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INSTRUMENTS

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PRELIMINARY INVESTIGATION OF A FIVE-CRYSTAL SCINTILLATION GAMMA-RAY SPECTROMETER

by

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ABSTRACT

A five-crystal scintillation gamma-ray spectrometer was constructed for use as a Compton coincidence spectrometer or as a pair coincidence spectrometer. Preliminary tests are discussed. The efficiency in either mode of operation was found to be low; however, the backgrounds were favorable and good definition of characteristic lines was achieved. As a Compton coincidence spectrometer, resolutions of the 0.662-Mev gamma ray from Cs^{137} on the order of 10 percent were observed. As a pair coincidence spectrometer, the 2.75-Mev gamma ray from Na^{24} was resolved to about 7 percent. Future tests and plans for improvements are discussed.

PREFACE

In June, 1958, it was planned to test electronic components for a five-crystal spectrometer and to make preliminary tests on the equipment in order to investigate the effects of various energies of gamma rays, source intensities, geometries, and applications of the equipment itself.

This report presents a summary of the results obtained by one of us (REM) while employed at the Los Alamos Scientific Laboratory during the summer of 1958. The data given for counts are considered to be reliable to within the usual statistical error associated with that particular number of counts. Extensive series of runs to establish averages and standard deviations were not made.

The results of the operation of this five-crystal spectrometer as either a Compton scintillation spectrometer or as a pair coincidence spectrometer are encouraging. However, these results are to be considered preliminary, and further development of the instrument is planned.

We would like to thank Judith Weinstein for her help in plotting much of the data.

I. INTRODUCTION

Several investigators[1,2] have constructed multi-crystal scintillation gamma-ray spectrometers which were designed for use as Compton spectrometers[1] in the range of gamma-ray energies of 0.2 to 1.0 Mev or as pair spectrometers for measuring gamma-ray energies of 1.02 Mev or higher.[2]

The Compton spectrometer is designed to detect in a second crystal the gamma ray which is Compton-scattered in a first crystal (Fig. 1). Electronic circuits restrict the pulse-height analysis to pulses in the first crystal which are time-coincident with the scattered gamma ray, detected in the second. A peak in the pulse-height distribution occurs which is due to the difference in energies between the incident and the scattered gamma rays, i.e., due to the energy of the Compton electron. This spectrometer has a basic disadvantage in that the scattering angle is poorly defined because of the finite volumes of the scattering and detecting crystals. A further disadvantage lies in the inherently low efficiency, dictated by the requirements of a higher order process for detection.

The pair spectrometer is designed to detect in opposite side crystals coincident and oppositely directed 0.511-Mev gamma rays which arise from the annihilation of a positron produced by gamma radiation incident on the center crystal (Fig. 2). A coincidence circuit selects those events in which a pulse in the center crystal is observed simultaneously with two 0.511-Mev coincident pulses in the side crystals. A pulse-height analysis of the center crystal pulses shows peaks due to the difference in energies between the

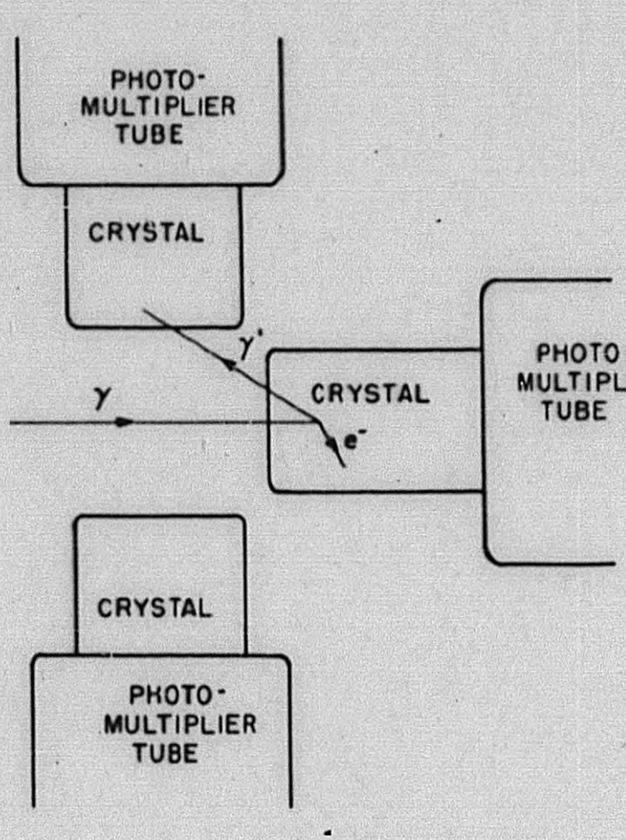

Fig. 1 Schematic diagram of crystals arranged as a Compton spectrometer.

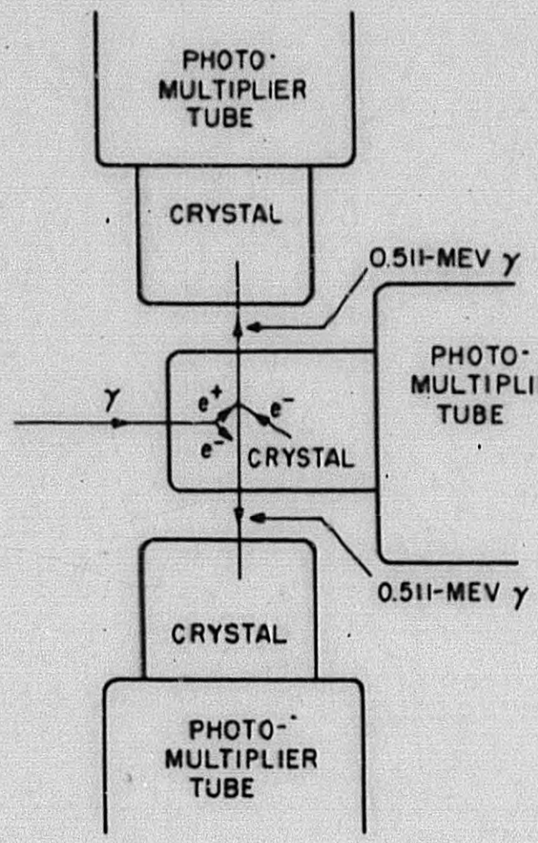

Fig. 2 Schematic diagram of crystals arranged as a pair spectrometer.

energy of the incident gamma radiation and the energy (1.022 Mev) expended in the pair production. Again, disadvantages are the poor definition of the solid angles involved and the requirements of two scattering processes for detection.

The primary advantage of such coincidence spectrometers over single-crystal spectrometers lies in the fact that, for incident monoenergetic gamma rays, the response (pulse-height distribution) is more unique. That is to say, in the pulse-height spectrum of a coincidence spectrometer a much larger fraction of the analyzed pulses will lie in a single characteristic peak than in the spectrum of a single-crystal spectrometer. Thus, in the former, analysis of pulse-height spectra containing peaks due to multiple gamma rays can be performed with more reliability or, what is the same, more peaks can be resolved.

However, the fraction of the incident gamma rays which are analyzed, i.e., detection efficiency, in the coincidence spectrometers is much lower than in single-crystal spectrometers. Howland et al.[1] give the efficiency of their Compton spectrometer as about 0.1 percent. The efficiency of a pair spectrometer is necessarily lower yet, depending upon the probability of pair formation in the center crystal and the probability of detection of coincident 0.511-Mev gamma rays in the side crystals. West and Mann[2] give the second factor as about 0.9 percent. One means of increasing this efficiency for pair detection is to increase the solid angle subtended by the side crystals by increasing the number of side crystals used.

A spectrometer has been designed by one of us (RMK) which employs four side crystals located about a center crystal (Figs. 3a and 3b). For Compton spectrometry, the center crystal can be adjusted (Fig. 4a) so that gamma rays are scattered through an angle of about 135 to 150 degrees into the four side crystals. This range of angles was chosen because the energy

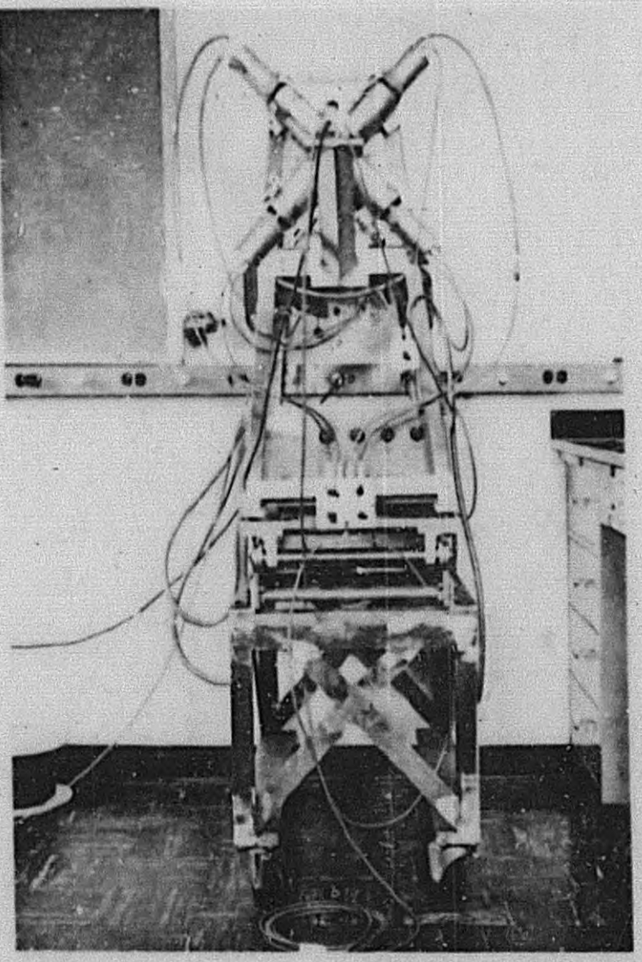

Fig. 3a Front view of the five-crystal scintillation spectrometer. Four series resistors for adjusting side crystal gains are contained in box in center of photograph.

