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ABSTRACT

To make use of the good energy resolution of Ge(Li) spectrometers at γ-ray energies of several MeV, the sensitive volume must be increased to beyond 100 cm^3. This volume is generally only attainable by operating several smaller spectrometers in parallel.

Three coaxial Ge(Li) detectors were fabricated, assembled in a cryostat and operated in parallel. The spectral performance and relative efficiency of this multi-element spectrometer were investigated for γ-rays of energies between 1 and 10 MeV. High energy γ-rays (5-10 MeV) were obtained by thermalising neutrons from a Pu-Be source and then absorbing them in materials with high cross sections for radiative capture.

The experience gained is summarised and alterations to future multi-element spectrometers are proposed.

Note: These results were presented at the A.I.N.S.E. Conference on Nuclear Physics, University of Melbourne, Melbourne, February 1970.

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CONTENTS

1. INTRODUCTION

To detect high energy γ-rays (1-10 MeV) satisfactorily with Ge(Li) spectrometers, large sensitive volumes are necessary. In the energy range 3-10 MeV, and for volumes up to 200 cm^3, the double escape peak (DEP) efficiency is much greater than the full energy peak (FEP) efficiency. Consequently data in this energy range are derived from the DEP while below 3 MeV the FEP is used.

Spectrometers may be single-element, consisting of a single Ge(Li) detector, or multi-element, consisting of an array of detectors operating in parallel. Present technology is such that it is almost impossible to produce single-element spectrometers having sensitive volumes greater than 100 cm^3. Only one reference in the literature describes such a spectrometer (Henck et al. 1969). Multi-element spectrometers with sensitive volumes of 180 cm^3 (Lalovic et al. 1967, Lalovic 1969) and 150 cm^3 (Malm 1967) have been described.

Even if very large volume single-element spectrometers could be produced they would not necessarily be the most suitable. The ratio of DEP efficiency to Compton background decreases as volume is increased and so the 'signal to background' ratio is worsened in the energy range above 3 MeV. It may also be desirable to limit the depletion depth (to perhaps 1 cm) to ensure efficient charge collection and uniform pulse rise times. Increased volume will then result in increased capacitance with a corresponding worsening in resolution.

There are three modes of operation of a multi-element spectrometer:

(i) a summed element data analysis mode (SEDA),
(ii) an individual element data analysis mode (IEDA), and
(iii) a combined data analysis mode (CDA).

SEDA: At some point before the multi-channel analyser the analogue data is summed. Time correlations are maintained so that events in which the γ-ray energy is shared between two or more elements are recorded in the FEP. The system energy resolution is determined by a summation of the resolutions of the individual elements.

IEDA: The data from each element is analysed separately. Time correlations between elements are lost. The FEP efficiency of this mode is less than for SEDA while the DEP efficiency is greater.

If efficiency were the sole consideration SEDA would be preferred in the energy range below 3 MeV and IEDA in the range 3-10 MeV. IEDA requires one multi-channel analyser or equivalent for each element of the array and hence may not be very practical.

CDA: This mode incorporates the features of SEDA and IEDA and so is the most versatile. However, since it requires a more complex analysis system,

perhaps an on-line computer, it may be even less practical than IEDA.

This report describes the operation of a three-element spectrometer operating in the SEDA mode. The results were obtained while preparing a four-element spectrometer for the Research Establishment's Physics Division. The completed spectrometer will have a sensitive volume of ~ 160 cm^3.

2. PREPARATION

The original intention was to prepare a multi-element Ge(Li) spectrometer consisting of four detectors housed in one cryostat and operating in parallel. Unfortunately one element failed and the array finally consisted of three elements. The fourth, although not used, was present in the cryostat and thus acted as a scattering body close to the three active elements, increasing the Compton background in the spectrometer.

The detectors were fabricated from two p-type Ga-doped Czochralski-pulled single-crystals grown in the ⟨111⟩ direction. The resistivity and minority carrier lifetimes were 10-20 ohm-cm and 500 μsec. The dislocation density was 1000 - 5000 cm^{-2}. The crystals were supplied by Hoboken.

Each detector was a double-open-ended coaxial Ge(Li) diode. The physical dimensions were similar; length 6 - 6.5 cm, outer diameter 3 - 3.5 cm, core diameter 1 - 1.5 cm. These dimensions determined the depletion depth, ~ 1 cm, the volume, 40 - 50 cm^3, and the capacitance, 50 - 60 pF for each of the diodes. The total sensitive volume was estimated to be 143 cm^3.

