6] very few determinations of energy as a function of range have been made. Lassen[7] measured specific energy loss of fission fragments as a function of range in H_2, He, and A; from these data energy *vs* range curves were constructed. Schmitt and Leachman,[8] using a time-of-flight method, obtained some very accurate energy *vs* range data for median mass light and heavy fission fragments in aluminum.

In the work reported here scintillation pulse heights in a CsI(Tl) crystal as functions of range ("range" is used here to denote distance traveled in the stopping material) in various materials were measured for median-mass light and heavy fission fragments. From these data properties of the scintillation response of CsI(Tl) crystals to fission fragments are determined, an energy calibration of the scintillation detector for fission fragments is obtained, and energy *vs* range curves are plotted for the light and heavy fragments in H_2, He, air, A, Al, Ni, and Au.

EXPERIMENTAL

The magnetic fission-fragment spectrograph previously described[9] was used to separate the fragments into the light and heavy groups. The fragments were detected with a 1-in.-diam CsI(Tl) crystal mounted on the end of a Lucite light pipe which passed through a flange, at the focal plane of the spectrograph, to a Dumont-6292 photomultiplier tube. After it was cemented to the light pipe the crystal was machined to a thickness of 0.003 inch. This is thick enough to stop the fission fragments and thin enough to prevent the background of gamma and beta rays from producing pulses comparable in size to those produced by the fragments. The electrical pulses resulting from the arrival of fission fragments at the crystal are amplified, analyzed by a single-channel, pulse-height analyzer, and counted. The electronic apparatus was checked for linearity with a NaI(Tl) crystal and gamma rays from Zn^{65}, Co^{60}, and Cs^{137}. The pulse height of Po^{210} alphas was measured frequently to check for drift in the system.

For each condition of gas filling, the $H\rho$ distributions of the fragments were determined by integral pulse counting with the discrimination level set just above the background. These data were used to set the magnet at the peaks of the $H\rho$ distributions, and thus pulse-height distributions were measured for the median-mass light and heavy fragments.

The fission fragments were reduced in energy by gaseous or metallic stopping materials in the path from the source to the detector. The effective thicknesses of the gaseous stopping materials were varied by adjusting the gas pressure in the system. The metallic stopping materials consisted of thin foils which were placed in the path of the fragments a short distance from the detector. For measurements in which metallic stopping materials were used, a pressure of approximately 25 microns of air was maintained in the system to achieve separation of the light and heavy groups of fragments. (In high vacuum the $H\rho$ distributions of the two groups overlap completely.) Scintillation pulse heights of the light and heavy fragments were measured for several thicknesses of each stopping material used.

Scintillation Response of CsI(Tl) Crystals to Fission Fragments

Typical scintillation pulse-height distributions of median light and heavy fission fragments are shown in Fig. 1. The pulse-height distribution of 5.3-Mev alpha particles, obtained with the same detector, is also

* Operated for the U. S. Atomic Energy Commission by Union Carbide Nuclear Company.
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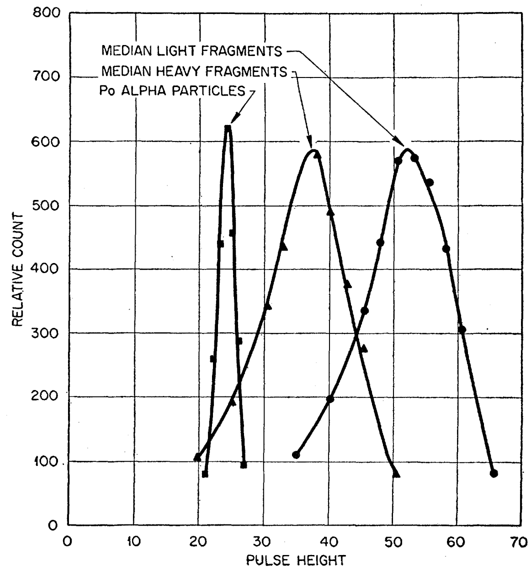

FIG. 1. Scintillation pulse-height distributions of 5.3-Mev alpha particles and light and heavy fission fragments in CsI(Tl) crystals. (The terms "median light fragments" and "median heavy fragments" refer to the median-mass light and heavy fragments.)

shown. There was enough gas in the system to reduce the energies of the median mass light and heavy fragments to 90 Mev and 63 Mev, respectively. The corresponding pulse heights, i.e., the abscissa values of the peaks plus half the channel width of the pulse-height analyzer, are 55 and 39. The ratios of the energies and of the pulse heights are equal, within the accuracy of the data. The resolutions of the pulse-height distributions, defined as the full width at half maximum, are 31%, 37%, and 14%, respectively, for the light fragments, heavy fragments, and alpha particles. Although the light and heavy fragments were separated magnetically and thus the pulse-height distributions determined individually, it is seen that the energy resolution of the scintillation detector is sufficient to distinguish between the two groups of fragments.