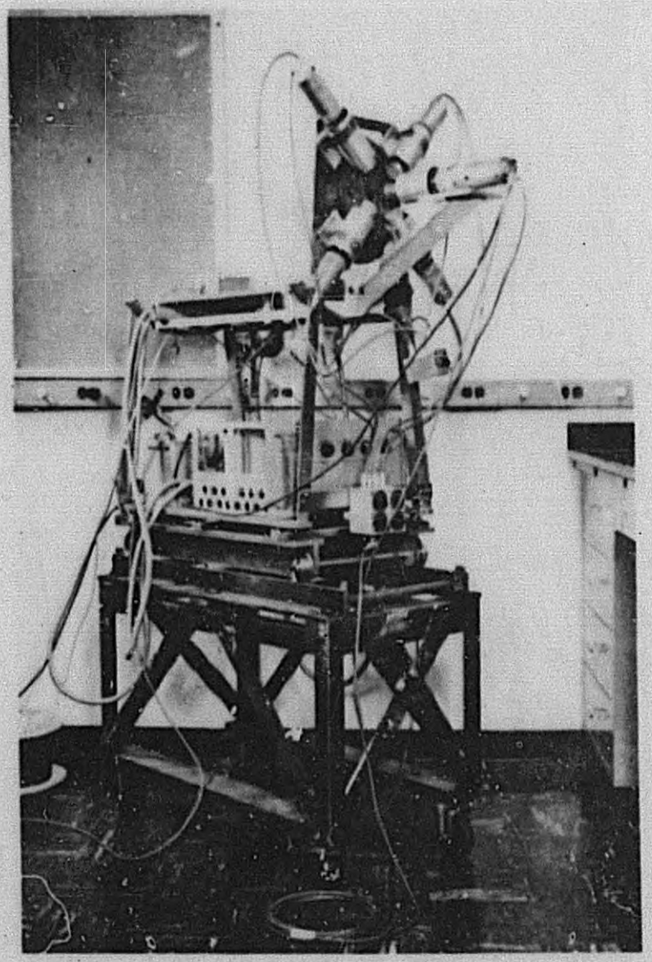

Fig. 3b Oblique view of the five-crystal scintillation spectrometer. Cradle in rear is to accommodate later shields and collimators.

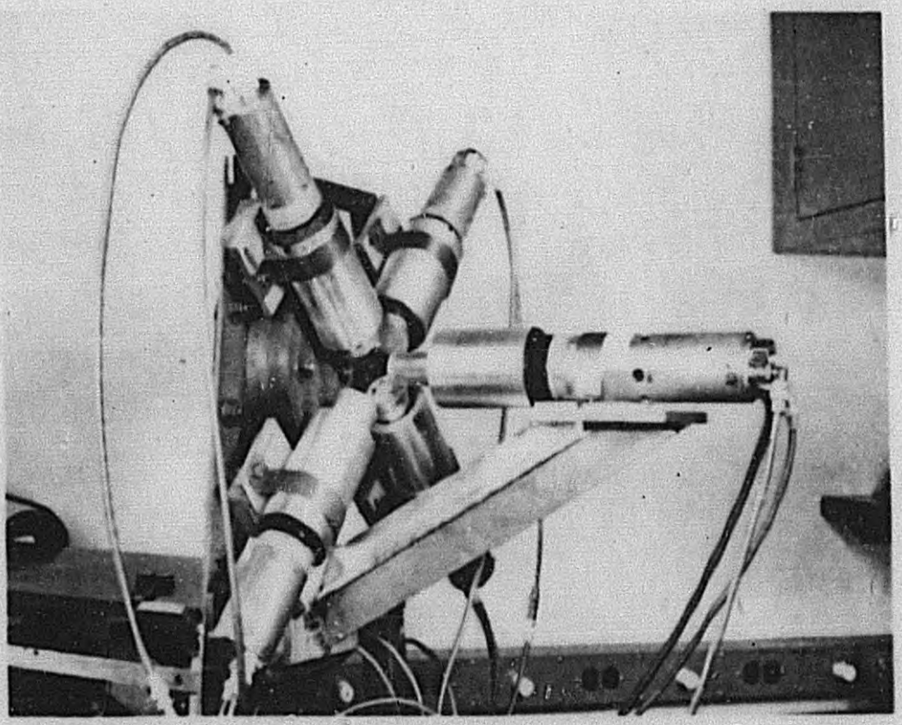

Fig. 4a Center crystal arranged for Compton coincidence detection.

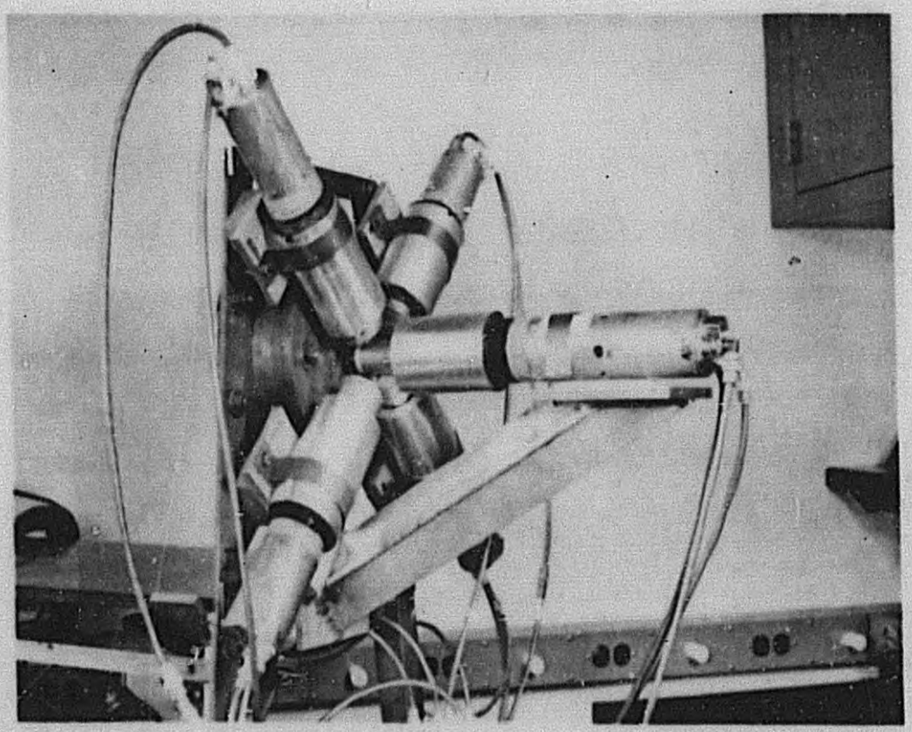

Fig. 4b Center crystal arranged for pair coincidence detection.

of the scattered gamma ray is more nearly independent of angle over this range than, e.g., forward angles. For the 0.662-Mev gamma ray from Cs^{137}, for example, the variation is less than 10 percent. For pair spectrometry, the center crystal can be adjusted so that it is directly between the side crystals. Opposite side crystals are then used in pairs to observe the radiation from positron annihilation in the center crystal (Fig. 4b).

II. CONSTRUCTION, INITIAL TESTING, AND ASSEMBLY

A. Construction

The apparatus shown in Fig. 3 was constructed in the shops at the Los Alamos Scientific Laboratory. Radiation is incident on the center crystal from behind a 2-inch-thick lead shield through a 1-inch-diameter hole. Additional collimation and shielding is to be obtained later from a large tank of hydrogenous material which is to be placed on the cradle in the rear of the apparatus.

B. Initial Testing

Several RCA 6342 photomultiplier tubes and commercial (Harshaw) NaI(Tl) crystals were tested in order to find an optimum combination. Criteria used for judging quality were the resolution and the peak-to-valley ratio of the single-crystal pulse-height spectrum of the 0.662-Mev gamma ray from Cs^{137}. Resolution is defined as the ratio of peak width at half-maximum to the pulse height at the center of the peak. The peak-to-valley ratio in the pulse-height spectra is the ratio of the counts/volt at the central position of the peak to the counts/volt at the center of the adjacent valley. A sample spectrum is shown in Fig. 5.

