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LUCAS HEIGHTS

RESPONSE FUNCTIONS OF A GERMANIUM-SODIUM IODIDE DETECTOR SYSTEM

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ABSTRACT

A gamma ray spectrometer is described which uses a lithium drifted germanium diode or a sodium iodide crystal as a central detector in conjunction with an annular segmented sodium iodide assembly. The system can operate as a total absorption, anticoincidence, or pair spectrometer and individual detectors may be used separately. Thus, the requirements of high resolution or high efficiency gamma ray spectroscopy can be met by suitable choice of mode of operation. The various modes of operation are compared and typical results given to illustrate their performance at a variety of gamma ray energies. A detailed analysis is given of the response of a 30 cm^3 Ge(Li) detector for gamma rays up to 17.6 MeV.

Note: This work has been submitted to a journal. Further details can be obtained from the author or from the Director of the Research Establishment.

CONTENTS

1. INTRODUCTION

In the study of charged particle or neutron induced reactions, gamma rays with energies up to 10 MeV or higher are observed. The performance of detectors at these energies is complicated by the variety of possible gamma ray interactions. A number of well known proton reactions provide simple gamma ray spectra which can be used to establish the details of the spectrometer performance. This method has been used to calibrate a detector system developed for use in studies of neutron capture. The system consists of a number of detectors which can be used separately, or together, in coincidence operation. The performance of a large coaxial lithium drifted germanium (Ge(Li)) detector has been studied, using gamma ray energies up to 17.6 MeV. In Section 2, the relatively complex response functions are analyzed in terms of the interactions involved.

A Ge(Li) detector or a small sodium iodide crystal is used as the central detector in the system shown in Figure 1. The central detector and an annular segmented sodium iodide assembly may be operated in any of the following modes:

(a) Total absorption spectrometer, having high efficiency but poor resolution (all outputs are summed to give one pulse height signal for analysis).

(b) Anticoincidence spectrometer, having the efficiency and resolution characteristic of the selected central detector, but with a peak fraction which is improved by the anticoincidence method. (Trail and Raboy 1959).

(c) Pair spectrometer, having low efficiency but a simple response function with a high peak fraction and good resolution.

These are discussed in Sections 3, 4, and 5 and typical results illustrate their performance at a variety of gamma ray energies. A comparison is then given of the characteristics of each kind of detector.

2. GERMANIUM SPECTROMETER

A detailed study has been made of the performance of a single ended Ge(Li) detector with trapezoidal cross section (Tavendale 1966a, 1966b). It has the following characteristics: Cross sectional area $7\frac{1}{2}$ cm^2, length 4.6 cm, active volume 30 cm^3 (approximately 90 per cent. of the total volume), capacity 42 pf, leakage current 10^{-10} amp at 900 volts. The detector was mounted in a liquid nitrogen cryostat designed to allow operation in conjunction with the sodium iodide annulus (Figure 1). The cryostat capacity of 8.5 litres was sufficient to maintain the detector at 77°K for 30 hours. An 8 litre per sec ion pump maintained a pressure lower than 10^{-7} mm mercury.

Since the aim was to obtain information on the response function of germanium detectors, extreme pulse height resolution was unnecessary. The resolution observed was in the range 15 to 30 keV for most gamma rays but in some cases Doppler broadening gave rise to larger peak widths. A PDP-7 computer was used to record 1024 channel spectra and to process data. In many cases, for the study of high energy gamma ray spectra, bias was necessary to obtain sufficient detail within the 1024 channels.

2.1 Response Function Measurements

Pulse height spectra were recorded for the germanium detector without the sodium iodide annulus or shielding. Gamma rays were incident parallel to the 4.6 cm length of the detector, from a point source at 5 - 10 cm from its end. Response functions are shown in Figure 2 for a variety of gamma ray energies from 0.66 to 11.13 MeV. Details of the sources are given in Table 1. The proton reactions were produced using a beam from a 3 MeV Van de Graaff accelerator with target arrangements chosen to minimize the effects of unwanted gamma rays.

The observed pulse height spectra were corrected for background, cascade gamma rays, and gamma rays from interfering reactions. In addition the continuum, which is observed to be flat over a considerable energy range for most gamma ray energies, was extrapolated to zero pulse height. This method removes backscatter peaks and other features at low energy which are very dependent on the material near the detector. There is some evidence that the response functions rise at low pulse heights to an extent that increases as the gamma ray energy increases. In particular, the result obtained for 17.6 MeV gamma rays shows a rising continuum and for this reason it is plotted separately in Figure 3. The broken curve in Figure 3 is an estimate of the response function after removal of the 14.8 MeV component of the gamma ray spectrum. On the other hand, the 11.13 MeV response function has a flat continuum at least down to 3 MeV. The curves in Figure 2 have been normalized to have the same level for the flat part of the continuum. The following typical results illustrate the main processes responsible for the structure of these response functions.

2.2 0.48 MeV Response Function

The observed pulse height spectrum for 0.48 MeV gamma rays is shown as the full curve in Figure 4. Strong back-scattering effects were observed in this spectrum as well as a steep rise at low pulse heights. An estimate of the spectrum was made after subtraction of these effects, using as a guide the expected ratio of peak to continuum events. The energy distribution of Compton scattered electrons calculated from the Klein-Nishina formula is shown with area equal to that of the

estimated experimental distribution. The effect of the photoelectric absorption of the scattered photons is shown. Nine per cent. of these events are transferred to the full energy peak. In addition 25 per cent. of the area is removed to allow for multiple scattering, leaving the dashed curve labelled C_1 as the estimated single scattering distribution. A similar treatment of the multiple scattered photons leads to the distributions C_2 and C_3 for double and triple scattered photons. In each case some photoelectric absorption took place, and 70 per cent. of the full energy peak is due to this process.

Fry et al. (1966) used a Monte Carlo method to calculate response functions for various detector dimensions and gamma ray energies. Their results show that the events just below the full energy peak are the result of beta escape events (electrons leaving the sensitive area of the detector) rather than multiple scattered photons. In any experimental measurements there will also be some contribution from photons which are scattered before interaction with the detector.

2.3 4.43 MeV Response Function

The peak region of the pulse height spectrum for 4.43 MeV gamma rays is shown as the full curve in Figure 5. The three peaks arising from the pair production process are considerably broadened by recoil motion in the $N^{15}(p,\alpha\gamma)C^{12}$ reaction. The dashed curves in Figure 5 are the results of Monte Carlo calculations reported by Fry et al.(1966) for a 14 cm^3 detector. The calculations include the effects of beta escape which will be more important for a 14 cm^3 detector than for the 30 cm^3 detector used for the measurements. Curve A does not contain any effects due to bremsstrahlung radiation by pair or Compton betas, whereas these effects have been included in Curve B. The inclusion of bremsstrahlung effects removes counts from the peak region of the spectrum. The experimental results show structure that is intermediate between that of the two calculated curves. A more accurate comparison would require use of the same size detector for both measurements and calculation. However the difference in shape on the low energy side of the double escape peak indicates that re-absorption of the low energy bremsstrahlung photons should be included in the calculations.

2.4 11.13 MeV Response Function

The peak region of the response function for 11.13 MeV gamma rays is shown in Figure 6. At this energy, the Compton and pair interaction cross sections have the ratio 0.7 but a variety of multiple processes are possible and the observed shape is quite complex. No Compton edge is observed at 10.88 MeV but electrons of this energy have a range of 1 cm in germanium so beta escape

events will be important. Also, it is calculated that 22 per cent. of the energy of these electrons will be emitted as bremsstrahlung radiation.

When the positron and electron from pair production both come to rest in the sensitive volume of the detector, the total energy deposited in the detector depends on the probability for interaction of the two 0.51 MeV annihilation gamma rays. The probabilities for capture (P_c) and scattering (P_s) of 0.5 MeV gamma rays determine the shape of the spectrum in Figure 4, and from this P_c/P_s is found to be 0.21. If the three peaks in Figure 6 are due entirely to the pair process, their areas should be given by:

$$F = P_c^2 \quad , \quad S = 2\,P_e P_c \quad , \quad D = P_e^2 \quad ,$$

where $P_e (= 1 - P_s - P_c)$ is the probability for escape of 0.5 MeV gamma rays from the sensitive region of the detector. Relative peak areas are shown in Figure 7 as a function of gamma ray energy. The ratio S/D is seen to be constant (0.26) for all energies and this combined with the value of P_c/P_s gives the values:

$$P_e = 0.56 \quad , \quad P_c = 0.08 \quad , \quad P_s = 0.36 \quad .$$

The expected area of the full energy peak is calculated from the expression above to be one third of the observed area at 11.13 MeV. The remaining two-thirds is thus due to absorption of scattered photons, a result similar to that found at 0.48 MeV.