The fabrication of these detectors closely followed the method reported by Tavendale (1964). Lithium was diffused from a lithium-in-oil suspension coated on the base material. Drifting was carried out in Freon TMC (boiling at 37°C) under constant current conditions. Typical bias and current values during drift were 200 V and 1.5 A.

Following drift, the lithium contacts were renewed and a clean-up drift was made at ~ 500 V with the diode temperature at ~ 5°C. After careful etching and installation in a cryostat each diode was given a final clean-up drift. This drift was carried out at that temperature at which the leakage current was 10 mA for a reverse bias of 1000 V. Drift times were typically 1 or 2 hours.

The diodes were then cooled to liquid nitrogen temperature and the leakage current and capacitance characteristics examined. The criteria for acceptance imposed at this stage were that the leakage current be less than 10 nA at a reverse bias of 1000 V, and that the capacitance be saturated from one or two hundred volts upwards. If the criteria were not met the diode was given a further clean-up drift, and if this was unsuccessful, further etching, followed by more clean-up. When the criteria had been met the spectral performance of

the individual diodes was checked. Resolutions of a few keV were expected and obtained for ^{60}Co γ-rays.

The detectors were then assembled on a mounting plate and installed in the cryostat. Figure 1 shows the Ge(Li) diodes in Al mounting cans, and the Al mounting plate. They then underwent a further period of clean-up drift, for which the conditions were as stated previously. The diodes underwent clean-up in order of decreasing temperature. They were then cooled to liquid nitrogen temperature and the same leakage current and capacitance criteria applied.

It was necessary to remove, etch, and reassemble the detectors and to repeat the above procedure before the criteria were finally met. In addition it was found necessary to maintain the applied bias continuously. Figure 2 shows the leakage current and capacitance characteristics finally obtained.

3. OPERATION

A SEDA mode may be set up in several ways, depending on where the summation is required to take place:

(i) Summation before the preamplifier. This system requires a single preamplifier, a main amplifier, possibly a biased amplifier, and a pulse height analyser. The input stage of the preamplifier may be inside the cryostat to reduce stray capacitance and to permit operation at a reduced temperature but this arrangement presents replacement difficulties. To obtain the best resolution from this method of summation the charge collection efficiencies of all the detectors must be identical, which is rather unlikely.

(ii) Summation before the main amplifier. This system requires one preamplifier for each detector. If the detectors are not perfectly matched (that is, if their charge collection efficiencies are different) correction can be made by varying the preamplifier gains.

(iii) Summation before the pulse height analyser (or biased amplifier). This system requires one preamplifier and main amplifier per detector. Matching can be achieved by varying the gain of the main amplifier which is normally simpler to adjust than the preamplifier.

Apart from intrinsic limitations, and in the absence of trapping, the resolution of a spectrometer depends on the leakage current and on the capacitative load presented at the first stage of the preamplifier. In system (i) the total leakage current contribution to the resolution is obtained by linear summation of the individual current components. The capacitance contribution is obtained similarly. In systems (ii) and (iii) a linear summation is still required in order to obtain the leakage current contribution but the capacitative components must be summed in quadrature after the preamplifiers.

The energy resolution of a multi-element spectrometer may be worsened by indadequate matching of the various signals. With a 1024 channel analyser, matching should be possible to one part in a thousand, and to one part in several thousand if a biased amplifier is used in association with the analyser. To achieve this degree of matching it must be possible to vary gains with a similar sensitivity. In our case the expected resolution is lower for systems (ii) and (iii) than for system (i). Since matching is simplest for system (iii) this was chosen and is shown schematically in Figure 3.

The charge sensitive preamplifiers were Ortec Model 118A which have an FET first stage operating at room temperature. The main amplifiers were Canberra Industries Model 1417. A summing amplifier, Canberra Industries Model 1465, was used ahead of the biased amplifier which was Canberra Industries Model 1461. The multi-channel pulse-height analyser was a Nuclear Data ND.1024. The reverse bias applied to each detector was 1000 V.