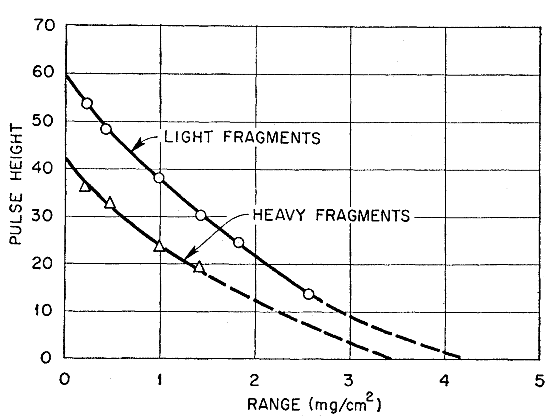

FIG. 2. Scintillation pulse heights of median-mass light and heavy fission fragments as functions of range in aluminum.

In Fig. 2 are shown graphs of the scintillation pulse height of the light and heavy fragments as a function of range in aluminum. Pulse height *vs* range curves were also obtained for hydrogen, helium, air, argon, nickel, and gold. From the data in Fig. 2 and the very accurate energy *vs* range data for fission fragments in aluminum which were determined by Schmitt and Leachman,[8] a graph of pulse height as a function of fragment energy was obtained. The resulting curve is shown in Fig. 3. The data for the light and heavy fragments agree rather well; the curve is approximately linear.

From the pulse height *vs* range curves and the energy *vs* range curves an estimate of specific fluorescence (dL/dx) as a function of specific energy loss $-(dE/dx)$ for fission fragments in CsI(Tl) is obtained, Fig. 4.

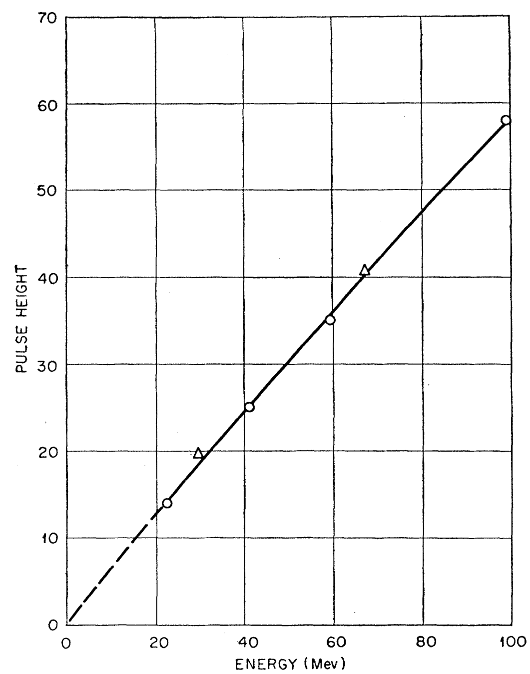

FIG. 3. Scintillation pulse height *vs* energy for fission fragments in CsI(Tl) crystals. Circles and triangles are for data obtained with median-mass light and heavy fragments, respectively.

The ranges of the fragments in cesium iodide are assumed to be equal to the ranges in silver, which from the data of Suzor[6] are 7.6 and 6.6 mg/cm^2 for the light and heavy fragments, respectively. It is further assumed that the ratio of the specific energy loss in two materials is equal to the inverted ratio of the ranges of fragments in the materials. Values of specific energy loss are obtained by differentiating the energy *vs* range curves for H_2 and A in Fig. 5. Corresponding values of specific fluorescence are obtained in the same manner from the pulse height *vs* range curves that were obtained. After multiplication by the ratio of the ranges in the stopping material and in cesium iodide and a conversion factor (converting millimeters of gas into mg/cm^2), the values which were obtained from measurements with hydrogen and argon gas are shown in Fig. 4. The reasonable agreement between the points obtained from argon and hydrogen data indicates that the assumed ranges of fission fragments in CsI are not much in error. Although the graph in Fig. 4 contains some approximations it shows clearly that the CsI(Tl) crystal does not saturate within the range of specific energy loss covered by fission fragments, but rather (dL/dx) increases monotonically with $-(dE/dx)$. This is different from the results obtained by Eby and Jentschke[10] for aplha particles in NaI(Tl) but in agreement with the data of Halbert[11] for nitrogen ions in CsI(Tl).