Between the peaks in Figures 5 and 6, structure is observed which may be fitted by using the results for Compton scattering of 0.5 MeV gamma rays. The dashed curve in Figure 6 is obtained by subtracting areas normalized to the expected values of $2\,P_e P_s$ and $2\,P_c P_s$ from the experimental results. The smoothness of this curve indicates that all structure above the double escape peak is caused by the interactions of the annihilation radiation.

Bremsstrahlung radiation by the pair betas is also to be expected and the narrow dip below the double escape peak can be explained by photoelectric absorption of this radiation. The dashed curve in this region was obtained by subtracting a calculated bremsstrahlung escape spectrum whose area was obtained from the area of the double escape peak (no correction was made for scattering or radiated photons or other multiple processes). Similar dips should be observed near the single escape and full energy peaks, but they are too small to be significant.

2.5 Peak Efficiencies

Absolute peak efficiencies may be obtained from the expression:

$$\eta = \frac{A}{A_T}\,(1 - e^{-L\tau}) \quad ,$$

where A is the area of the peak being considered, A_T is the total area in the pulse height spectrum, L is the detector length, and τ is the absorption coefficient for germanium.

Because of difficulties in observing the true pulse height spectrum at low pulse heights, a first estimate of the total area was made by assuming a flat extrapolation to zero pulse height as discussed in Section 2.1. Results obtained in this way were found to lie on smooth curves but, to fit these curves to absolute calibrations of the same detector by Tavendale (1966a) it was necessary to multiply the results by 0.80. This factor serves as a correction to the total area for errors in the flat extrapolation technique as well as for the effects of the inactive region of the detector. However the correction may not be independent of gamma ray energy and consequently the shape of the efficiency curves may be in error at high energies.

Additional information was obtained from an analysis of the results for the 0.992 keV resonance in the Al^{27} (p,γ) Si^{28} reaction. Using previous results (Ophel and Osgood 1965) for the branching ratios in this reaction, the ratios of efficiencies at several pairs of energies were obtained. The use of this method at lower energies was described by Freeman and Jenkin (1966).

Efficiency values are plotted in Figure 8 for the double escape and full energy peaks as well as for the peak sum. The values obtained from aluminium cascade gamma rays are shown as linked points for which the lower energy point has been assumed to lie on the peak sum curve. The results for relative efficiency given by Ewan et al. (1966) for a 25 cm^3 detector are shown as dotted curves in Figure 8. The agreement is satisfactory, the difference being chiefly in the efficiency at 0.5 MeV where the two sets of results were normalized.

The lowest curve in Figure 8 is the result obtained by Ewan and Tavendale (1964) for the double escape peak efficiency of an 0.85 cm^3 detector. The 30 cm^3 detector is only four times more efficient than the 0.85 cm^3 detector at 4 MeV, but at higher energies the small detector efficiency drops very quickly and it is one thirtieth as efficient at 9 MeV.

The curve labelled D' in Figure 8 is the efficiency calculated for the 30 cm^3 detector using the pair production cross section for germanium and the

calculated probability for double escape peak events. The difference between D and D' is the result of energy loss events which remove 90 per cent. at 10 MeV, and 99 per cent. at 17.6 MeV, of the counts expected to appear in the double escape peak.

3. TOTAL ABSORPTION DETECTOR

The sodium iodide annulus shown in Figure 1 was obtained from Harshaw Chemical Co., together with a central sodium iodide detector with diameter 2.32 inches and length 6 inches. The annulus is optically divided into six segments and attached to each is an EMI 9536B photomultiplier tube. Separate signals may be obtained from each segment and from the central detector inserted into the annulus. The pulse height resolution of the annulus segments varies from 14 to 17 per cent. for Cs 137 gamma rays because of the poor geometry for light collection. The pulse height resolution of the central detector is much better and by suitable choice of size a resolution of 8 per cent. or less is possible.

When pulses from all components of the detector system are added, the system operates as a single detector with effectively 100 per cent. efficiency and a resolution of 15 per cent. for Cs137 gamma rays. Pulse height spectra are given in Figure 9 for two gamma ray energies. The full energy peak contains approximately 30 per cent. of the area in these spectra. The annulus may be used as a large solid angle detector, but the full energy peak fraction is only of the order of five per cent. for all sources of gamma rays at the centre of the annulus.

4. ANTICOINCIDENCE SPECTROMETER

The sodium iodide detector system described above has the same dimensions as the anticoincidence detector described by Trail and Raboy (1959). Similar results are therefore obtained when pulses from the central detector are analyzed provided no pulse greater than 30 keV occurs in the annulus at the same time. Figure 10 gives the results for 2.62 MeV gamma rays showing a factor of four reduction in the escape peaks and Compton continuum when the anticoincidence method is used. A sodium iodide central detector was used to obtain these results and this may be replaced by the Ge(Li) detector described in Section 2 to obtain a similar reduction in the pulse height spectrum below the full energy peak. This technique has advantages for relatively low energy gamma rays, but for energies above 5 MeV the full energy peak fraction is too small for the use of Ge(Li) detectors to be attractive.

5. PAIR SPECTROMETER

The segmented sodium iodide annulus may be used as a pair spectrometer with either a sodium iodide or Ge(Li) central detector. The circuit shown in Figure 11 allows operation as either a pair or anticoincidence spectrometer. The chief features are as follows:

(a) Multiple coincidence unit: Fast pulses from the photomultiplier anodes are delay line clipped to 60 nanoseconds width and summed at the input to a tunnel diode discriminator. The discriminator level may be switched to give an output if more than N input pulses are in coincidence (N = 1 to 4).

(b) Annulus window: Pulses from the last dynode of the photomultipliers are summed into a single channel analyzer, which for pair spectrometer operation is set to give an output if the sum corresponds to 1.02 ± 0.16 MeV.

(c) Triple coincidence unit: The outputs of (a) and (b) are used in coincidence or anticoincidence with a pulse from a single channel analyzer from the central detector. For the pair spectrometer an acceptable event is one giving a total of three pulses, one in the central detector and two in the annulus which add to 1.02 MeV.

(d) Pulse height measurements: A second pulse from the central detector is fed tc the pulse height analyzer and analyzed if the required criteria are met. Alternatively, separate spectra may be triggered in different sections of the anlyzer using output pulses from suitable stages in the electronics system.

(e) Timing: Leading edge or cross-over timing may be used, the latter being most useful for sodium iodide detectors. For Ge(Li) detectors with leading edge timing, distributions have been observed similar to those presented by Graham et al. (1966). Asymmetric time distributions are obtained as a result of non-uniform field distribution in the coaxial type detector and a resolving time greater than 100 nanoseconds is needed if all events are to be accepted.

Pulse height spectra are presented in Figure 12 for gamma ray energies of 2.6, 4.4 and 11.1 MeV. These results were obtained using a 23 cm^3 active volume Ge(Li) central detector mounted as shown in Figure 1. The pair spectra show a dramatic improvement in peak fraction compared to the singles spectra. However they still contain a pulse height continuum which increases in importance as the gamma ray energy increases. In addition, there is a tail on the high side of each peak

which is critically dependent on the position and width of the annulus window. The tail may be reduced by raising and narrowing the window, but beyond an optimum setting, this leads to a corresponding reduction in the area of the peak. For the optimum setting, the peak in the pair spectrum has 35 per cent. of the area of the double escape peak in the singles spectrum. This factor was confirmed using a source of annihilation radiation at the centre of the annulus.

The observed peak fractions are given in Table 2 together with values calculated for a 30 cm^3 detector using curves D and D' in Figure 8. The similarity between the results shows that the loss of peak efficiency for high energy gamma rays, which is responsible for the shape of curve D in Figure 8, is also responsible for the continuum observed in the pair spectra. The germanium pair spectrometer is therefore of limited use for gamma ray energies above 10 MeV since energy loss processes give rise to a rapid fall in peak efficiency and at the same time to a corresponding reduction in peak fraction.

The value of the pair spectrometer at intermediate energies is shown by Figure 13 which gives normal and pair spectra for the three gamma rays from the F^{19} $(p,\alpha\gamma)$ O^{16} reaction. The lifetimes of the O^{16} excited states are such as to cause Doppler broadening of the two gamma rays at 6.92 and 7.12 MeV. The normal Ge(Li) spectrum is much more difficult to interpret than the pair spectrum which was obtained in the same length of time.

The efficiency of the pair spectrometer is given by the double escape peak efficiency for the Ge(Li) detector multiplied by a mode efficiency of 0.35. It is thus approximately 0.5 per cent. per incident gamma ray for a 30 cm^3 detector and gamma ray energies in the range 3-9 MeV.

6. COMPARISON OF DETECTORS

Three main factors affect the usefulness of a particular type of detector in the study of complex gamma ray spectra. These are resolution, efficiency, and the complexity of the response function. The latter may be represented qualitatively by the use of a peak fraction although this does not give a measure of all the problems that arise with complex response functions. These factors are summarized in Table 3 for the types of detectors discussed in this paper. Variations with gamma ray energy make it impossible to give an accurate summary but the values in Table 3 provide an indication of performance at typical energies.