4. SPECTRAL PERFORMANCE

The spectral performance of the multi-element spectrometer was assessed by examining γ-rays from ^{60}Co and ThC". Resolutions were measured for the FEPs at 1173, 1333 and 2614 keV and also for the 1592 keV DEP of ThC". For comparison the resolutions of the individual detectors were recorded. System resolution (P) was recorded in all instances. Table 1 gives results for a 1 μsec main amplifier time constant. Resolutions of 9.1 and 12.0 keV at 1333 and 2614 keV respectively were measured with the multi-element spectrometer. Figure 4 shows a ^{60}Co spectrum obtained with the spectrometer.

Efficiency measurements for the array and for the individual detectors are summarised in Table 2. Efficiency is determined by the number of counts in the various peaks for equal time intervals and constant source-detector geometry. The symbol Σ denotes the sum of events from the individual detectors at the quoted energy. The data presented do not permit an examination of the variation of efficiency with γ-ray energy. As expected, the FEP efficiency of the multi-element spectrometer is greater than that of the corresponding Σ and the DEP efficiency is less. For FEP events the multi-element spectrometer was 7.5 per cent more efficient at 1333 keV and 8.4 per cent more efficient at 2614 keV than the three detectors operating individually. Data from the DEPs show the multi-element spectrometer to be 13 per cent less efficient than the three detectors in detecting a 2614 keV γ-ray.

It was proposed that the spectral performance of the multi-element spectrometer with higher energy γ-rays be examined. Rather than shift the spectrometer from the laboratory to the Van de Graaff accelerator where a reaction such as ^{27}Al(p;γ)^{28}Si could have been utilised, a source of high energy γ-rays was set

up close to the spectrometer. This source produced a flux of thermal neutrons some of which were radiatively captured in selected materials placed close to the spectrometer.

The neutron source was an ~ 5 x 10^5 n sec^{-1} Pu-Be source immersed in a thermalising tank of water, which in turn was surrounded with boron loaded paraffin wax. The materials examined were metallic Fe and Cu, and Cl (in CCl_4). These elements have high cross sections for radiative capture of thermal neutrons. Radiative capture γ-rays from Fe are particularly useful for testing Ge(Li) spectrometers because of the doublet at 7.63 - 7.64 MeV. The multi-element spectrometer was not able to resolve this doublet (14 keV separation). Data from the DEP of the 7.194 MeV line of Cu are included in Tables 1 and 2. A resolution of 24.4 keV was measured and the multi-element spectrometer was found to be 14 per cent less efficient than the individual detectors.

The resolution measured from these high energy γ-rays was markedly worsened by the high background present. At energies above 5 MeV this was due to radiative capture in the cryostat body and other nearby materials. Below 5 MeV the background was dominated by 4.43 and 2.23 MeV γ-rays from the $^9Be(\alpha,n\gamma)^{12}C$ and $p(n,\gamma)d$ reactions respectively. The 4.43 MeV γ-ray is Doppler broadened and so is unsuitable for testing Ge(Li) spectrometers.

5. CONCLUSIONS

Given good material, fabrication of Ge(Li) single-element spectrometers is still difficult owing to the behaviour of lithium in germanium; precipitation and out-diffusion. In addition extreme cleanliness is essential when handling is required. These difficulties are magnified many times when preparing a multi-element spectrometer, especially when the elements are housed in the same cryostat. The failure of one of the elements of our spectrometer to meet final selection criteria emphasises this problem.

Good matching of the individual detectors is important if optimum resolution is to be realised. Matching was achieved by varying the gain of the main amplifiers, which could be adjusted to 1 part in 1000. This was quite compatible with the 1024 channel analyser, provided a biased amplifier was not used, but resolutions were normally measured using a biased amplifier and were therefore not optimised. The degree of matching can be estimated quantitatively by summing in quadrature the individual system noises and comparing the result with that measured from the multi-element system. Any future system should have improved gain control in order that better matching may be obtained.

The resolutions measured using thermal neutron radiative capture γ-rays were disappointing owing to high background. Improved source and cryostat shielding and geometry, and selection of more suitable cryostat materials would reduce this

background and permit better resolution measurements. It is doubtful whether useful efficiency or resolution measurements can be made over the whole energy range up to 10 MeV with such a γ-ray source. In the energy range below 5 MeV the γ-rays from the reactions $^{9}Be(\alpha,n\gamma)^{12}C$ and $p(n,\gamma)d$ are always dominant.

