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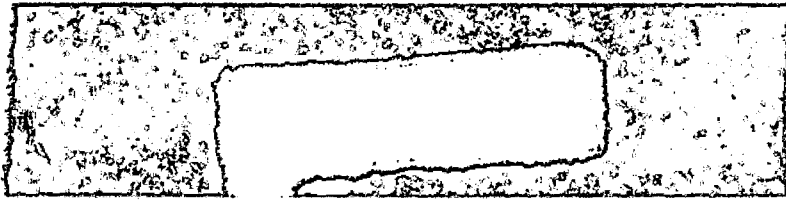
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-2-

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OF NUCLEAR REACTIONS INDUCED BY HEAVY IONS*Almon E. Larsh, Glen E. Gordon[†], and Torbjørn SikkelandLawrence Radiation Laboratory
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ABSTRACT

Experiments in which silicon p-n junctions have been used as detectors of fission fragments and elastically scattered heavy ions are described. The curve of pulse height vs energy for carbon particles is linear and passes through the origin. Points for Cf²⁵² fission fragments and alpha particles fall on the curve determined by the carbon-particle points. This result implies that the energy required for electron-hole pair formation is the same for the three types of particles. Also, no "ionization defect" is observed for the fission fragments. Some other possible uses for the detectors of this type are suggested.

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-3-

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I. INTRODUCTION

The results of previous investigations on p-n junction¹⁻⁴ and surface-barrier radiation detectors⁵⁻⁸ suggested that they would be useful in the types of experiments that we have been doing. We have used silicon p-n junctions as detectors of fission fragments and elastically scattered heavy ions in experimental studies of fission induced by heavy ions.⁹ In the course of our experiments we have studied some of the properties of the detectors.

II. EXPERIMENTAL PROCEDURES

The detectors used in these experiments were obtained from two sources, William Hansen of Lawrence Radiation Laboratory and Dr. S. S. Friedland's group at Hughes Aircraft Co. Properties of the two detectors used in obtaining the results described herein are given in Table I. These detectors, similar to those previously described by Friedland et al.,¹ were formed by diffusion of one type of impurity into one face of a silicon wafer containing an excess of the opposite type of impurity. The electronic system used with the detectors is shown in Fig. 1.

Table I. Properties of the silicon p-n junctions

Detector number	Base material		Diffusant type	Approximate surface area of counting region (cm ²)	Apparent "window" thickness (microns)
	Type	Resistivity (Ω cm)			
Ha-2	n	100	p	0.22	1.9
Hu-18	p	1000	n	0.02	1.4

Heavy-ion beams used in these experiments were obtained from the Berkeley heavy-ion linear accelerator (Hilac), a resonant-cavity machine that accelerates heavy ions to 10.4 Mev per nucleon. Experiments were performed in a vacuum tank that contained the detectors, targets, and sources of particles studied.

Typical spectra obtained with the detectors are shown in Figs. 2, 3, and 4. The spectra shown in Fig. 2 were obtained when carbon particles of the indicated energies struck the Hu-18 detector, reverse-biased by 94 v. The carbon particles were elastically scattered by a thin gold target (approx 200 $\mu\text{g}/\text{cm}^2$ Au vaporized onto 0.1-mil Al foil) and observed at 30 deg to the beam. The energy of the beam particles was varied by placing weighed aluminum foils in the beam path ahead of the target. Energies were determined from the range-energy curves of J. R. Walton.¹⁰

The satellite peak on the spectrum obtained with 121.3-Mev C^{12} particles is not understood. This effect also appeared in spectra obtained with 121.3-Mev C^{12} particles when the reverse bias was lower, but was not observed in any spectra taken with lower-energy carbon particles.

The resolution of the peak obtained with 103.6-Mev C^{12} particles is 2.2%. This figure includes inherent resolution of the detector, spread in pulse heights due to noise in the electronic system, and energy spread in the degraded carbon beam. As the energy of the carbon particles is decreased, the resulting peaks become broader, mainly as a result of fluctuations of the energy loss in the aluminum foils.