The efficiency (η) is the number of observed peak counts per incident gamma ray. If experimental considerations do not otherwise determine the available solid angle, the minimum source to detector distance must also be taken into account.

In many experiments the use of an annulus (as in the anticoincidence or pair spectrometers) makes it necessary to increase the source distance, with a resultant drop in absolute efficiency. However, when one detector system can be operated in any of the modes described, it is possible to choose the mode best suited to the requirements of a particular experiment.

7. ACKNOWLEDGEMENTS

The Ge(Li) detectors used in this work were prepared by A. J. Tavendale and we gratefully acknowledge his advice and assistance in various aspects of the work. We also acknowledge the help and cooperation of members of the 3 MeV Accelerator Group and of the General Physics Section at Lucas Heights.

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TABLE 1

GAMMA RAY SOURCES

Gamma Ray Energy (MeV)	Source	Proton Energy (MeV)	Curve Number (Figure 2)
0.478	$Li^7(p,p'\gamma)$	1.66	
0.662	Cs^{137}		A
1.274	Na^{22}		B
1.333	Co^{60}		
1.841	Y^{88}		C
2.614	ThC^{11}		D
3.507	$C^{12}(p,\gamma)$	1.698	E
4.433	$N^{15}(p,\alpha\gamma)$	0.898	F
6.135	$F^{19}(p,\alpha\gamma)$	0.874 or 0.602	
6.844	$Be^9(p,\gamma)$	1.083	G
9.17	$C^{13}(p,\gamma)$	1.747	H
10.78	$Al^{27}(p,\gamma)$	0.992	
11.13	$Al^{27}(p,\gamma)$	1.372	I
17.64	$Li^7(p,\gamma)$	0.441	

TABLE 2

PAIR SPECTROMETER PEAK FRACTIONS

E (MeV)	2.62	4.43	6.14	10.78
Measured Peak Fraction (%)	46	30	25	$8\frac{1}{2}$
Calculated Peak Fraction (%)	53	46	30	8

TABLE 3

DETECTOR PERFORMANCE CHARACTERISTICS

Spectrometer	Size	Gamma Ray Energy (MeV)	Resolution (MeV)	Interaction Probability	Peak Fraction	Mode Efficiency	Efficiency η
Total Absorption	8 in x 12 in	0.5	0.085	1.0	0.4	1.0	0.4
Total Absorption	8 in x 12 in	5.0	0.6	1.0	0.3	1.0	0.3
Small NaI	2.3 in x 6 in	0.5	0.04	1.0	0.4 (F)	1.0	0.4 (F)
Small NaI	2.3 in x 6 in	5.0	0.15	0.85	0.02 (D)	1.0	0.02 (D)
NaI A/Co	2.3 in x 6 in	0.5	0.04	1.0	0.6	1.0	0.4
NaI Pair	2.3 in x 6 in	5.0	0.15	0.85	0.6	0.35	0.006
Germanium	30 cm^3	0.5	0.005	0.9	0.1 (F)	1.0	0.09 (F)
Germanium	30 cm^3	5.0	0.005	0.5	0.04 (D)	1.0	0.02 (D)
Ge A/Co	30 cm^3	0.5	1.005	0.9	0.3	1.0	0.09
Ge Pair	30 cm^3	5.0	0.005	0.5	0.3	0.35	0.007