6. ACKNOWLEDGEMENTS

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TABLE 1

RESOLUTIONS IN keV

Energy keV / CAN	FEP[1] 1173		FEP 1333	DEP[2] 1592		FEP 2614	DEP 6892	
1	6.7		7.9	13.7		12.1	27.1	
P[3]		4.6			5.0			9.3
3	5.1		6.1	9.5		7.9	17.9	
P		4.1			4.6			9.3
4	5.5		6.1	11.4		7.8	19.1	
P		4.4						11.6
Array	8.9		9.1	12.1		12.0	24.4	
P		8.3			8.8			

TABLE 2

EFFICIENCY MEASUREMENTS

Energy keV / CAN	FEP[1] 1173	FEP 1333	DEP[2] 1592	SEP[4] 2103	FEP 2614	DEP 6892
1	5657	5084	828	162	1035	612
3	5844	5056	780	185	1003	340
4	7499	6501	1012	251	1320	251
Σ	19000	16641	2620	598	3358	1203
Array	20413	17966	2365	559	3641	1031

[1]FEP = Full Energy Peak

[2]DEP = Double Escape Peak

[3]P = System Resolution

[4]SEP = Single Escape Peak

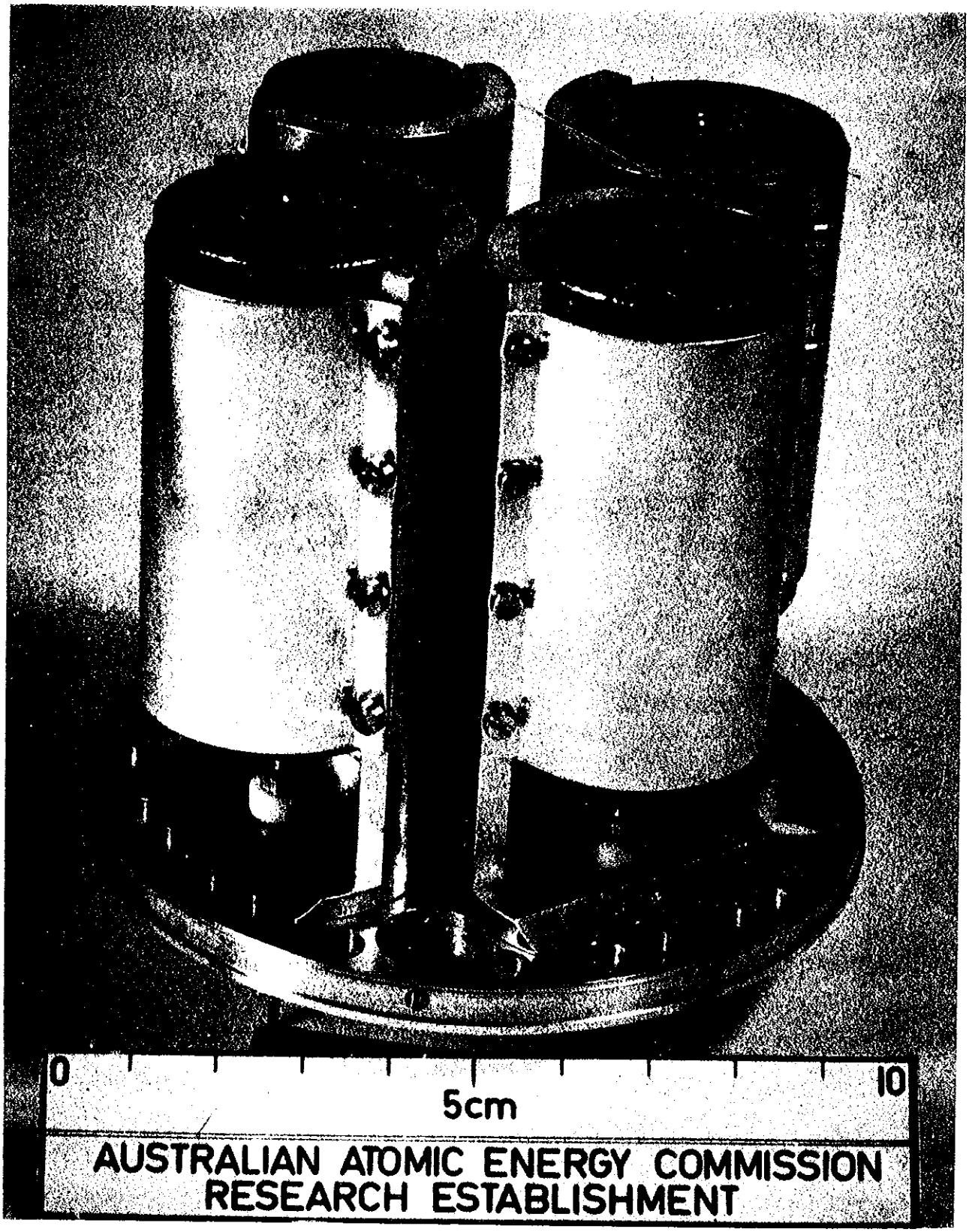

FIGURE 1. THE Ge(Li) DIODES ASSEMBLED FOR THE MULTI-ELEMENT SPECTROMETER

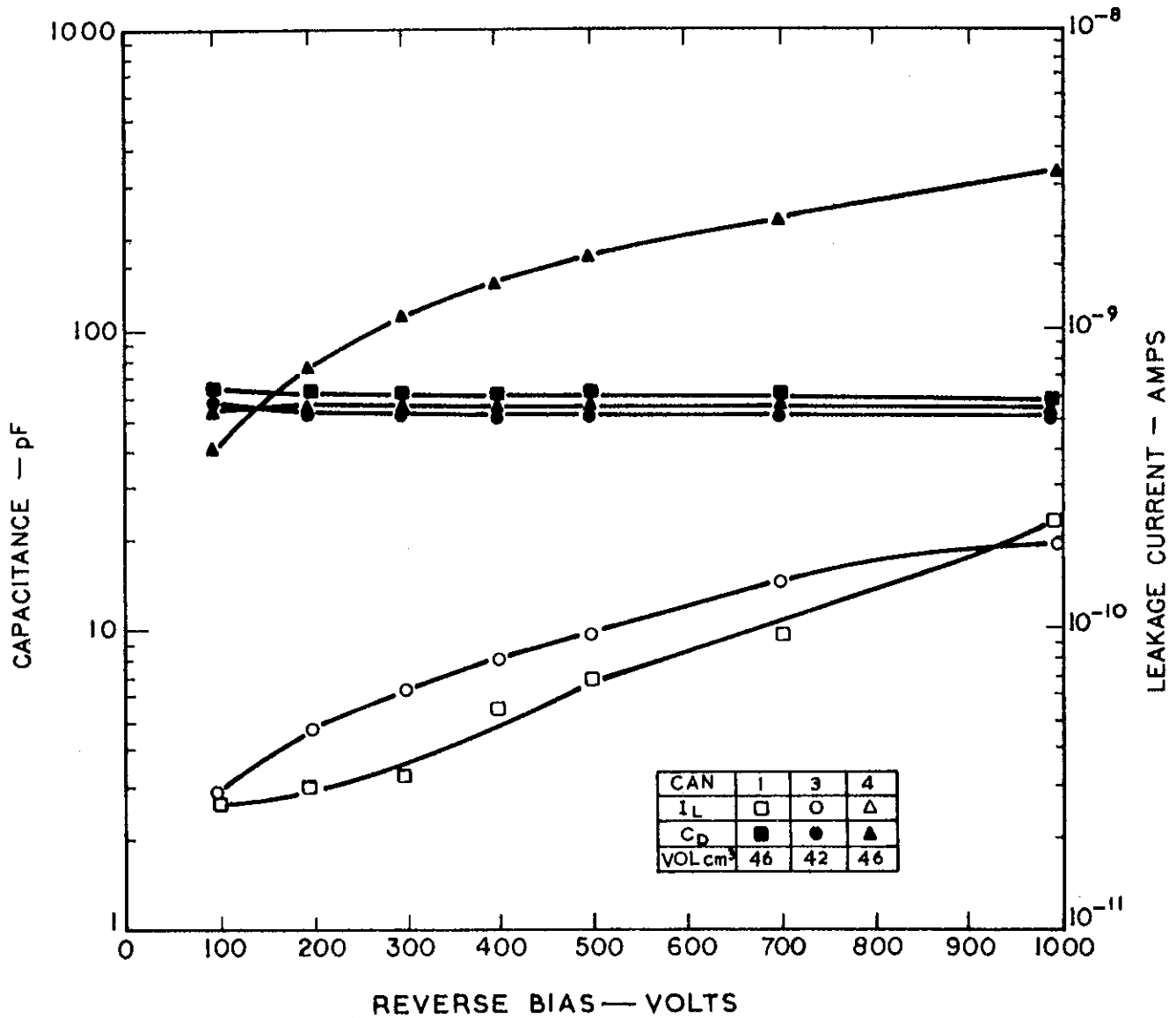