The pulse height *vs* range data obtained here are very similar to those reported by Milton and Fraser[12] for fission fragments in a KI(Tl) crystal. The graph of (dL/dx) *vs* $-(dE/dx)$, Fig. 4, differs somewhat from the one obtained by Milton and Fraser for fragments in KI(Tl), principally because values of specific energy

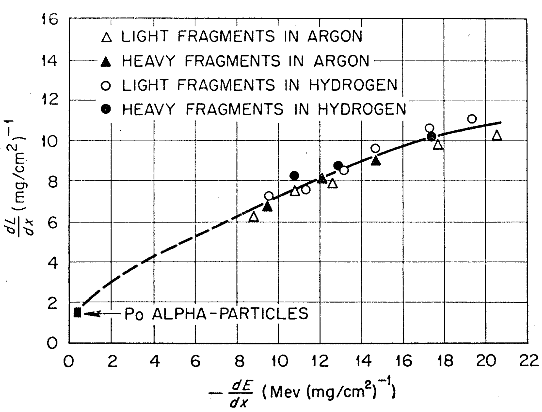

FIG. 4. Specific fluorescence as a function of specific energy loss of fission fragments in CsI(Tl) crystals.

loss as determined by Lassen[7] were used to plot the latter.

Energy *vs* Range of Fission Fragments in Various Materials

From the pulse height data as a function of range obtained for the median mass light and heavy fission fragments, curves of energy as a function of range, for the various stopping materials used, are plotted in Figs. 5, 6, and 7. The conversion from pulse height to energy was made by using the pulse height *vs* energy curve of Fig. 3, which served as a calibration of the scintillation detector. With the exception of nickel, the full ranges of the fragments in the various materials are known from the data of Suzor[6] and of Katcoff, Miskel, and Stanley,[4] and thus the curves are extended, as shown by the dotted portions in Fig. 5. The curves

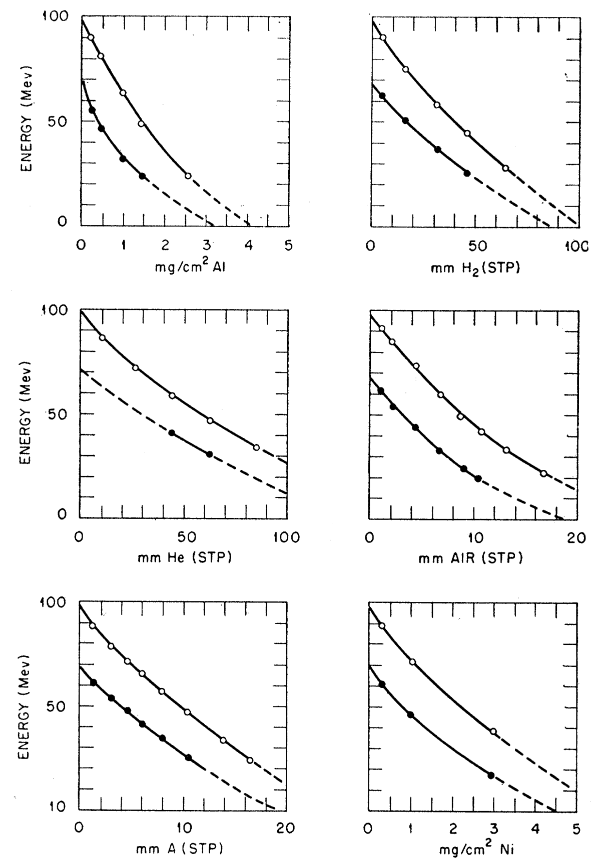

FIG. 5. Energy *vs* range for median-mass light and heavy fission fragments in various stopping materials. Open circles and full circles refer to light and heavy fragments, respectively.

probably should deviate from the dotted portions because of the predominance of nuclear stopping near the end of the ranges. The data obtained here do not give detailed information about this part of the range.