F = full energy peak

D = double escape peak

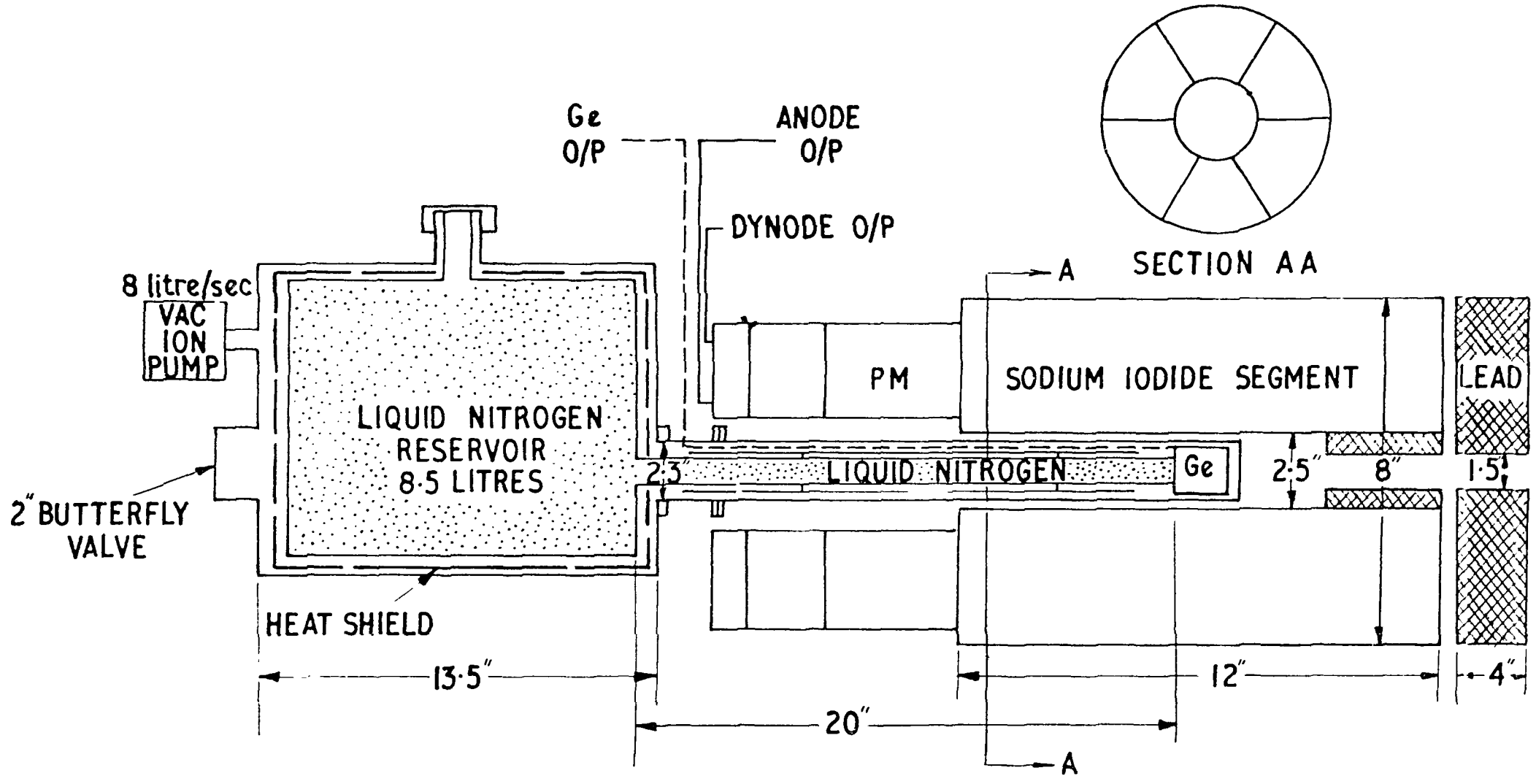

FIGURE 1. SCHEMATIC GAMMA SPECTROMETER ASSEMBLY

F·1050

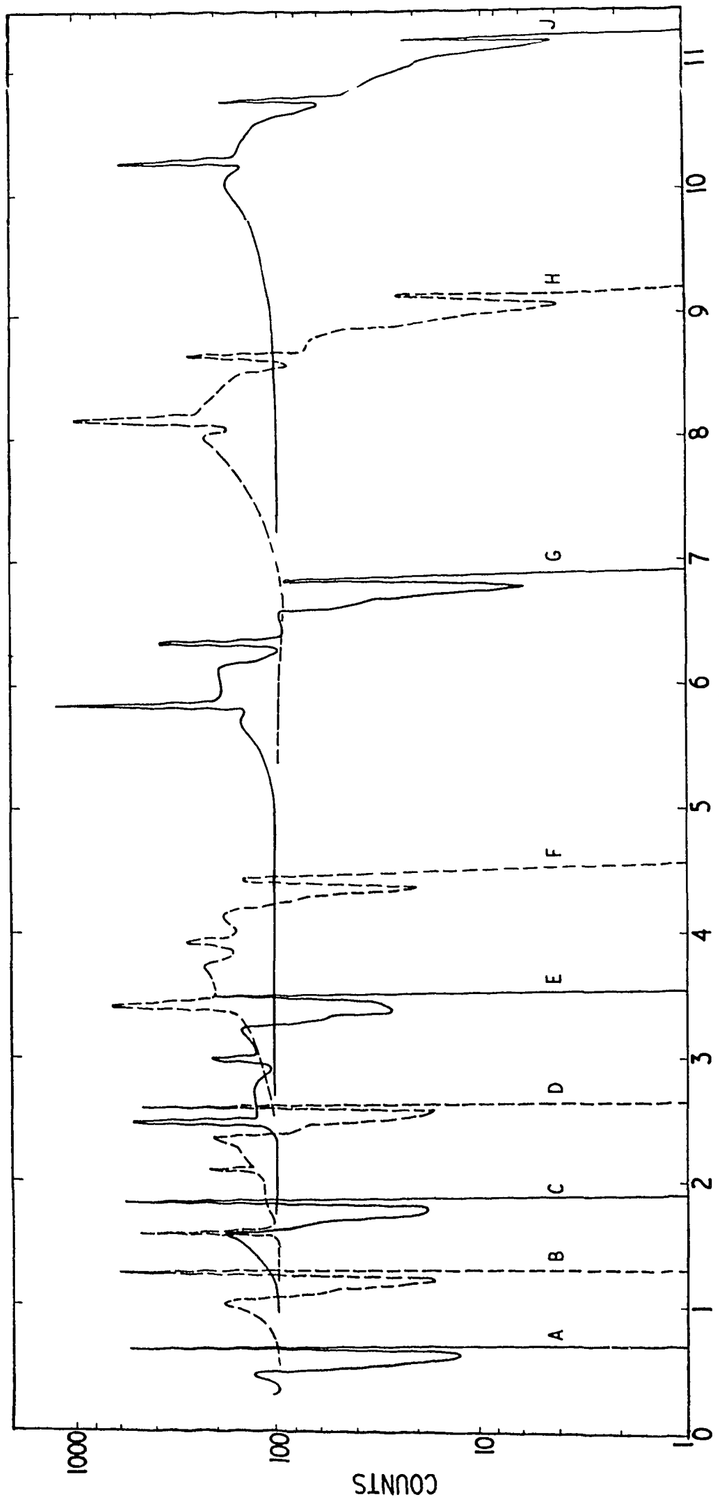

FIGURE 2. NORMALIZED 30cm³ GERMANIUM RESPONSE FUNCTIONS

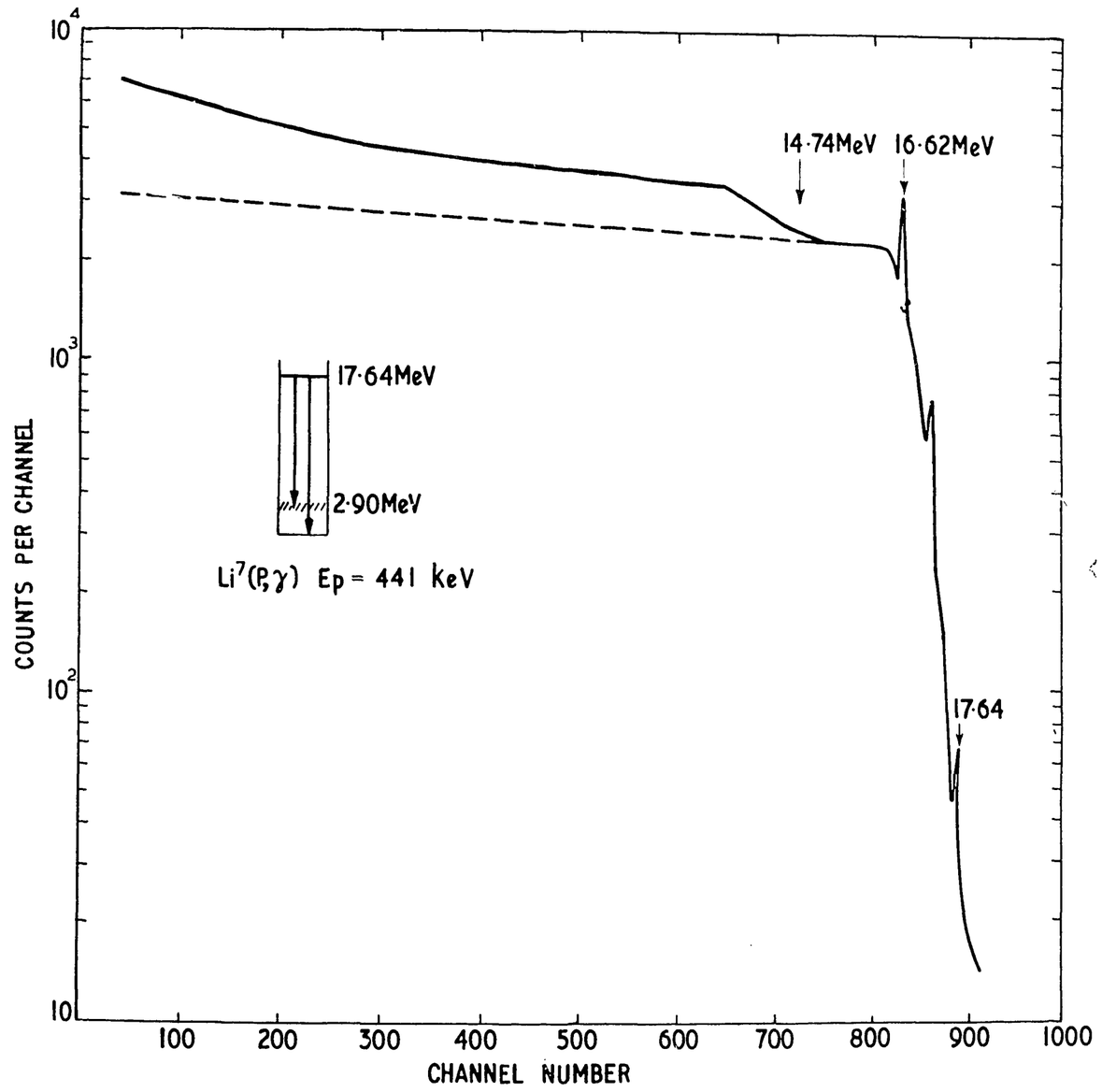

FIGURE 3. 30cm³ GERMANIUM RESPONSE FUNCTION (17.6 MeV)

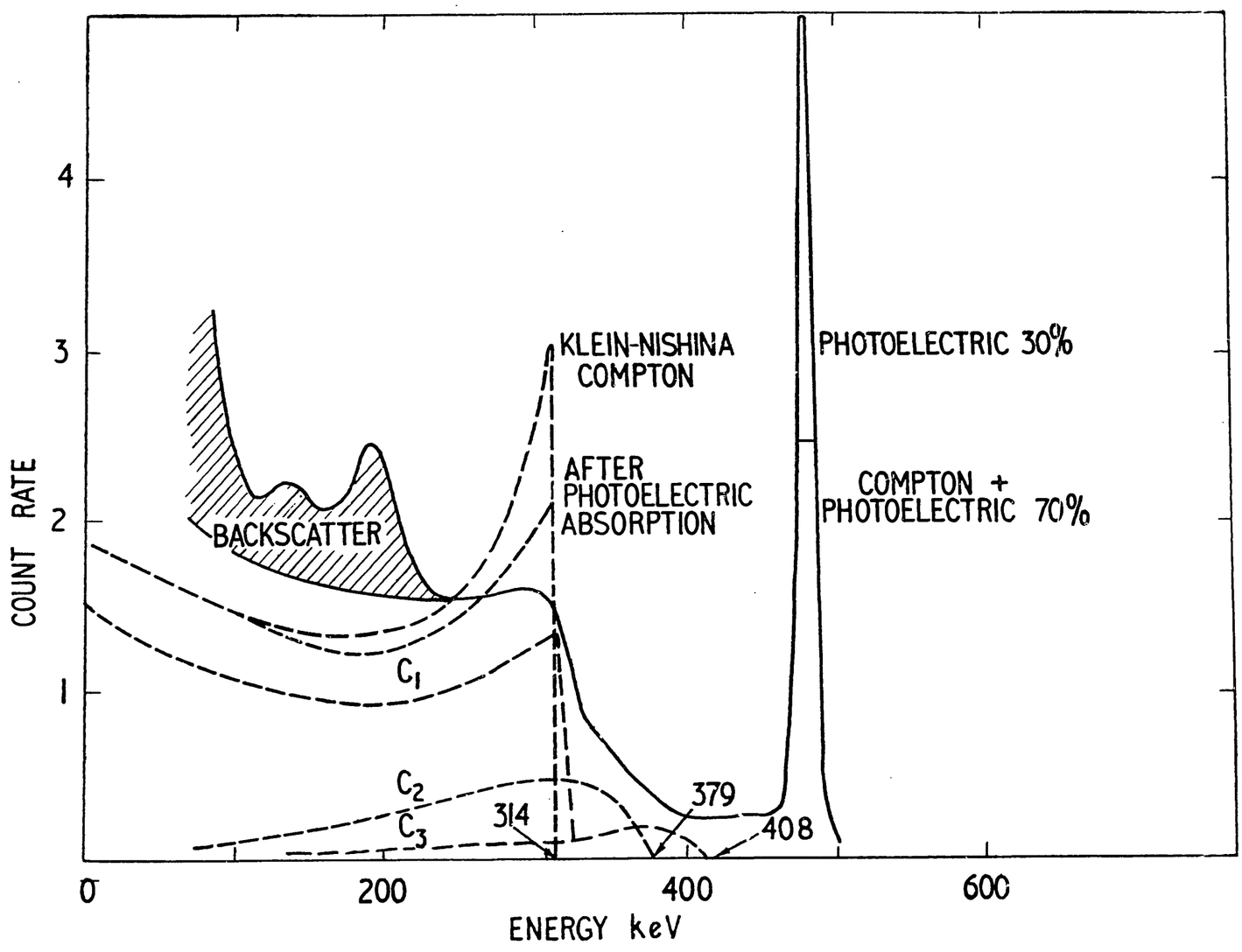

FIGURE 4. GERMANIUM RESPONSE FUNCTION (0.48 MeV)