Figure 3 shows the spectrum of fragment kinetic energies observed from a Cf^{252} spontaneous-fission sample with the Ha-2 detector, reverse-biased by 9 v. In Fig. 4 is shown the spectrum of fragments from fission of Au^{197} with 93-Mev C^{12} particles, observed at 90 deg to the beam in the Ha-2 detector with reverse bias of 9 v. The large number of counts appearing in the lowest channels resulted from "pile-up" of small pulses due to scattered particles in the electronic system.

III. DISCUSSION

A. Pulse Height vs Applied Potential

The relative pulse heights produced by 121.3-Mev C^{12} particles and Cf^{252} alpha particles in the Hu-18 detector as a function of reverse bias are shown in Fig. 5. The rapid rise in the curve for alpha-particle pulses is due mainly to a decrease in capacity of the detector with increasing reverse bias. For a given amount of charge collected, Q , the height of the pulse produced V_{PH} is given by¹

$$V_{PH} = \frac{Q}{C_{ex} + C_d}, \quad (1)$$

where C_{ex} and C_d represent the capacities of the external circuit and the detector, respectively. The detector capacity is approximately proportional to $1/\sqrt{V_0 + V_a}$, where V_0 is the internal potential barrier of the p-n junction (approx 0.7 v) and V_a is the applied potential.¹¹ With increasing reverse bias, C_d rapidly becomes small compared with C_{ex} ; thus, V_{PH} asymptotically approaches Q/C_{ex} . Also, at very low reverse bias, the range of the alpha particles may be slightly longer than the thickness of the sensitive counting region. Therefore, some of the rise in the pulse height may be due to extension of the sensitive counting region, and increase in the amount of energy deposited in it by the alpha particles. Another factor that may contribute to this trend is increasing charge-collection efficiency with increasing reverse bias,^{12,13} although we have found no evidence that suggests that this is important.

Although the curve for alpha-particle pulses asymptotically approaches a limiting value, the curve for 121.3-Mev C^{12} particles continues to rise with increasing reverse bias. This is because the range of the carbon particles is greater than the thickness of the sensitive counting region of the detector. Evidence given below indicates that with a reverse bias of 94 v, the thickness of the counting region is approximately equal to the range of the 121.3-Mev C^{12} particles.

B. Pulse Height as a Function of Energy

Data obtained from the curves shown in Fig. 2 have been used to construct the curve of pulse height vs energy shown in Fig. 6. A pulse-generator calibration of the electronic system was used to determine the position of zero pulse height on the pulse-height analyzer scale. Points for the alpha particles and the two mass groups of spontaneous fission fragments of Cf²⁵² have also been included in Fig. 6.

In the case of fission fragments, a correction has been applied for loss of energy in passing through the insensitive front surface of the detector. Two different approaches have been used in making this correction. On one hand, one may assume that the pulse-height-vs-energy relationship is the same for fission fragments as for carbon particles. The positions of the peaks for the two mass groups of fission fragments correspond to energies of 91.4 and 65.6 Mev on the curve of Fig. 6. From Fraser and Milton's time-of-flight data, the energies of the two fragment groups before passage through the window are known to be 104.7 and 79.8 Mev for the light- and heavy-mass groups, respectively.¹⁴ The "window" thickness is then determined from the energy loss by the light fragment group and the range-energy data of Schmitt and Leachman, for fission fragments in aluminum.¹⁵ The check on the self-consistency of this approach is to use the window thickness determined for the light fragments to correct the energy of the heavy group. This procedure yields an energy of 80.4 Mev for the heavy group, in good agreement with the expected value of 79.8 Mev.

The second method is to assume that the curve of pulse height vs energy deposited by the fragments is linear and passes through the origin. Various window thicknesses are assumed and energy corrections are made until the ratio of corrected energies is 1.31 (= 104.7/79.8). The results of this analysis of the data are identical with those of the first method. In each case the window thickness is found to be approx 350 $\mu\text{g}/\text{cm}^2$. The estimated window thicknesses listed in Table I were obtained by this procedure. The fission-fragment deposition energies obtained by this method are plotted in Fig. 6.