FIGURE 2. LEAKAGE CURRENT AND CAPACITANCE OF INDIVIDUAL DIODES T = 77°K

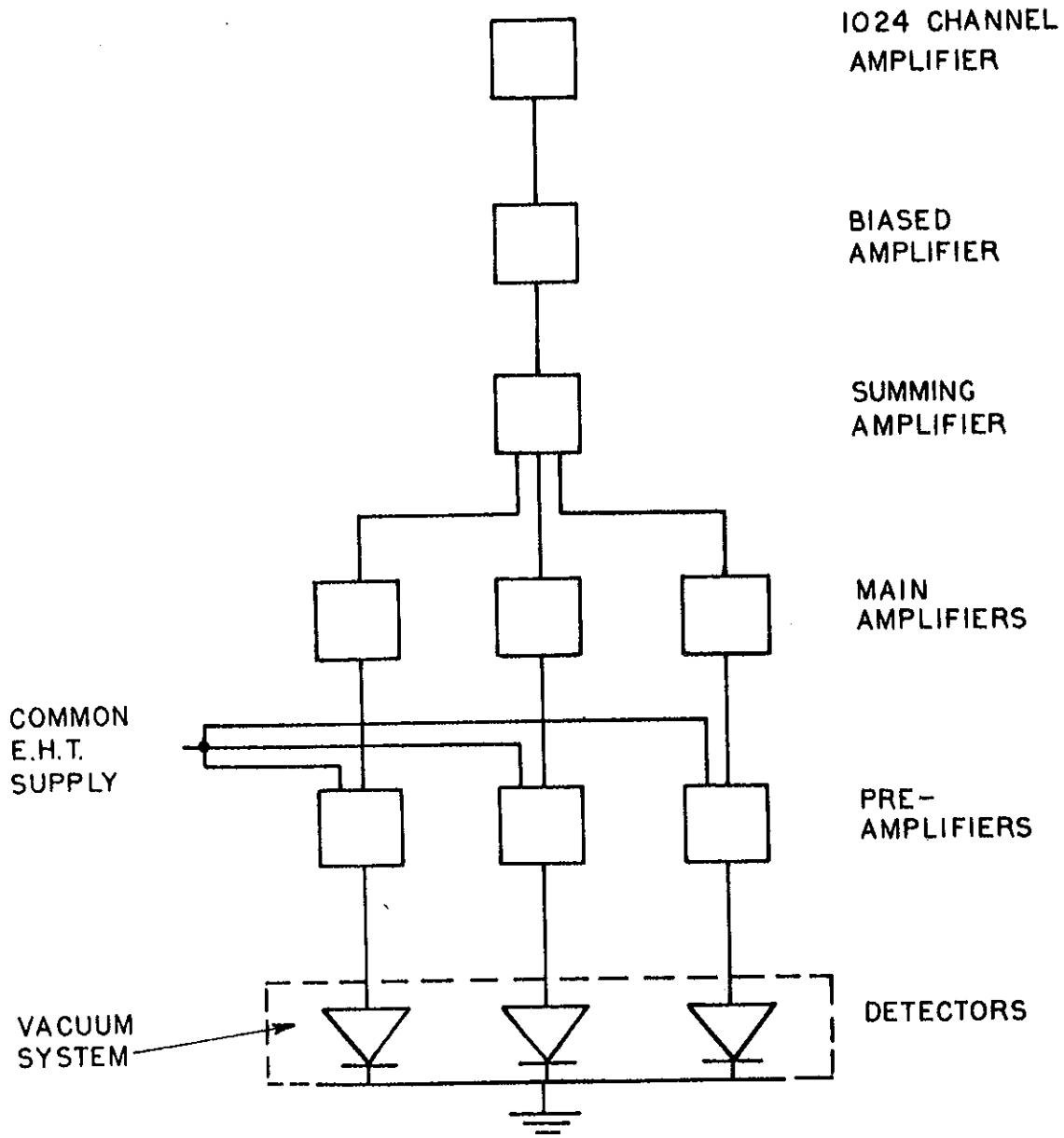

FIGURE 3. SCHEMATIC DIAGRAM OF THE MULTI-ELEMENT SPECTROMETER

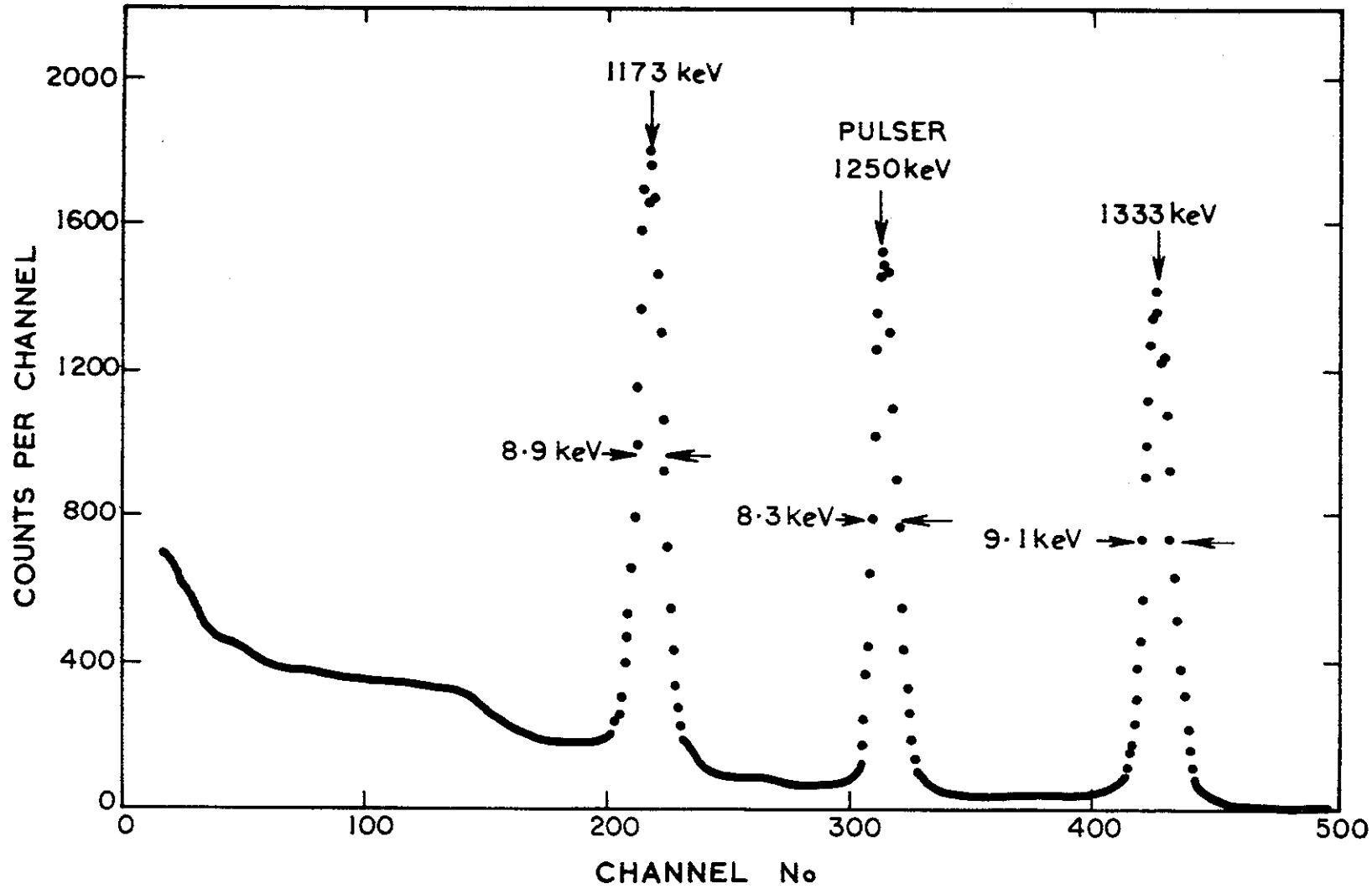

FIGURE 4. RESPONSE OF THE MULTI-ELEMENT SPECTROMETER TO THE γ-RAYS FROM ^{60}Co