P1050

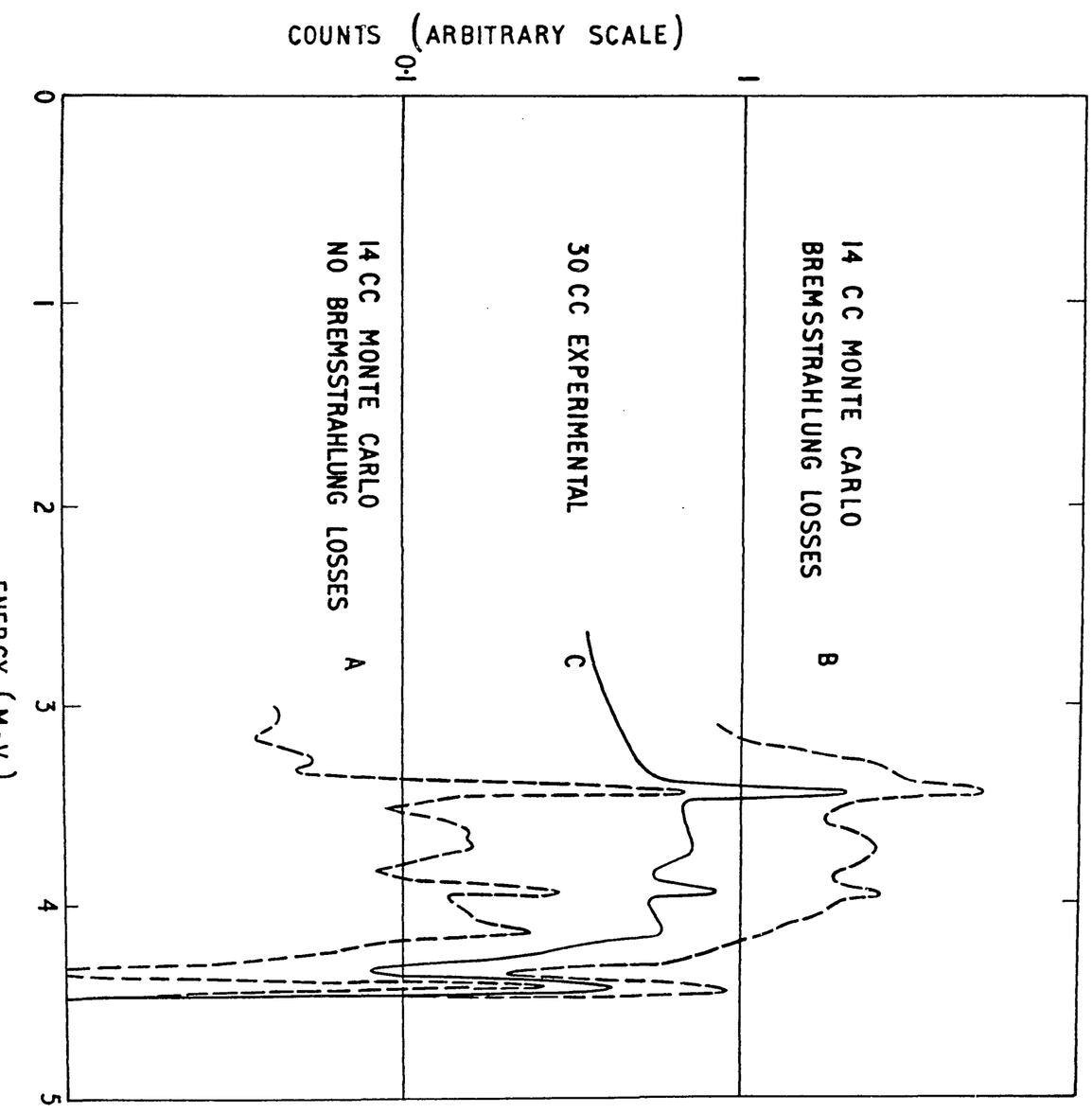

FIGURE 5. GERMANIUM RESPONSE FUNCTION (4.43 MeV)

P1050

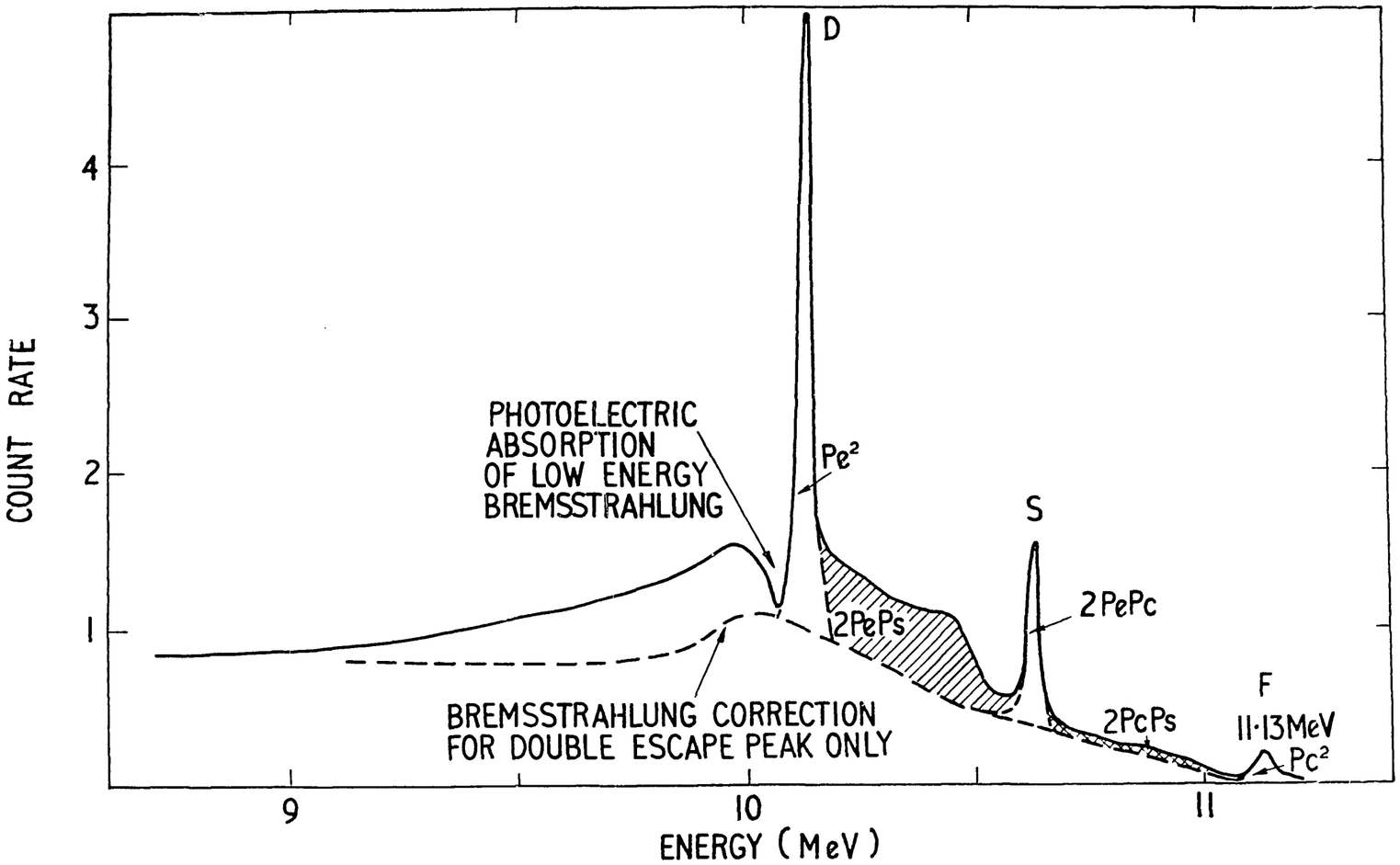

FIGURE 6. GERMANIUM RESPONSE FUNCTION (11.13 MeV)