These observations may be made from the results presented in Fig. 6.:

-7-

- (a) Pulse height is proportional to the energy deposited by the particle in the sensitive counting region.
- (b) Alpha-particle and fission-fragment points fall on the curve determined by the carbon-particle points.

The first observation is in agreement with previous studies of pulse height vs energy,^{1,5,12,13,16} but this is the first demonstration that the proportionality is valid over such a wide range of particle energies. The alpha-particle result is in agreement with previous work in which pulse heights produced by protons, He³ particles and alpha particles,⁷ and alpha particles and nitrogen ions¹⁴ were studied. The fission-fragment results, in agreement with those of Miller, et al.,¹² suggest that the "ionization defect" for fragments in semiconductor detectors is too small to be observed. This is to be expected because of the small amount of energy required for electron-hole pair formation in the semiconductor material (approx 3.5 ev)¹³ relative to the energy used in ionization of most counting gases (about 30 ev).

C. Thickness of the Sensitive Counting Region

If one assumes that the rapid rise in the alpha-particle pulse-height curve of Fig. 5 is due entirely to the decreasing capacity of the detector, the pulse heights for 121.3-Mev C¹² particles may be corrected for that effect. The resulting corrected pulse heights and the pulse-height-vs-energy curve of Fig. 6 can be used to determine the amount of energy deposited by the 121.3-Mev C¹² particles in the sensitive counting region at the various applied potentials. Using this information and the range-energy data for carbon particles in aluminum¹⁰ (the data for silicon being not presently available) we have estimated the thickness of the sensitive counting region as a function of applied potential. The resulting curve is shown in Fig. 7. Also shown in Fig. 7 is the thickness of the depletion layer, W, calculated according to the equation:

$$W = 1.44 \times 10^{-6} \sqrt{\rho\mu} (V_o + V_a)^{1/2} \text{ cm}, \quad (2)$$

where μ is the sum of the electron and hole mobilities in silicon, and ρ is the resistivity of the base material of the detector in Ω cm. From the results presented in Fig. 7, it appears that the sensitive counting region is greater

-8-

than the depletion-layer thickness by a roughly constant amount. This is apparently due to collection of electrons (in p-type base material) from the region beyond the depletion layer. The pulse produced by electrons and holes that are formed in the depletion layer is quite fast (on the order of 10^{-10} sec) because of the large electric fields in that region. The region beyond the depletion layer is essentially field-free, thus, electrons formed there enter the depletion layer only by the slow process of diffusion. However, if the pulses from the detector are not clipped with a fast time constant in the external circuit, contributions from the electrons produced beyond the depletion layer are included in the pulses. Because of these effects, Halbert and Blankenship have shown that for surface-barrier counters, the thickness of the sensitive counting region is a function of clipping time in the circuit.¹³

For all the detectors that we have studied, the fission-fragment data indicate that the thicknesses of the insensitive layers on the front surfaces stay very nearly constant with increasing reverse bias. The existence of these "windows" indicates that holes (in the case of p-type base, n-type diffusant) produced in the front surface outside the depletion layer are not efficiently collected in the pulse. Apparently this is because the holes have only a very short lifetime in the region of high impurity concentration on the front surface, and, therefore, do not migrate far before being trapped. Also, The constancy of the window thickness with increasing applied potential shows, in agreement with semiconductor theory,¹¹ that the increase in depletion-layer thickness is almost entirely in the direction of the material containing the lower concentration of impurities, or the base material in the body of the detector.

IV. APPLICABILITY OF SOLID-STATE DETECTORS IN NUCLEAR-REACTIONS STUDIES

The silicon p-n junction detectors have been very useful in our studies of heavy-ion-induced nuclear reactions. The main purpose of our research has been to observe fission-fragment kinetic energy distributions at various angles to the beam. In order to determine absolute fission cross sections, we relate the number of fragment counts to the number of elastically scattered beam particles observed at small angles to the beam. One of the main advantages

-9-

of the solid-state detectors is that one can use the same detector for both types of measurements. When observing fragment kinetic energy distributions, we apply very small potentials to the detectors; thus, the sensitive counting region is longer than the paths of the short-range, densely ionizing fission fragments, but short enough that the scattered beam particles and light reaction products deposit only small fractions of their energies in the sensitive region. This yields a clear distinction between fragment pulses and those produced by light particles. For observation of scattered beam particles, the reverse bias is increased, thus increasing the size of the pulses produced.