The photomultiplier tube base whose schematic diagram is shown in Fig. 6 was constructed and used to test the photomultiplier tubes and the

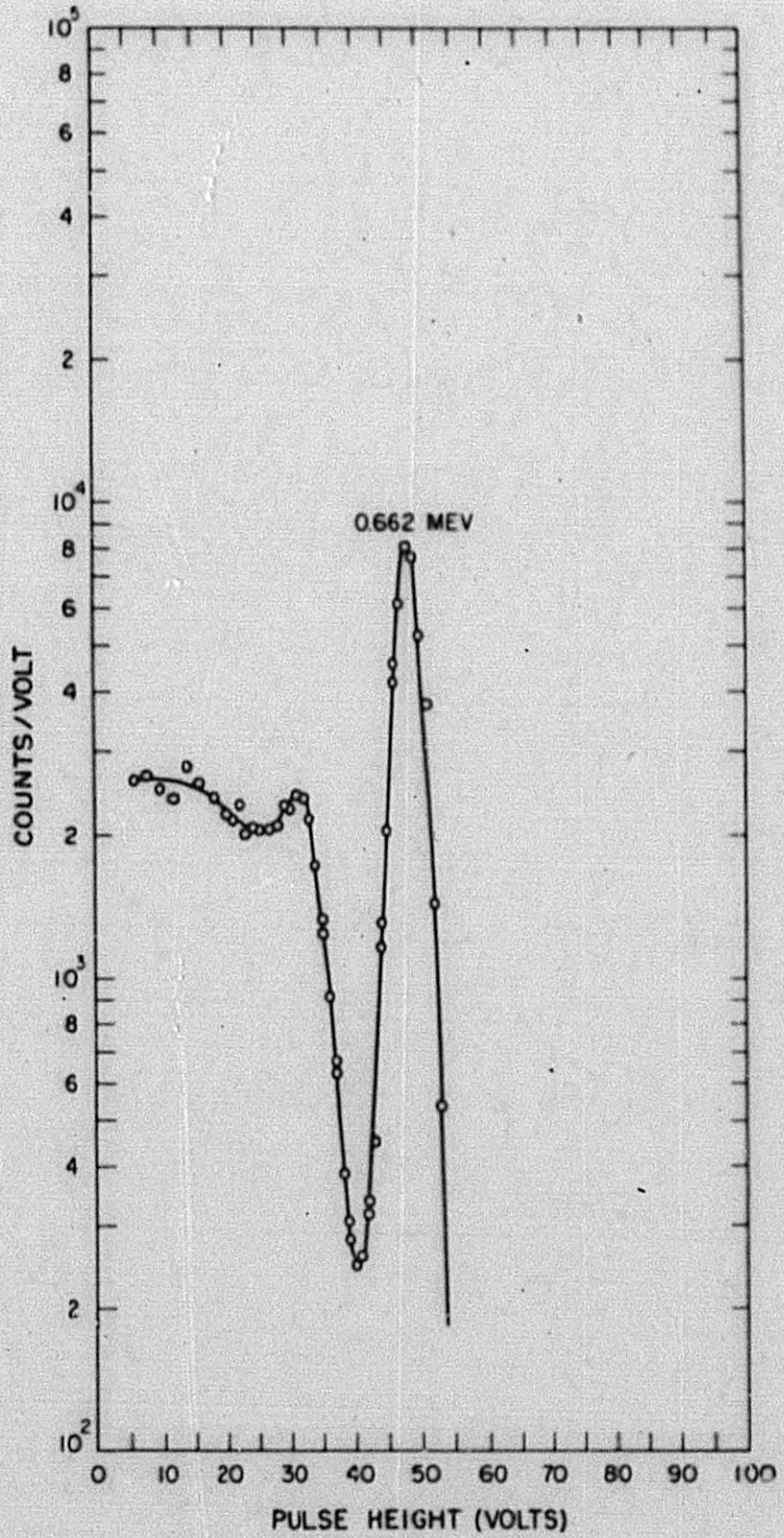

Fig. 5 Typical pulse-height spectrum resulting from Cs^{137} gamma rays on a single NaI(Tl) side crystal. Peak-to-valley ratio: 33. Percent resolution: 10.

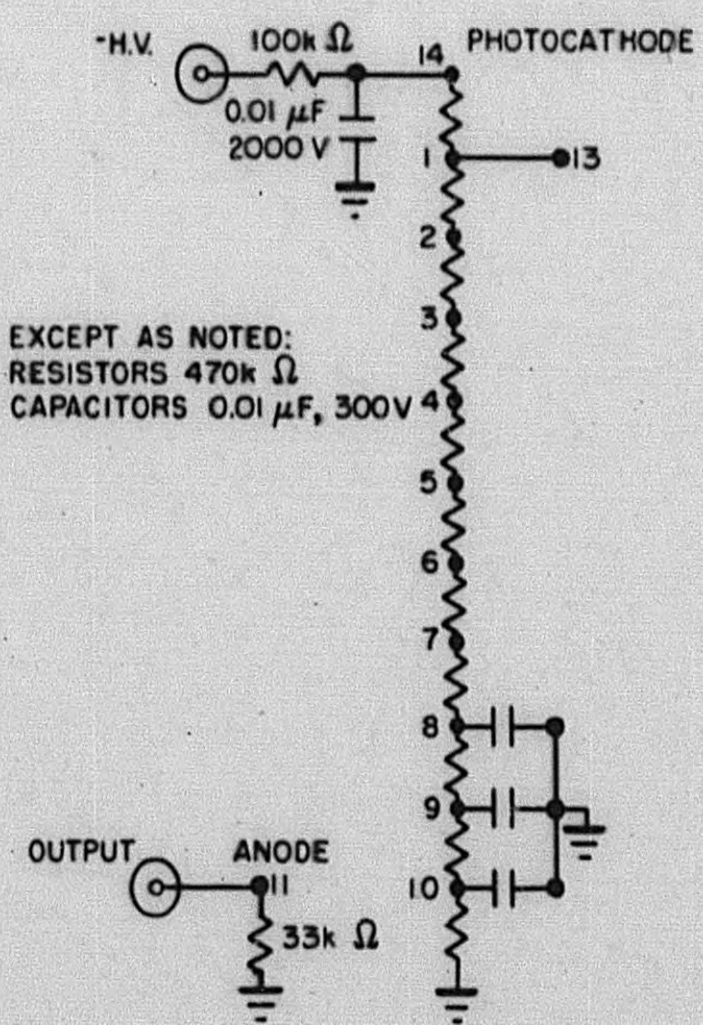

Fig. 6 Schematic diagram of the base used with the RCA 6342 photomultiplier tubes. Photocathode was maintained at high negative voltage with respect to ground.

crystals. With a particular RCA 6342 photomultiplier tube which had been tested previously, eight crystals were bench-tested. In a bench stand, a crystal was mounted on the photomultiplier tube using Dow Corning 200 fluid, one million centistokes, as an optical coupling medium between the tube and the crystal. Black electrical tape was used in the bench test as a binding to insure light tightness. A Cs^{137} source was mounted 5.5 cm above the face of the crystal. The output from the photomultiplier tube, operated at −1000 volts, was fed into a 250-N pre-amplifier and thence to a 250-A amplifier, whose output in turn led into a ten-channel, self-gated, pulse-height analyzer. The relative gain of the Model 250 amplifier system was monitored by applying a 50.00-volt pulse from a 507 pulser through either a 100:1 or a 10:1 attenuator, depending on the gain, to the 250-N, and observing the threshold at which counts occurred on the pulse-height analyzer.

The results of these tests are shown in Table I.

TABLE I

COMPARISON OF NaI(Tl) CRYSTALS

Crystal*	Percent Resolution	Peak-to-valley Ratio	Photopeak Voltage (volts)	Counts
W337(6D6Q)	11	26	47	9.2×10^3
W336(6D6Q)	10.4	31	44	9.1×10^3
0919(6H4)	12.5	21	46	7.4×10^3
A820(X6L4)	10	33	48	8.2×10^3
Z498(8D8Q)	9	35	86	1.3×10^4
Z499(8D4Q)	11.3	15	82	6.7×10^3
Z500(8D4Q)	12.3	17	80	6.5×10^3
Z501(4D8Q)	16	21	68	2.7×10^3

*The first letter and three numerals are a Harshaw serial number; the numbers in parenthesis refer to the size of the crystals in 1/4 inches. Thus Z499(8D4Q) refers to a crystal whose serial number is Z499 and which is 8/4 inches in diameter and 4/4 inch long.

The 2-inch-diameter by 2-inch-long crystal was chosen to test the relative performances of the eleven RCA 6342 tubes. The source geometry and electronic setup were unchanged. The results of these measurements are shown in Table II.

A check of the variation of percent resolution and the peak-to-valley ratio as functions of the high voltage applied to the photomultiplier tube and the gain of the 250 system was made with the same arrangement as above, using the RCA 6342 tube I and the 2-inch-diameter by 2-inch-long crystal with the Cs^{137} source. The results are shown in Table III.

Since there was some indication that the resolution improved with an increase in the voltage applied to the photomultiplier tube, it was decided to use 1400 volts. This was the voltage which gave the maximum tube amplification which could usually be accommodated with the 250 system without placing the photopeak voltage so high that the output of the 250-A was non-linear. In another series of tests, no appreciable variation of the resolution was noted with changes of gain.

When different sources were used, the resolution of the characteristic gamma rays was found to be described fairly well by the usual relation that the percent resolution is inversely proportional to the square root of the gamma-ray energy.

It is desirable to have the photocathode at the same potential as the crystal in order to reduce the photomultiplier tube noise. To insulate the crystal from ground and maintain the photocathode potential above ground would run the undesirable risk of developing surface charges on the crystal. Thus it was decided to ground the mounted crystals and maintain the photocathode at ground potential by applying a positive high voltage to the anodes of the photomultiplier tubes. Bases which were suitable for this purpose were constructed and tested (see Fig. 7). They showed no appreciable difference in the spectra obtained.

TABLE II

COMPARISON OF RCA 6342 PHOTOMULTIPLIER TUBES

Tube	Percent Resolution	Peak-to-valley Ratio	Counts	Relative Gain	Photopeak Voltage (volts) Actual	Corrected for Gain
I	9	35	1.3×10^4	2.12	86	41
II	10.7	27	1.7×10^4	1.00	56	56
296	9.4	32	1.5×10^4	1.00	70	70
326	10.1	31	2.2×10^4	1.00	64	64
334	11.5	26	2.2×10^4	1.00	40	40
414	11.5	26	2.3×10^4	2.13	38	19
575	10.5	27	1.4×10^4	1.00	39	39
724	10.3	30	1.3×10^4	0.66	70	106
620	10	30	1.5×10^4	1.84	75	41
769	10	30	1.5×10^4	2.14	64	30
890	10.9	29	1.3×10^4	1.67	70	42

TABLE III

DEPENDENCE OF RESOLUTION AND PEAK-TO-VALLEY RATIO
ON PHOTOMULTIPLIER TUBE HIGH VOLTAGE
[RCA 6342 Tube I with Z498(8D8Q) Crystal]

Tube Voltage (volts)	Relative Gain	Percent Resolution	Peak-to-valley Ratio	Photopeak		
				Counts	Actual Voltage (volts)	Scaled Voltage* (volts)
900	9.1	9.4	33	1.4×10^4	77	8.5
1000	5.7	9.2	37	1.3×10^4	83	14.5
1100	2.44	9.1	39	1.4×10^4	81	$33._2$
1200	1.00	8.0	37	1.4×10^4	81	81
1300	0.49	7.9	43	1.5×10^4	81	16_5
1400	0.26	7.7	40	1.5×10^4	81	31_5

*Scaled voltage refers to the voltage of the photopeak adjusted to a standard 250 amplifier gain.