P1056

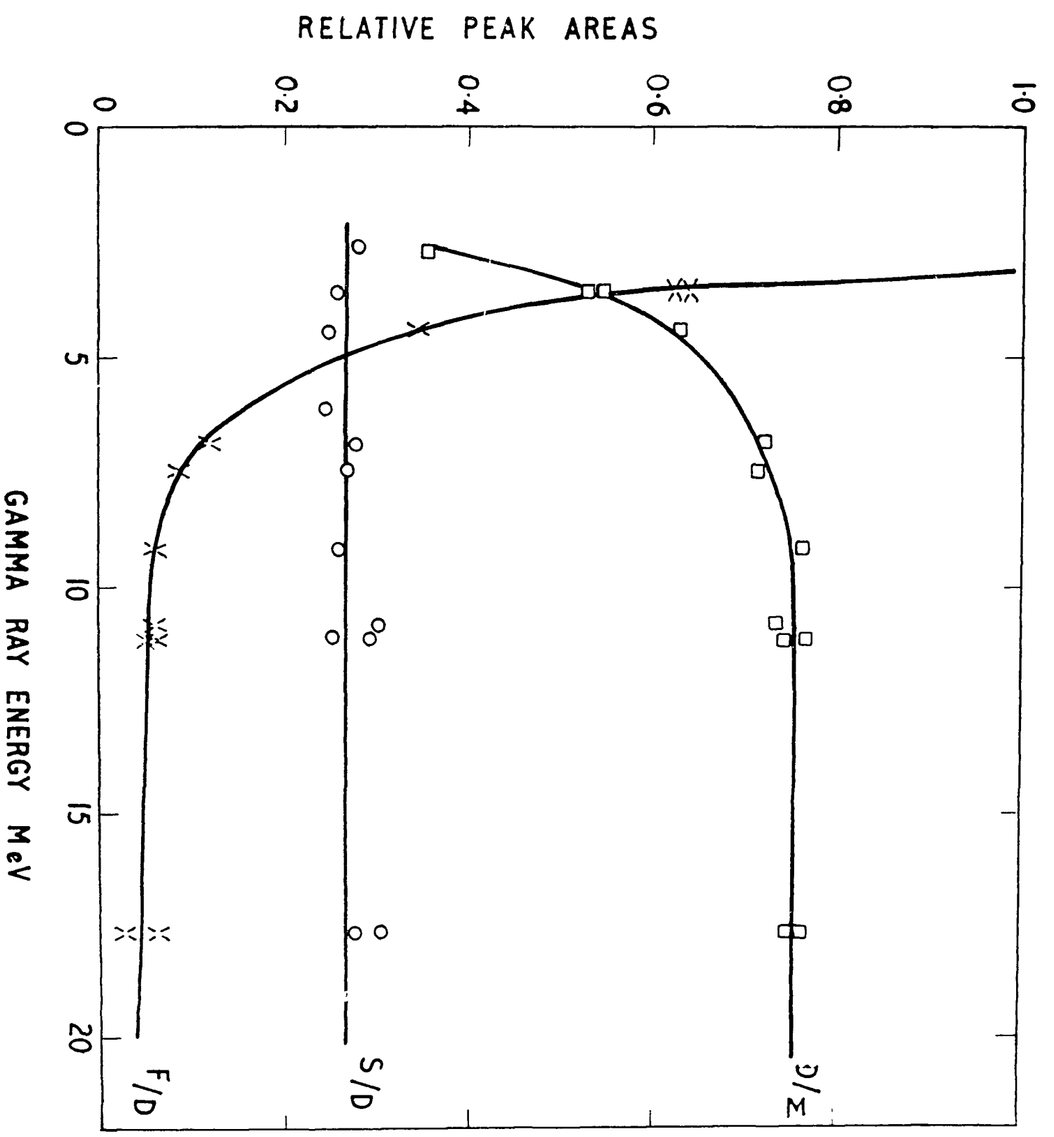

FIGURE 7. RELATIVE PEAK AREAS

P1050

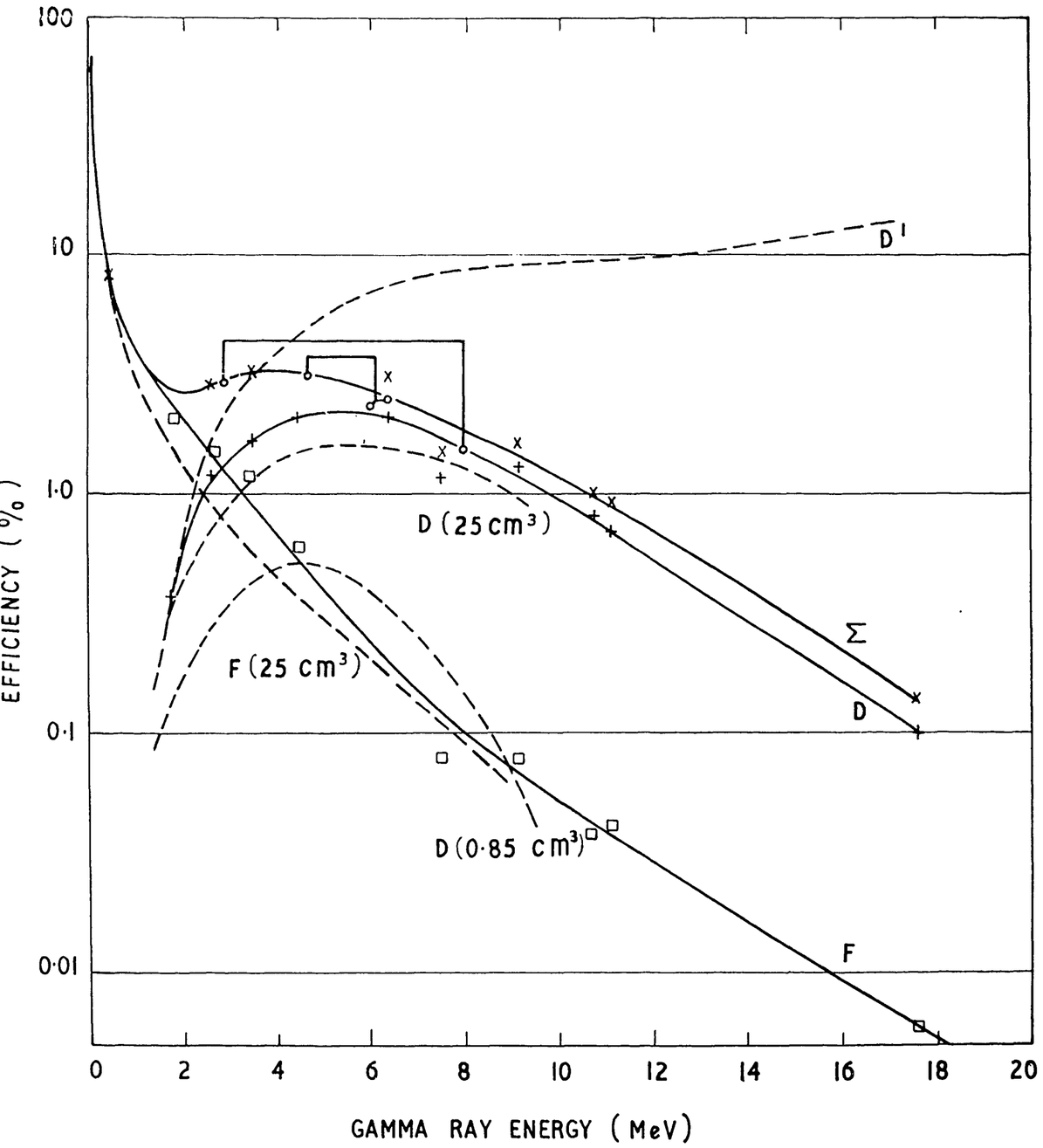

FIGURE 8. GERMANIUM DETECTOR EFFICIENCY

P1050