The small size of the detectors is a distinct advantage in angular-distribution experiments. For a given size of vacuum tank, one can obtain better angular resolution and a wider range of observation angles with these detectors than with bulkier devices. Also, the use of solid-state detectors eliminates the inconveniences of getting gas lines and high-voltage leads into the vacuum tank, as is frequently necessary with other types of counters.

The detectors have proved quite stable over the period of each series of experiments (normally about 8 hr), as shown by calibrations done before and after the other experiments. Also, they appear to have fairly long lifetimes. We have used one detector over a period of 10 months and, as yet, there have been no signs of deterioration.

An important feature of the detectors for counting experiments conducted near the heavy-ion beam is their insensitivity to the large neutron and gamma-ray background that is always present. We have had some difficulty with electrons that are knocked out of the target, collimators, etc., by the heavy ions. Although individual pulses produced by these electrons are quite small, "pile-up" of the pulses made the resolution of the pulse-generator and scattered-particle peaks quite poor. This difficulty was eliminated by placing a magnet near the front surface of the detector, thereby deflecting the electrons away from it but having little effect upon the fission fragments and scattered beam particles. We observed no effect of the magnetic field (approx 100 gauss) upon the detector.

In addition to the uses we have made of the detectors, there are several related areas in which they should be applicable. From our work with elastically scattered beam particles it is apparent that these detectors

-10-

could be used in a permanent setup, similar to that described by Northrop and Stokes for solid scintillation counters,¹⁷ as a monitor of charged-particle beam currents and energy. It appears also that, with careful calibration, detectors of this type could be used to rapidly determine the residual energy and energy straggling of charged-particle beams after passage through various thicknesses of absorbers. It has also been suggested that p-n-p or similar types of detectors could be fabricated for use as combined dE/dx and energy counters for use in identification of small particles emitted in nuclear reactions.^{13,18}