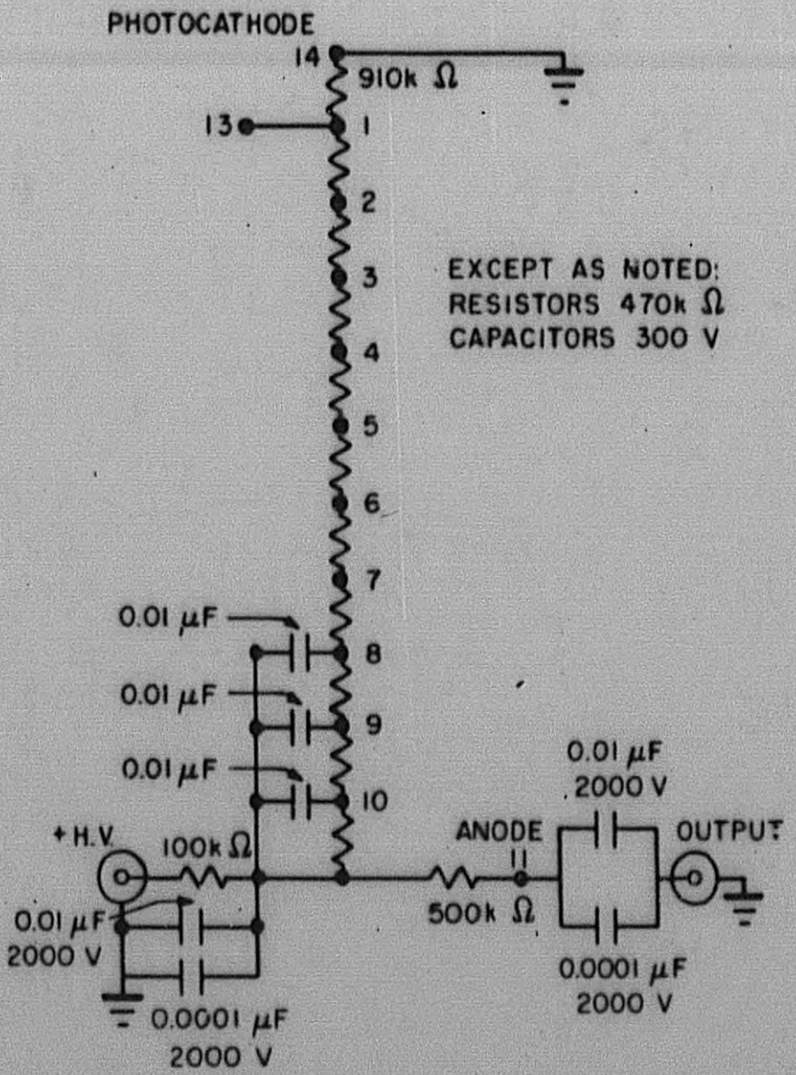

Fig. 7 Schematic diagram of the base used with the RCA 6342 photomultiplier tubes in which the photocathode is grounded. This base requires a high voltage supply in which the negative terminal is grounded.

C. Assembly

The tubes and crystals which were chosen for use in the coincidence spectrometer were mounted in aluminum cans as shown in Figs. 8a and 8b. Dow Corning 200 fluid, one million centistokes, was used as the optical coupling medium. A bead of vacuum putty was placed at the outer edge of the crystal-DC 200-tube junction in order to retain the fluid when the tube was tilted. An aluminum ring was fastened to each tube base with Armstrong adhesive. Aluminum adapter rings were used over an O-ring on the crystal. The aluminum can was fitted over this assembly and was secured on bayonet pins in the aluminum ring on the base of the tube. Vacuum putty was placed over the joints at the top and the bottom of the assembly to insure light tightness.

A slightly different photomultiplier tube base was used on the center crystal to accommodate a future modification. The chief difference between this base and those used with the side crystals was that the output signal from the tube was taken from the tenth dynode rather than from the anode.

A block diagram of the electronic apparatus used during alignment is shown in Fig. 9. The negative outputs from the side photomultiplier tubes were fed in parallel through 250-N pre-amplifier into a 250-A amplifier. The positive pulse from the center tube was fed into a 250-P pre-amplifier; the output from this into another 250-A amplifier. The output from either of these 250-A's could be sent into the ten-channel analyzer. A single positive high voltage supply was used to provide the high voltage for all the tubes. The gains of the side tubes were made adjustable by placing a variable resistor in series with the high voltage lead to each base. Equalization of the gains of the tubes was achieved roughly by comparing on an oscilloscope the outputs of the individual tubes with a Cs^{137} source. The tube voltages were adjusted so that the photopeak traces all fell at approximately the same level.

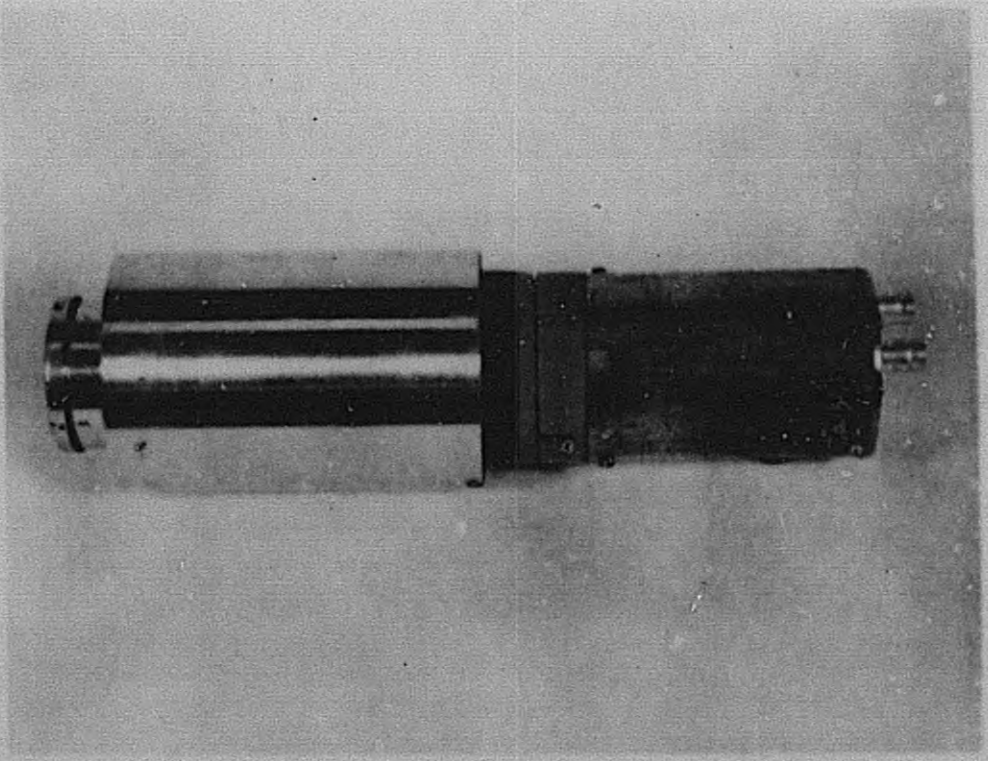

Fig. 8a View of assembled photomultiplier tube and crystal.

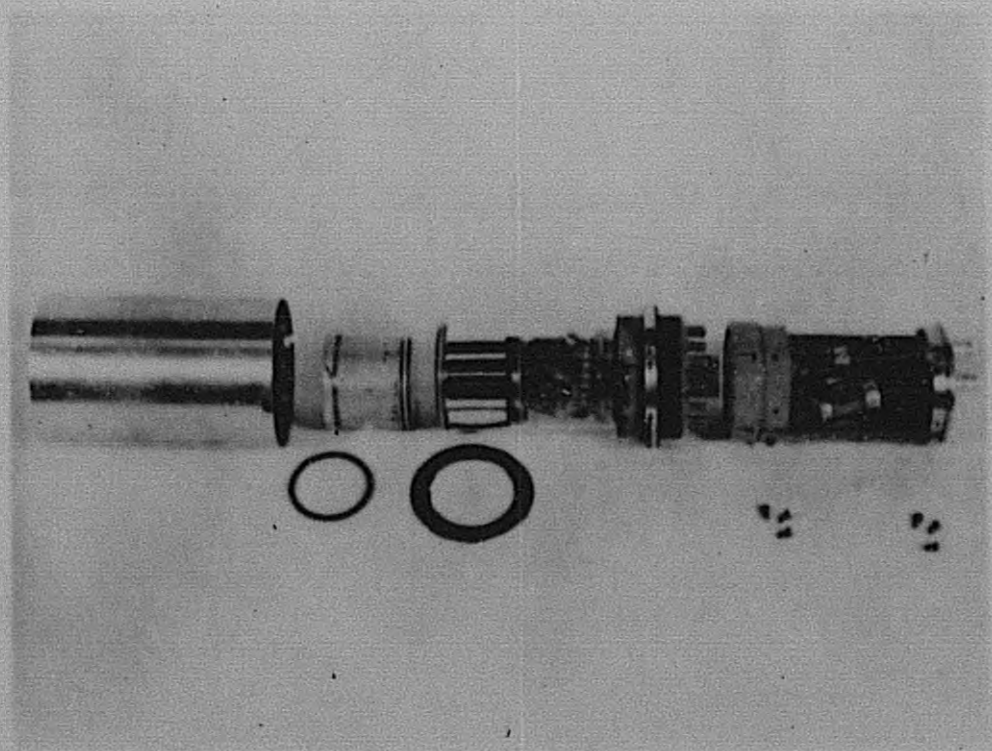

Fig. 8b Exploded view of photomultiplier tube and crystal.