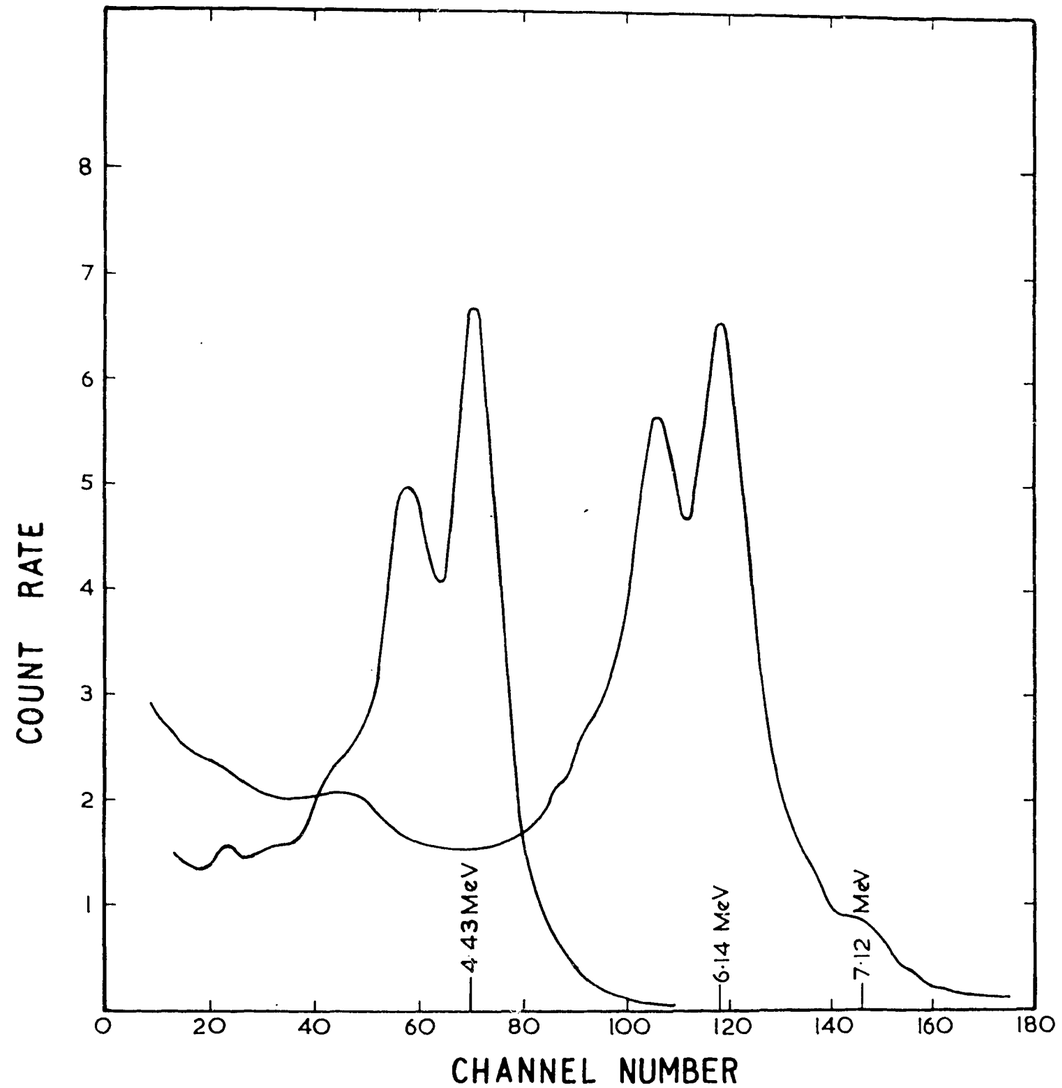

FIGURE 9. TOTAL ABSORPTION DETECTOR RESPONSE FUNCTIONS

P1050

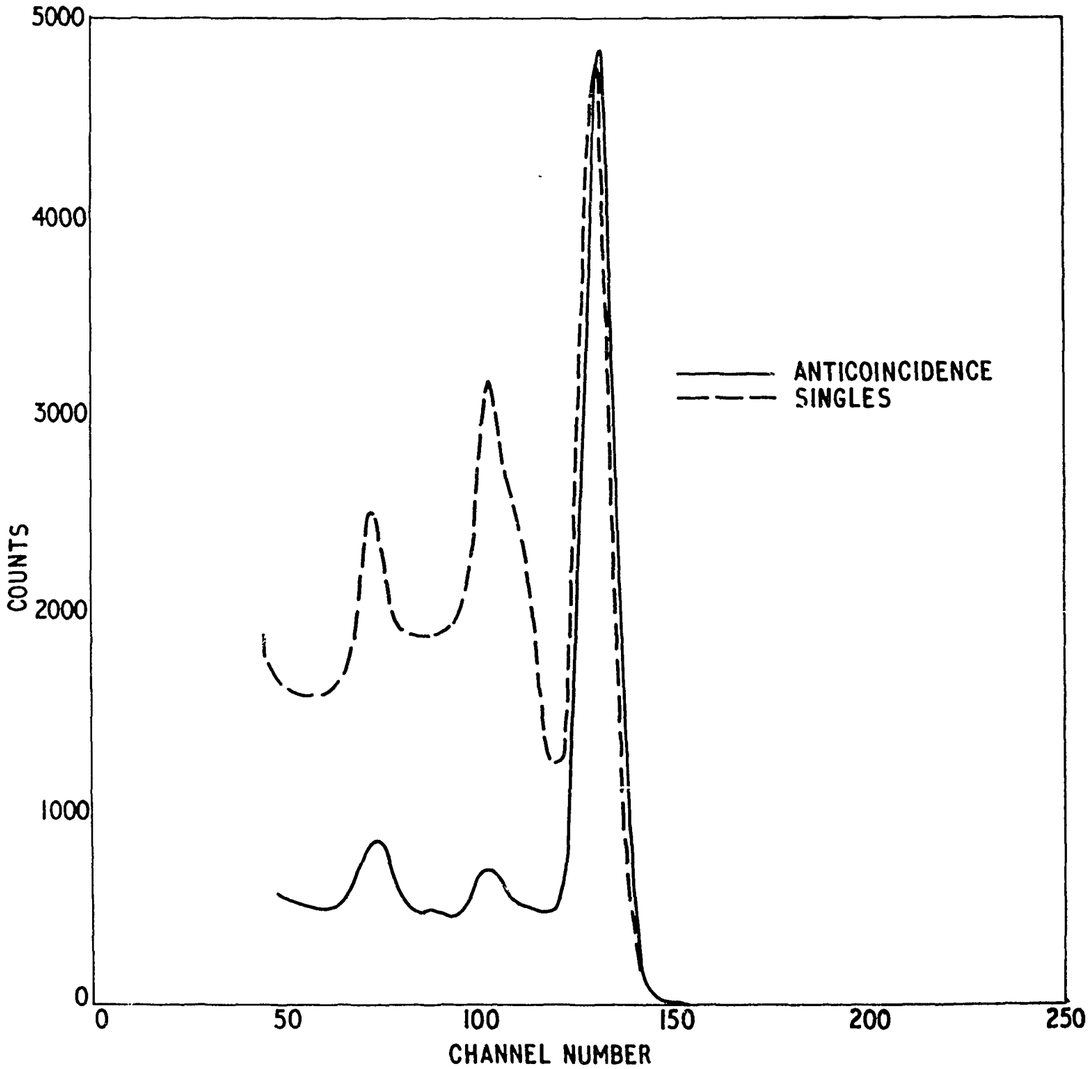

FIGURE 10. ANTICOINCIDENCE SPECTRUM (2.62 MeV)