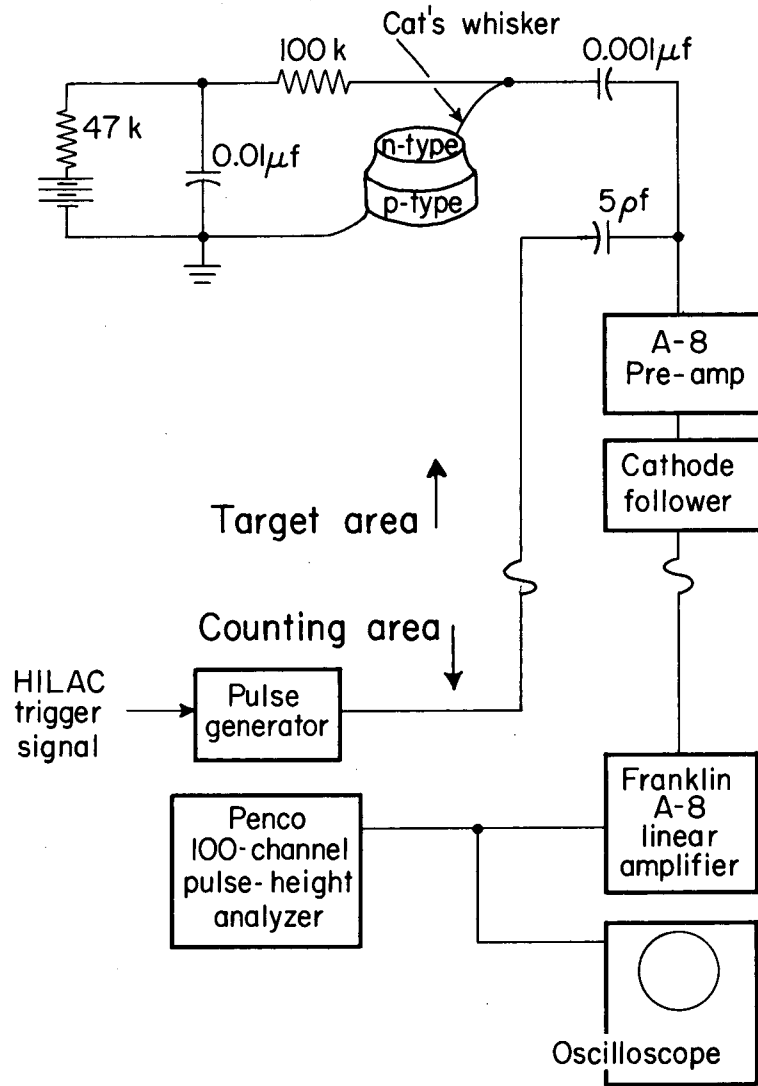
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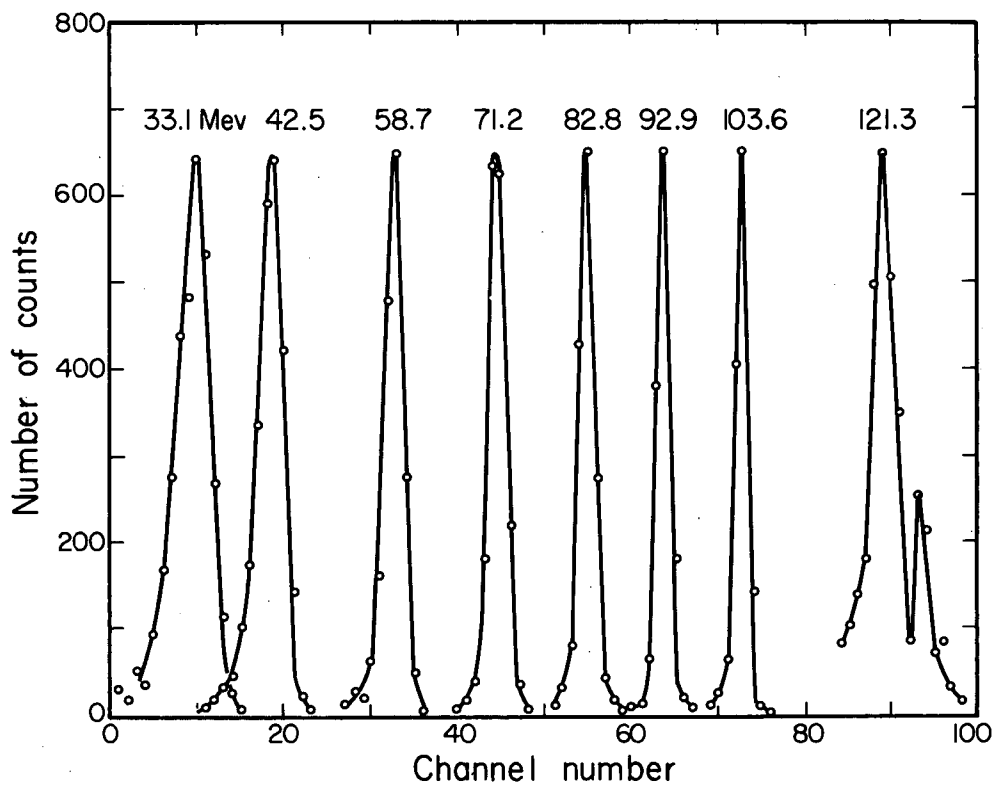
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Fig. 1. Electronic system used with the solid-state detectors.



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Fig. 2. Spectra obtained when carbon particles of various energies struck the Hu-18 detector, reverse-biased by 94 v.