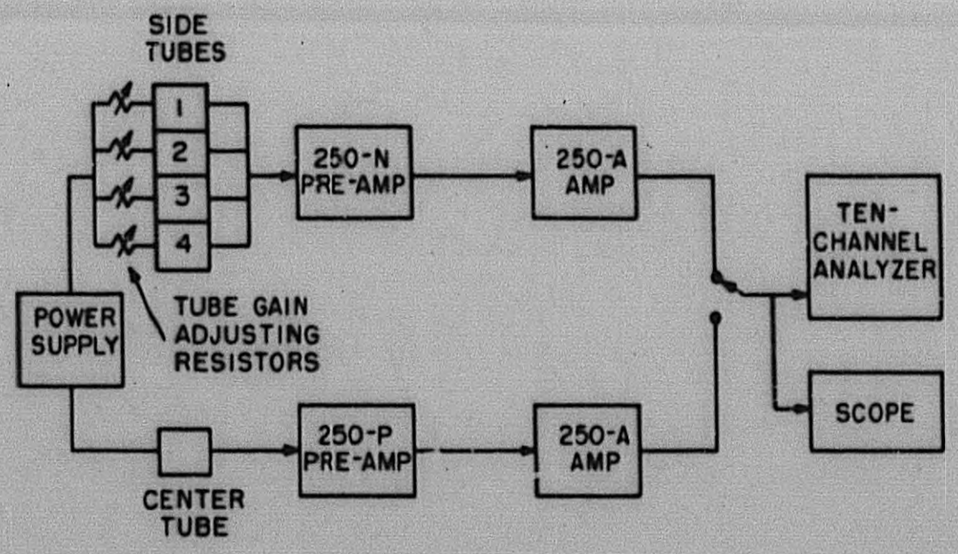

Fig. 9 Block diagram of the electronic set-up for initial alignment as a Compton spectrometer.

The ten-channel analyzer with 1-volt channel widths was then used to observe the photopeak pulse height for a final adjustment of the photomultiplier tube gain. The individual photopeak pulse heights could thus be aligned to within about one volt. This adjustment was found to be stable over a period of several days if the high voltage setting was not changed. However, a change in the setting of the high voltage supply necessitated a change in the alignment resistors. This was probably due to a variation in the gain of the individual tubes at different high voltages.

Several spectra were taken using Cs^{137}, Hg^{203}, and Am^{241} sources. It can be seen by comparison of Figs. 5 and 10 that the percent resolution of the spectra taken with the four side tubes properly aligned was comparable to that of the individual tubes.

The Hg^{203} source was deposited on the outside of a thin tube which could be mounted coaxially with the collimating hole in the lead shield. This cylindrical source was mounted in place of the center crystal so as to simulate the Compton-scattered gamma rays from the center crystal.

The Am^{241} source was mounted near the crystals (not in the same manner as the Hg^{203} coaxial source, although other factors such as gain and counting time are the same). The spectrum was taken purely for calibration.

Figure 11 shows spectra taken with all side crystals in parallel using the Hg^{203} and the Am^{241} sources. The 0.279-Mev line and the 0.060-Mev line which are indicated are the respective characteristic gamma rays of these two sources. The wide peak at about 0.142 Mev is due to the unresolved peaks from the Compton electron and the Compton back-scattering, the Compton scattering taking place inside the side crystals. The energies of these unresolved peaks are very nearly the same. The peak at 0.073 Mev is believed due to three unresolved x-ray lines which are emitted by the Hg^{203}

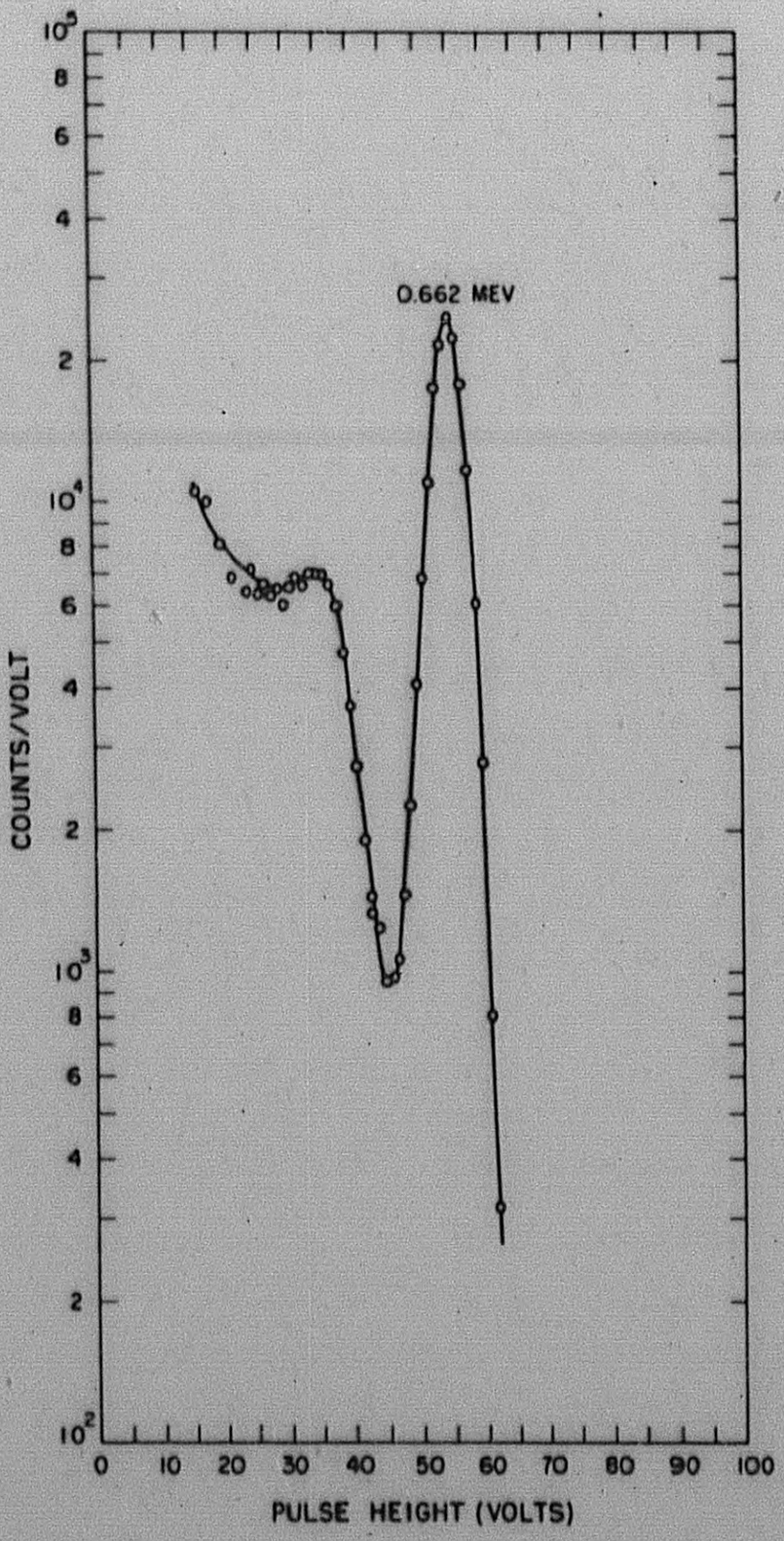

Fig. 10 Pulse-height spectrum of Cs^{137} gamma rays on four paralleled side crystals. Peak-to-valley ratio: 26. Percent resolution: 10.4.