The energy *vs* range curves all show that the specific energy loss of fragments in the various materials decreases as a function of range, but not as rapidly as is

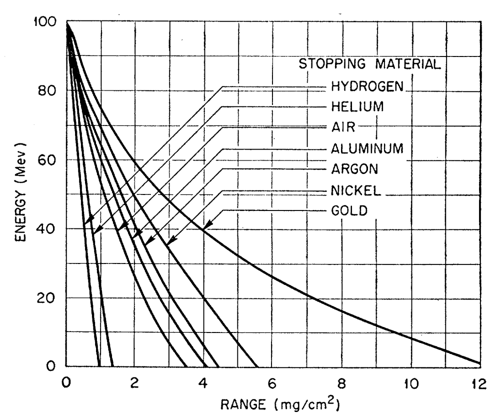

FIG. 6. Energy of median-mass light fission fragments as a function of range in various materials.

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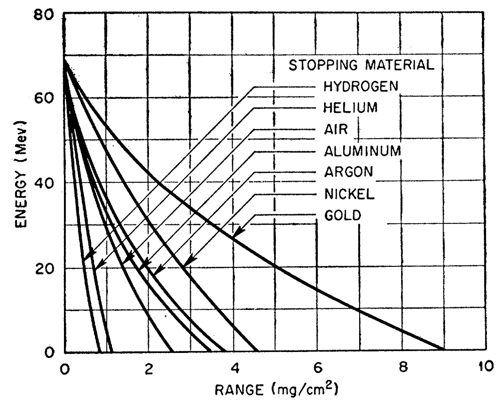

FIG. 7. Energy of median-mass heavy fission fragments as a function of range in various materials.

indicated by the data of Lassen[7] for hydrogen and argon. The curves of fragment energy *vs* range for hydrogen and argon differ considerably from those of Lassen, which were determined by integrating curves of specific energy loss as a function of range. Lassen's data were obtained by measurement of specific ionization of the fission fragments as a function of range. These data were used to plot curves of specific energy loss as a function of range by a linear conversion of ionization pulse height to specific energy loss, the conversion factor being chosen so that the integral of the area under the curves would correspond to the initial energy of the fragments. The "ionization defect," which has been discussed by Knipp and Ling[13] and measured experimentally by Schmitt and Leachman,[8] was not taken into account. This explains partially, but not completely, the difference between the energy *vs* range relations as determined by Lassen and the results reported here.

In addition to accurately measuring the energy of fission fragments as a function of range in Al, Schmitt and Leachman[8] measured the energies of median-mass light and heavy fragments which had passed through a Ni foil 1.1 mg/cm^2 thick. These measurements agree within 3% with the curves of Fig. 5 for Ni. Thus, the energy *vs* range measurements obtained here are checked by another method at one point for each group of fragments.

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Some Questions in Relativistic Hydromagnetics*

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The basic equations describing the motion of an ideal relativistic fluid in the presence of electromagnetic fields are formulated both in their differential and in their integral form. From the integral equations shock conditions are derived. In the limit of weak shocks the velocities of propagation of the various kinds of shocks and the discontinuities of the various physical quantities are calculated.

I. INTRODUCTION

IN this paper we shall consider the basic equations describing an ideal relativistic fluid capable of carrying charge and electric currents and shall investigate some properties of these equations. The jump conditions across a shock discontinuity will be derived and for the case of weak shocks the velocities of propagation and the jumps for the various kinds of shocks will be calculated explicitly in terms of the physical quantities of the underlying flow.

The subject matter of this paper has several points in common with a paper by de Hoffmann and Teller.[1] We wish to point out here two main differences. Our calculations refer throughout to the relativistic case, while de Hoffmann and Teller consider in some cases only the nonrelativistic limit. Furthermore, we emphasize from a systematic viewpoint the relation between differential equations, integral equations, and jump conditions, in particular making use of the concept of weak solutions of differential equations.

After the major part of our work had been completed, we became aware of an unpublished report by Reichel[2] in which the problem of weak relativistic hydromagnetic shocks is treated with results practically identical to ours although with a somewhat different formalism. We would like to thank Professor K. O. Friedrichs for making the Reichel manuscript available to us and for an illuminating discussion on the topics considered here.

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