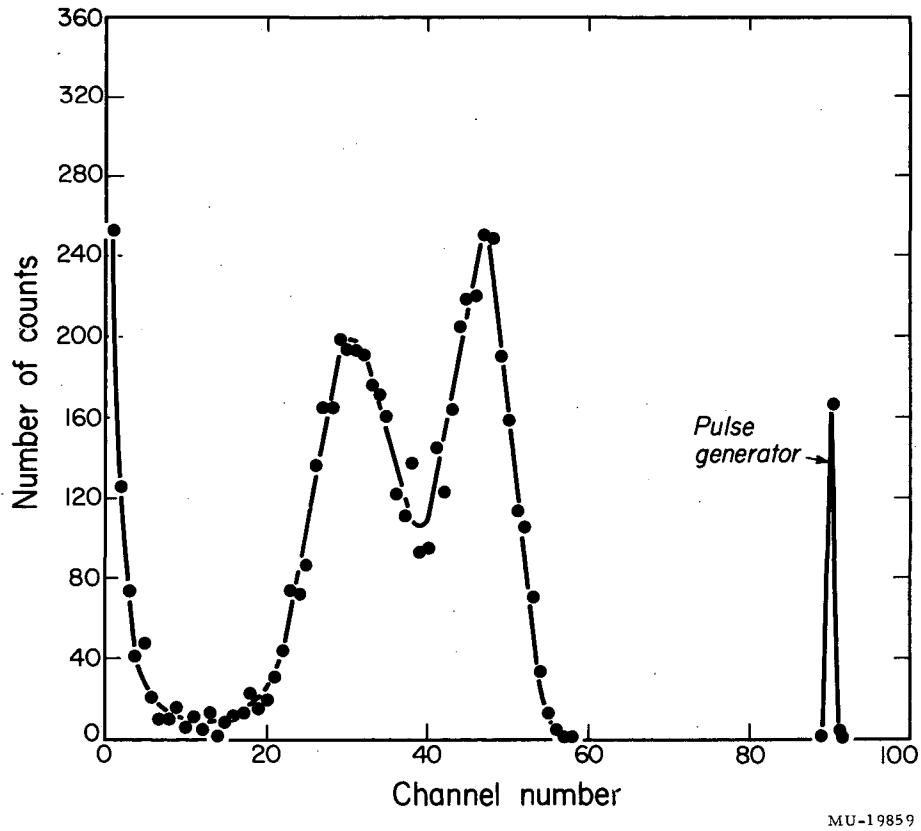


Fig. 3. Fragment kinetic energy spectrum from spontaneous fission of Cf^{252} . Observed with the Ha-2 detector, reverse-biased by 9 v.