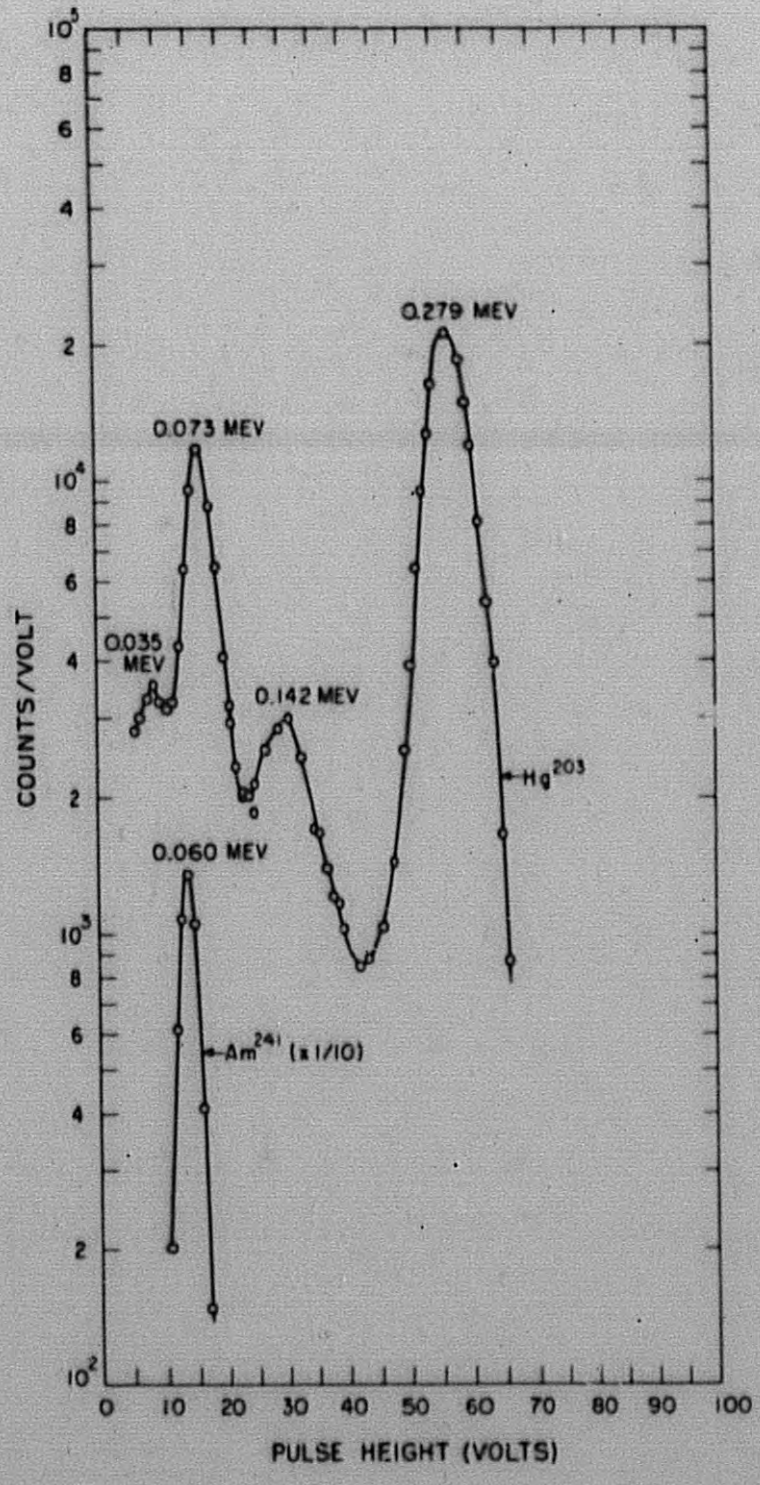

Fig. 11 Pulse-height spectra of Hg^{203} and Am^{241} on four paralleled side crystals. For Hg^{203} 0.279-Mev line: Peak-to-valley ratio: 26. Percent resolution: $13._1$. For Am^{241} 0.060-Mev line: Peak-to-valley ratio: 16. Percent resolution: $25._7$.

isotope. These values for the energies of the various peaks were obtained by interpolation using the formula

$$E = [(5.09 \times 10^{-3}/\text{volt})P - 0.011] \text{ Mev}$$

in which E is the energy of the peak and P is the pulse height of the peak. This straight line was based on the characteristic lines of the two sources.

Figure 12 shows a spectrum taken using a Cs^{137} source whose gamma rays were allowed both to shine directly on the side crystals and to be Compton-scattered from the center crystal onto the side crystals. The radiation shining on the side crystals directly was partially shielded by mounting the source inside the collimating hole but near the side crystals so that the counts from the two origins would be of roughly the same order. The peak marked "0.662 Mev" is the characteristic line of the source. The peak marked "0.433 Mev" is due to Compton electrons within the side crystals. The peak marked "0.228 Mev" is due to the back-scattered gamma rays both from within the side crystals and from the center crystal. The peak marked "0.096 Mev" is believed to be due to the Compton electrons arising from scattering of the 0.228-Mev gamma rays in the side crystals. The estimation of the energies of the various peaks was based on the characteristic Cs^{137} line and assumed that the energy intercept of the E vs. P line was zero.

III. INITIAL OPERATION AS A COMPTON SPECTROMETER

Coincidence components were added to the electronic arrangement so that the output from the four side crystals in parallel, when in coincidence with the output of the center crystal, would gate the ten-channel analyzer. Figure 13 shows in a block diagram the electronic arrangement.

The analyzer was fed with the amplified output of the center crystal.

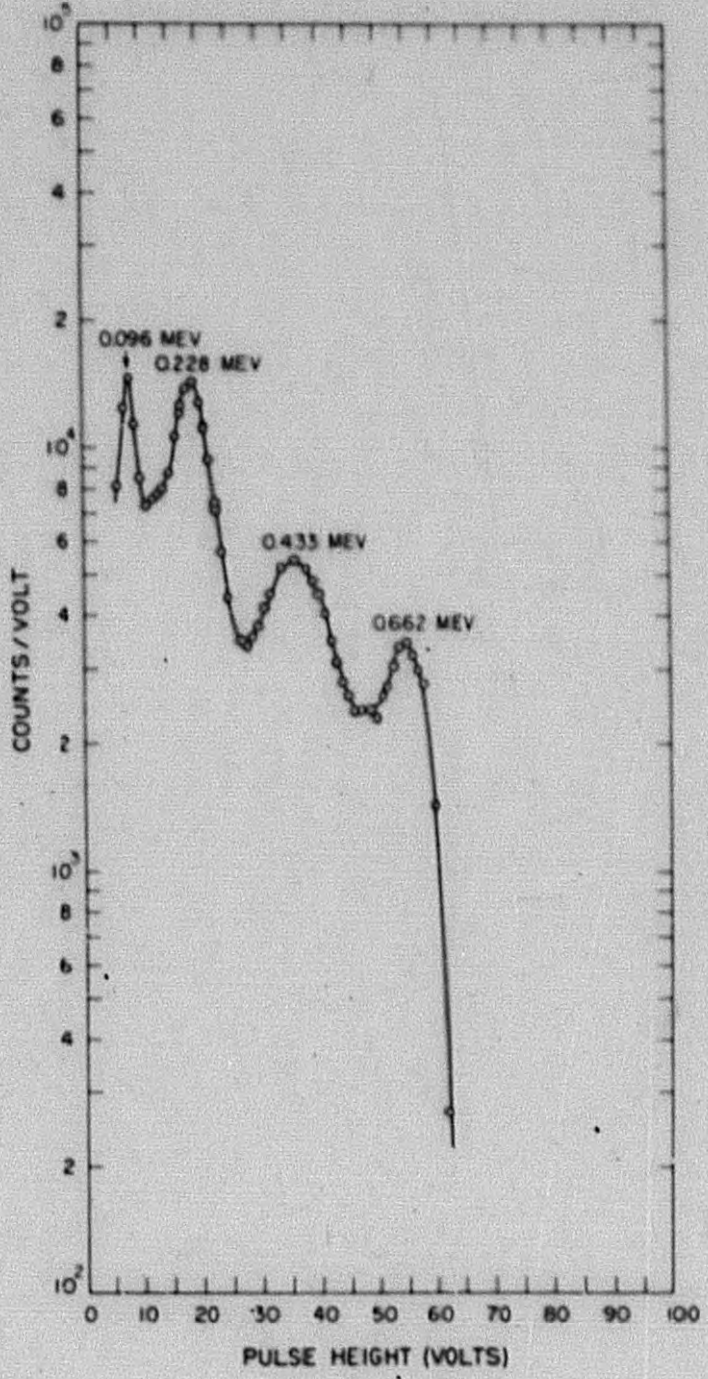

Fig. 12 Pulse-height spectrum of Cs^{137} on the four paralleled side crystals. Peaks are due to 0.662-Mev gamma rays directly on the side crystals and to those which are Compton-scattered from the center crystal.

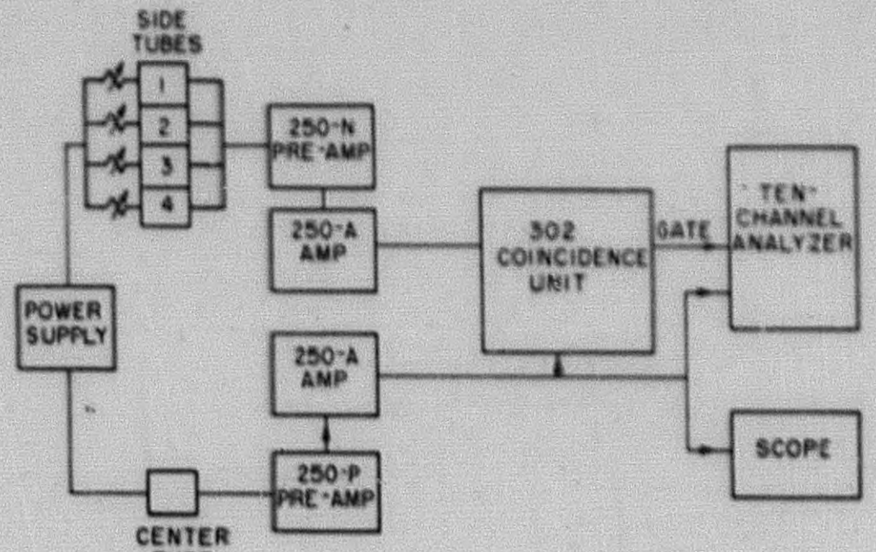

Fig. 13 Block diagram of the electronic set-up for operation as a Compton coincidence spectrometer.

About three hundred feet of RG/71 cable was required to delay this signal. The delay controls on the 302 coincidence unit were varied to maximize the coincidence gates to the analyzer and to an oscilloscope. The pulse-height gates for the center crystal were set with the upper limit slightly below the lines from a Co^{60} source and with the lower limit at the level of the 60-kev line from the Am^{241} source. For the side crystals, the upper limit was set at the level of the characteristic line from the Hg^{203} source (0.279 Mev), and the lower limit was set at the level of the Am^{241} line. Thus pulses in the center crystal from about 0.06 to 1 Mev were detected, and pulses from the side crystals from about 0.06 to 0.28 Mev were detected.