P1050

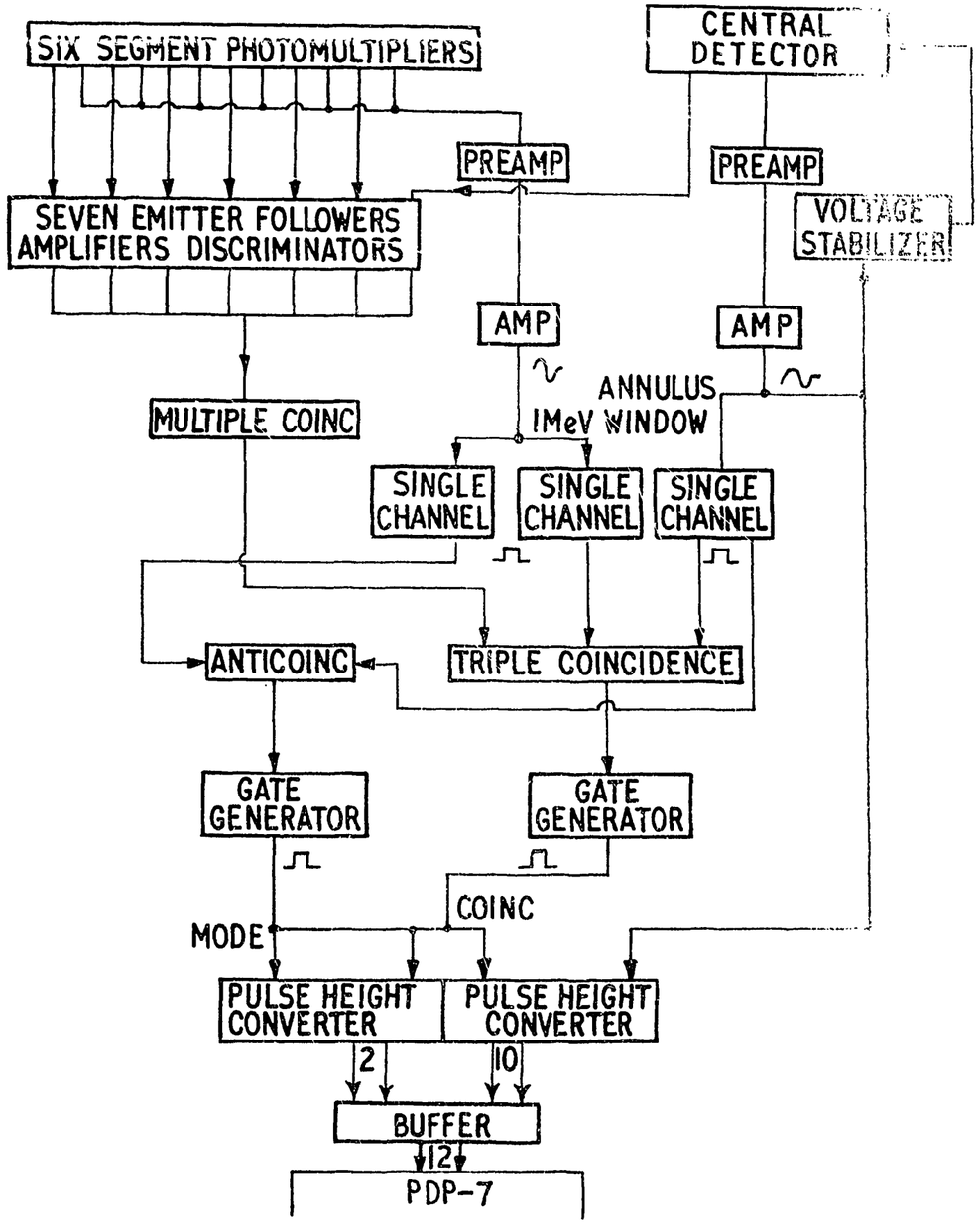

FIGURE 11. NaI ANTICOINCIDENCE AND PAIR SPECTROMETER ELECTRONICS

P1050

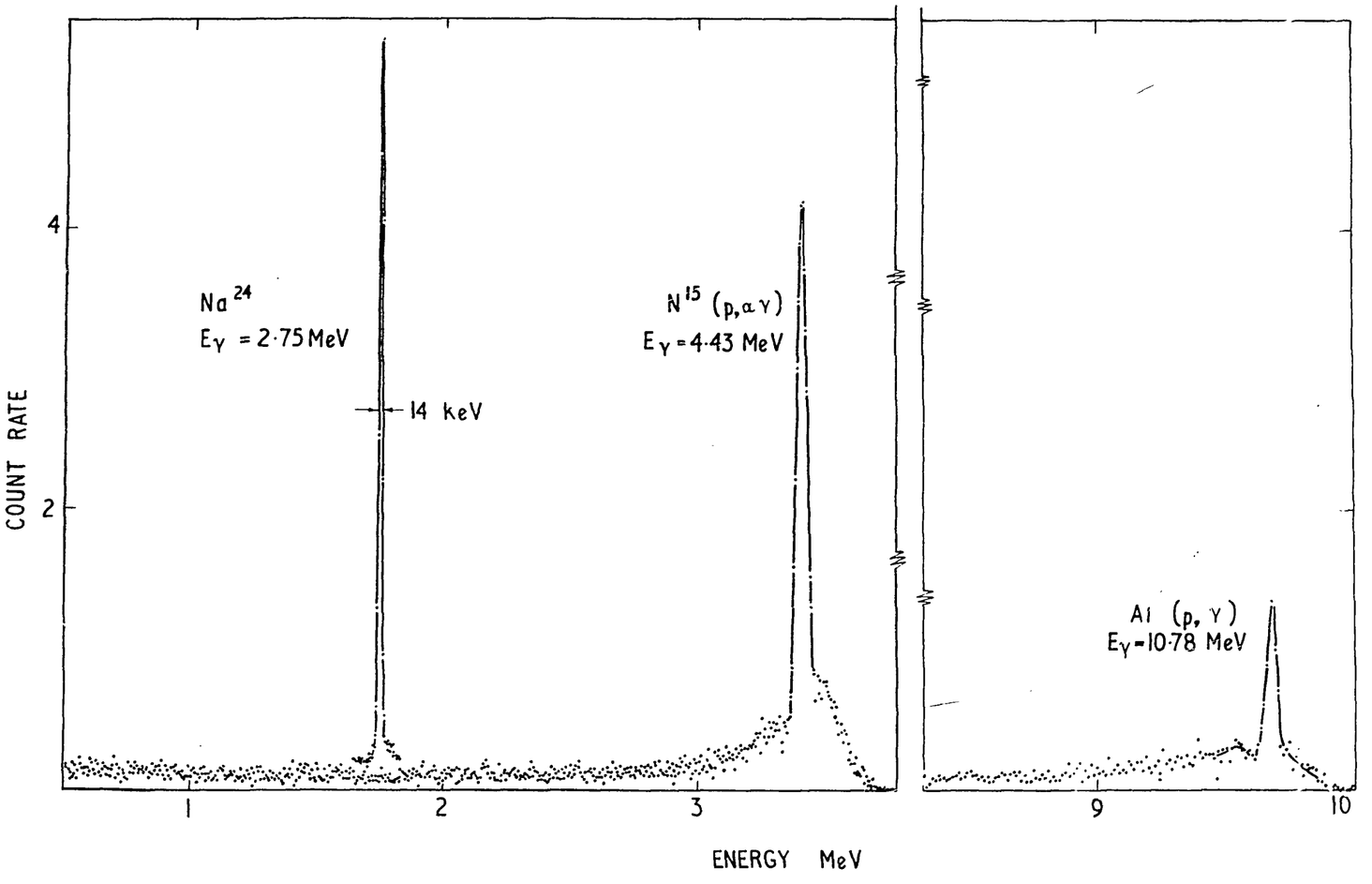

FIGURE 12. GERMANIUM PAIR SPECTRA

P1050

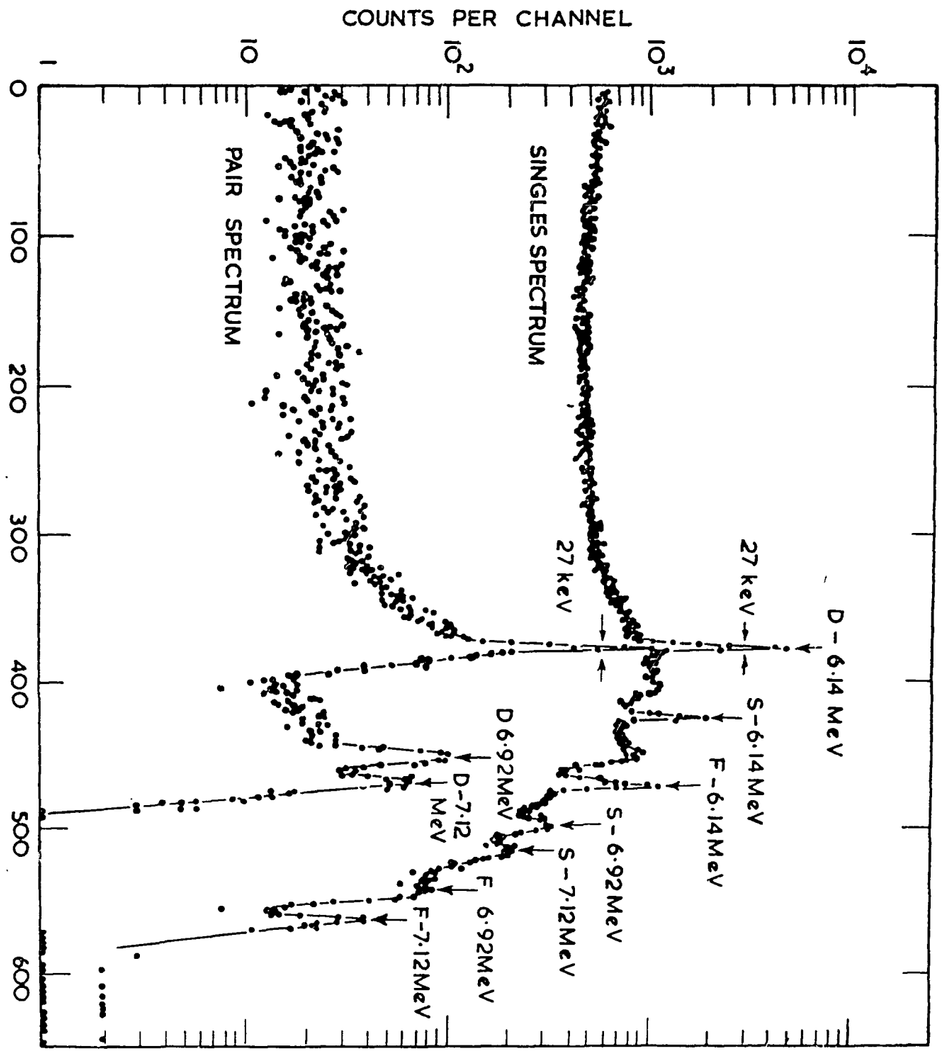

FIGURE 13. GERMANIUM SINGLES AND PAIR SPECTRA

P1050