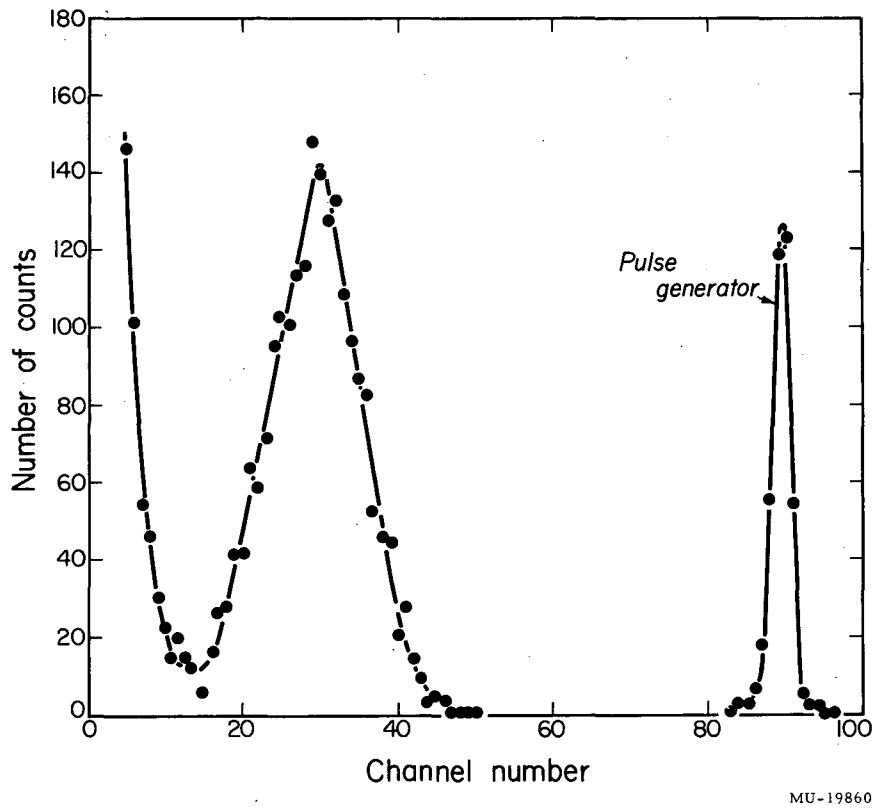
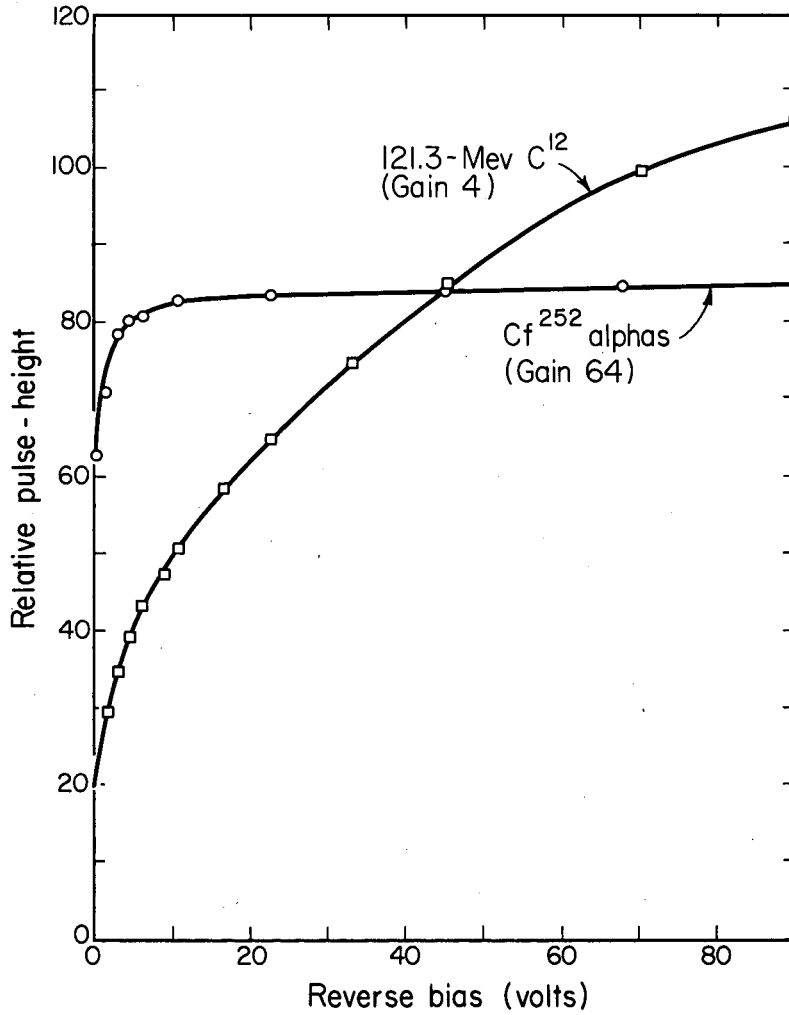