Spectra were taken using Co^{60} and Cs^{137} sources. Energy calibration was obtained by taking spectra with the center crystal alone. Figure 14 shows such a calibration spectrum and an associated coincidence spectrum using a Cs^{137} source. A slight difference in pulse height of the coincidence photopeak from the pulse height of the Compton electron peak can be noted. This may be due to a small fluctuation in the power supply voltage. The coincidence requirement is seen to reduce the number of counts in this peak by a factor of about five. The low-energy tail has been noticed by other investigators,[1] and it is suggested by them that it may be due to multiple scattering. Figures 15 and 16 show similar curves taken with a Co^{60} source. The poorer figure obtained for the percent resolution from the coincidence spectra can be attributed in part to the lower energy. Furthermore, the finite solid angle causes a spread in the range of Compton electron energies and hence reduces the resolution.

Several variations in the geometry were tried. A 1-inch-diameter lead tube, whose inner diameter was 1/2 inch, was inserted in the 1-inch hole in the lead shield. It was found that the main effect of this improved collimation was to reduce the counting rate. No improvement in the spectra was

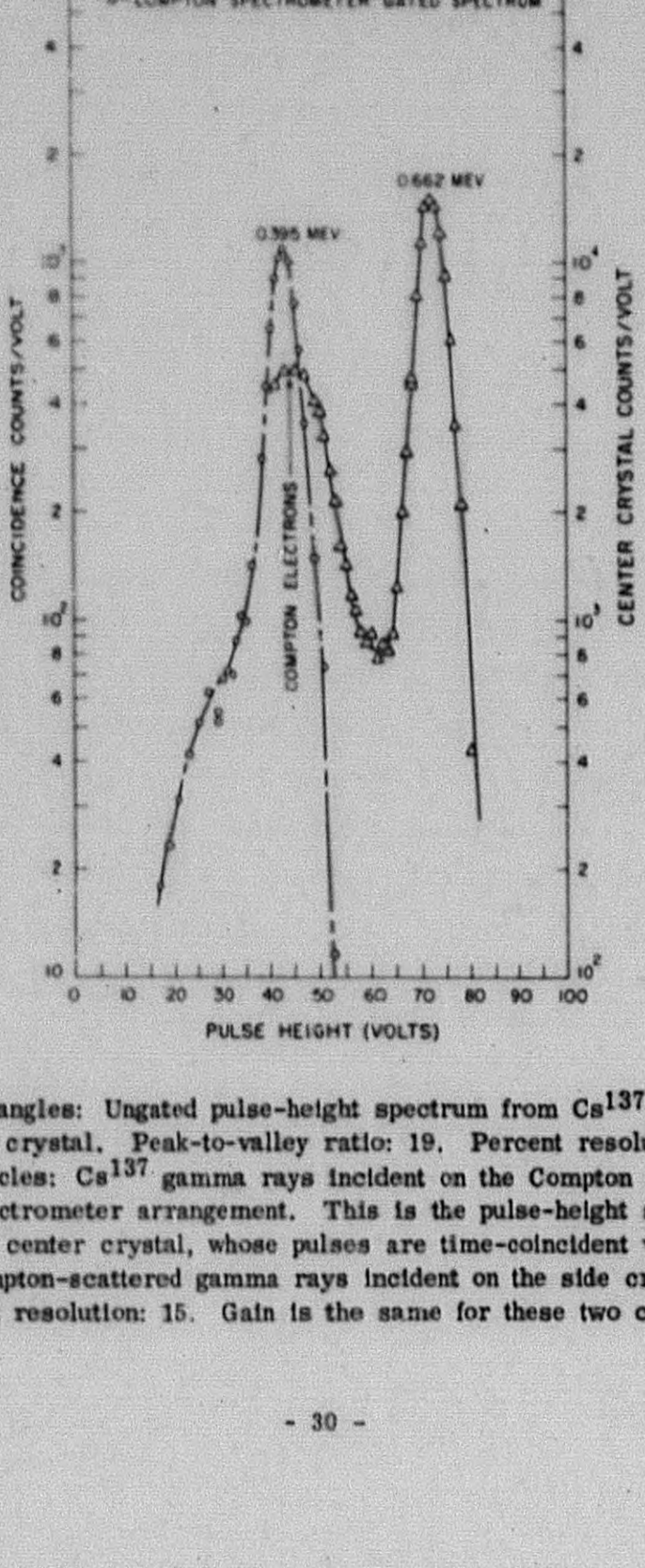

Fig. 14 Triangles: Ungated pulse-height spectrum from Cs^{137} on the center crystal. Peak-to-valley ratio: 19. Percent resolution: 8.5. Circles: Cs^{137} gamma rays incident on the Compton scintillation spectrometer arrangement. This is the pulse-height spectrum in the center crystal, whose pulses are time-coincident with the Compton-scattered gamma rays incident on the side crystals. Percent resolution: 15. Gain is the same for these two curves.

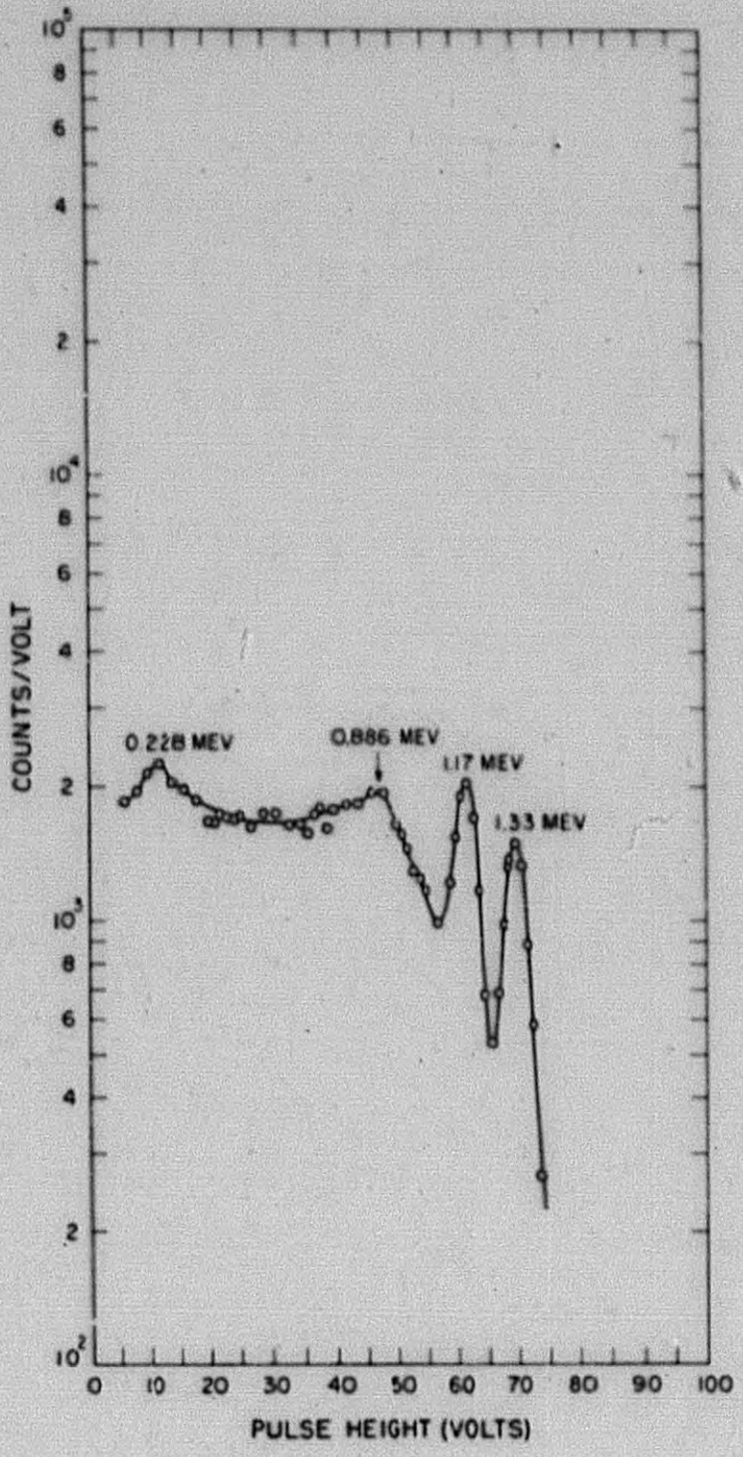

Fig. 15 Pulse-height spectrum of Co^{60} on the center crystal. For 1.33-Mev peak the peak-to-valley ratio is 2.9. Percent resolution: 7.4.