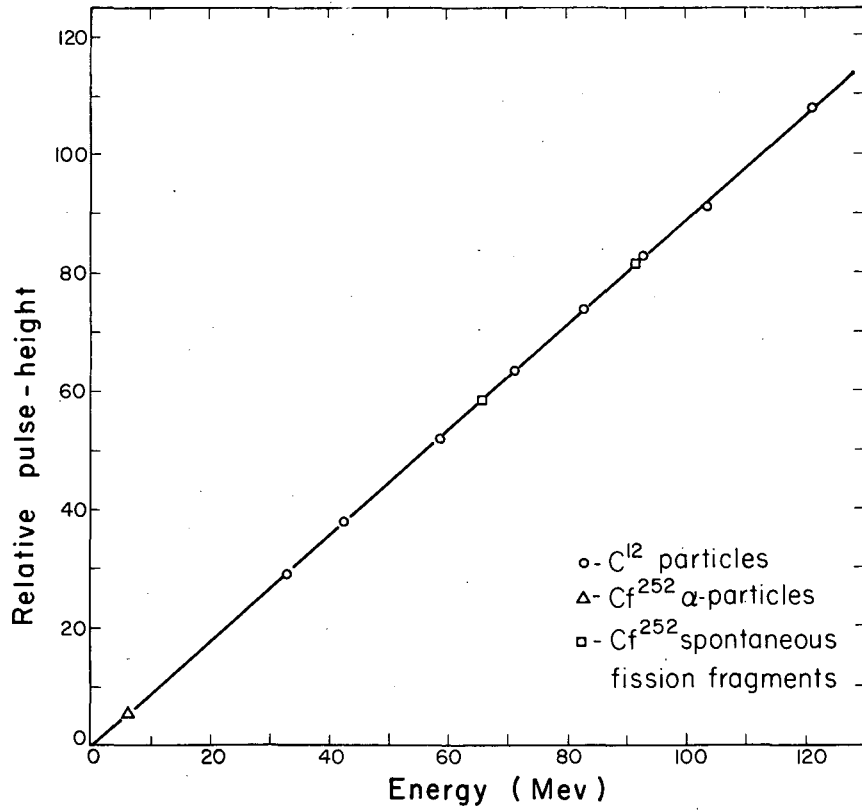
Fig. 4. Spectrum of fragment kinetic energies from fission of Au¹⁹⁷ with 93-Mev C¹² ions. Observed at 90 deg to the beam with the Ha-2 detector, reverse-biased by 9 v.

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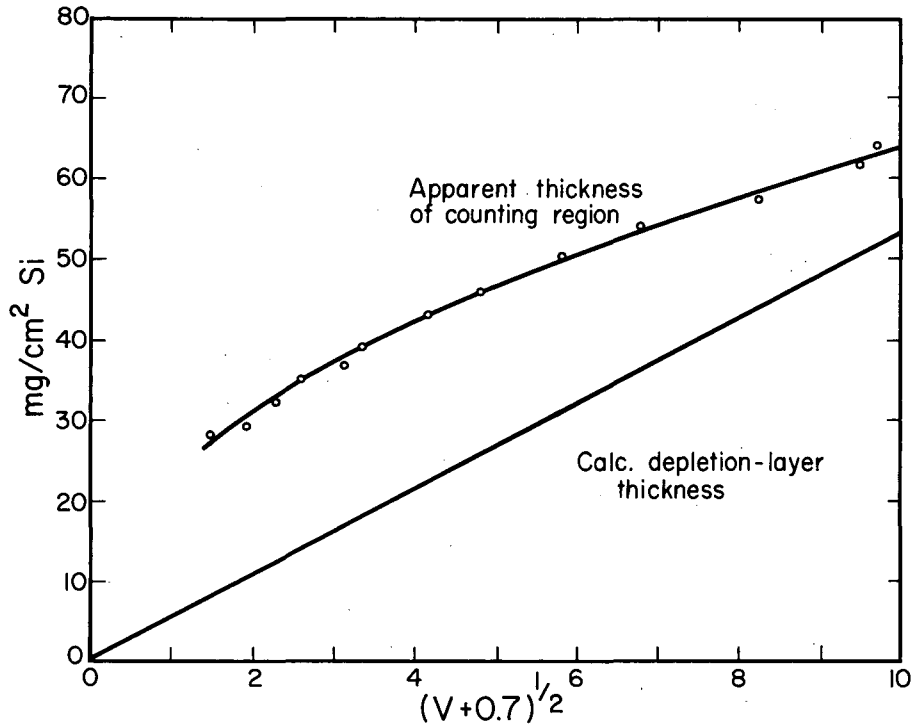
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Fig. 5. Pulse heights produced by 121.3-Mev C¹² particles and Cf²⁵² alpha particles in the Hu-18 detector as a function of reverse bias. Amplifier gain factors shown in the figure are only approximate values.



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Fig. 6. Pulse heights produced by C^{12} particles of various energies and Cf^{252} alpha particles and fission fragments observed with the Hu-18 detector reverse-biased by 94 v.



MU-20125

Fig. 7. Apparent thickness of the counting region of the Hu-18 detector and the calculated depletion-layer thickness as a function of $(V_a+0.7)^{1/2}$.

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