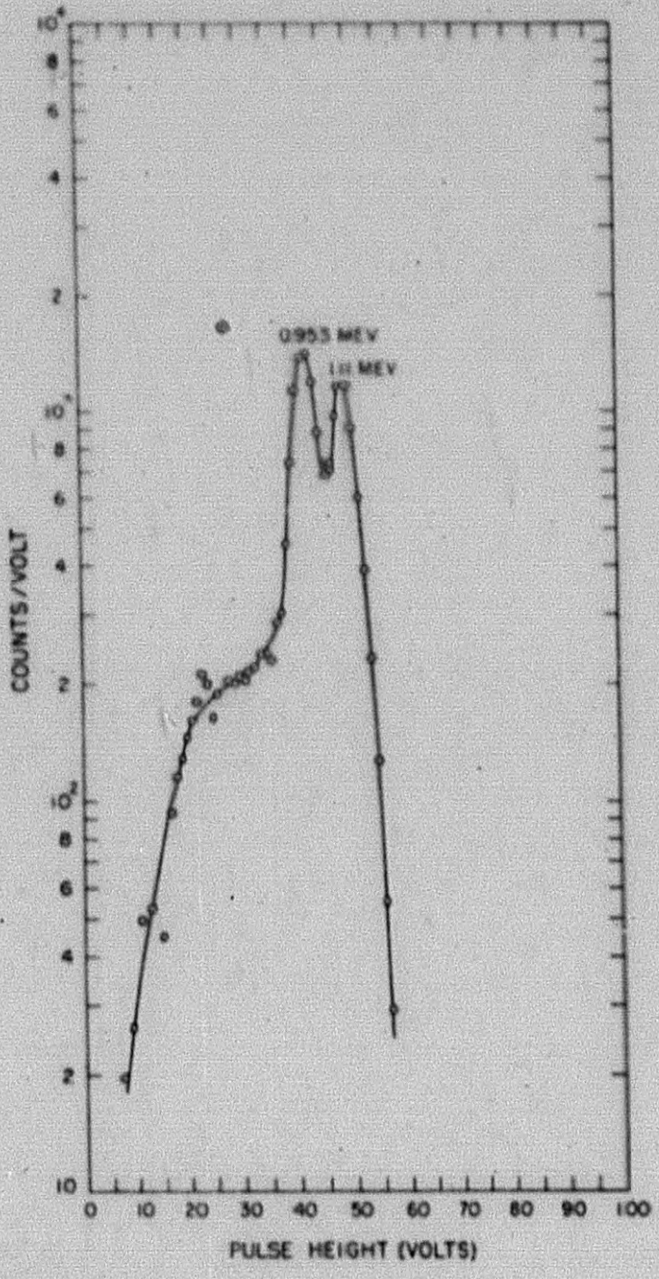

Fig. 16 Co^{60} gamma rays incident on the Compton scintillation spectrometer arrangement. This is the pulse-height spectrum in the center crystal, gated with the Compton-scattered gamma rays in the side crystals which are in time-coincidence with the pulses in the center crystal. Peak-to-valley ratio: 1.7.

noted. In order to reduce possible counts in the center crystal due to Compton electrons which might be forward-scattered from the lead shield, a 1/16-inch aluminum plate was placed immediately before the center crystal in the path of the gamma ray from the source. It was found that the peak-to-valley ratio in the coincidence spectrum from the Co^{60} source was slightly improved. Moving the side and center crystals as close together as possible improved the counting rates considerably, due to the increase in the solid angle subtended by the side crystals.

Another significant improvement in the spectra was noted when additional shielding was provided for the side crystals. This additional shielding was, in fact, mandatory when the Co^{60} source was used. A total of about six inches of lead between the source and the side crystals was eventually used.

The energy of the Compton electron and the energy of the back-scattered gamma ray are given by the expressions

$$E_c = \frac{E_\gamma}{1 + \frac{mc^2}{E_\gamma(1 - \cos\theta)}}$$

and

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{mc^2}(1 - \cos\theta)}$$

where E_c is the energy of the Compton electron, E_γ is the energy of the incident gamma ray, $E_{\gamma'}$ is the energy of the back-scattered gamma ray, θ is the angle through which the gamma ray is scattered, and mc^2 is the rest mass of the electron, 0.511 Mev. Although a precise angle of scattering cannot be determined because of the finite volumes of the scatterer and

the detector, an upper limit to the energy of the Compton electron, sometimes called the Compton edge, can be obtained by setting θ equal to 180 degrees. Similarly, a lower limit to the energy of the back-scattered gamma ray can be obtained. This limit is then a rough, but definitely not a precise, estimate of the energy represented by the back-scatter photopeak.

The detection efficiency was not measured.

IV. INITIAL OPERATION AS A PAIR SPECTROMETER

For operation as a pair spectrometer, electronic components were arranged as shown in the block diagram of Fig. 17 so that pulses in the center crystal, when coincident with simultaneous gamma rays of energy 0.511 Mev in the opposite side crystals, would gate the ten-channel analyzer. The latter was fed by pulses from the center crystal which had been amplified in a Model 250 amplifier system. The pulse-height gates for the center crystal were set at 2 volts for the lower limit and for no upper limitation. The pulse-height gates for the side crystals were set to pass pulses from detection of the 0.511 Mev gamma rays from a Na^{22} source. The delays in the coincidence circuits were adjusted, using a Na^{22} source, so as to maximize first the number of coincidence counts from the side crystals, and then the number of triple coincidences from the center and two side crystals. Side crystals 2 and 4 (Fig. 3) were used. The Na^{22} source was placed on the end of a rod so that it could be mounted coaxially with the collimating hole in the lead shield. It was found that the triple coincidence counting rate was only a few hundred counts per minute.

A Na^{24} source was prepared by neutron bombardment in the Water Boiler reactor at Los Alamos. This source was mounted coaxially in the collimating hole in the lead shield and the spectrum of Fig. 18 was taken. The length of the counting time shown varied from 1.5 hours at the

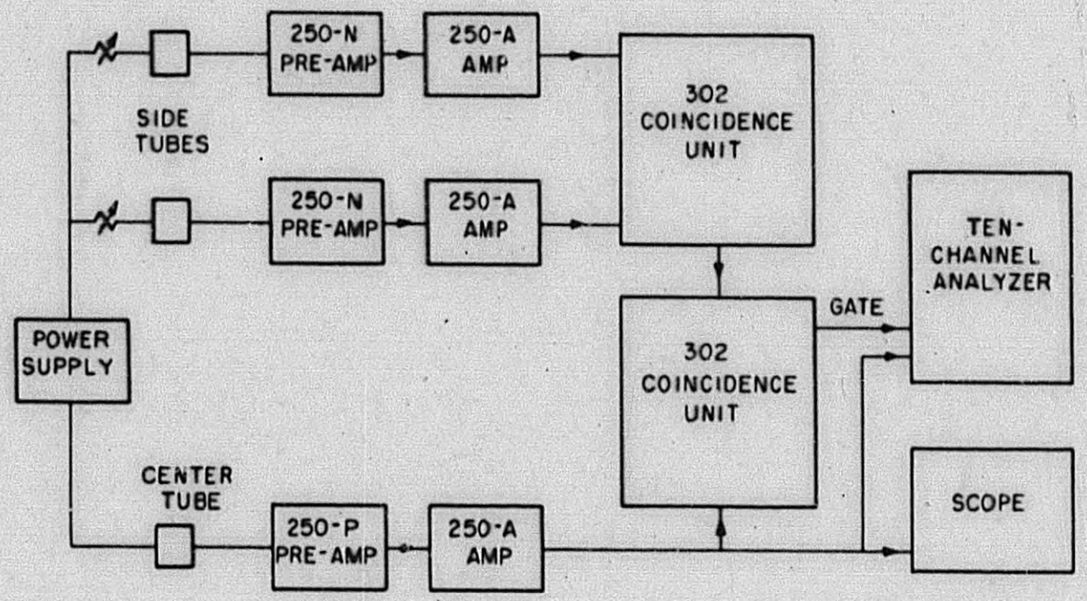

Fig. 17 Block diagram of the electronic set-up for the pair coincidence spectrometer.

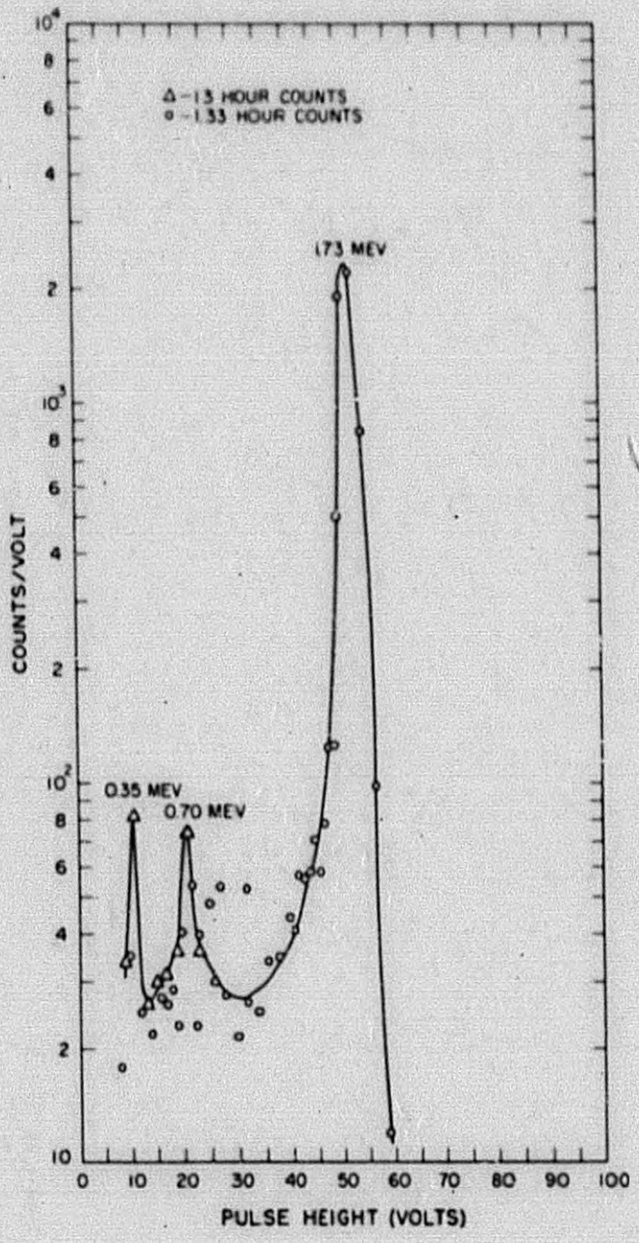

Fig. 18 Na^{24} gamma rays incident on the pair scintillation coincidence spectrometer. This is the pulse-height spectrum in the center crystal, gated with the coincident and oppositely directed 0.511-Mev gamma rays in the side crystals which are in time-coincidence with the pulses in the center crystal. For the 1.73-Mev peak the percent resolution is 6.8.

higher-pulse-height end of the curve to 13 hours at the lower-pulse-height end of the curve. The half-life of Na^{24}, which beta-decays to Mg^{24}, is given as 15.0 hours. Accordingly, corrections were made for the decay of the source in the data plotted. The peak marked "1.73 Mev" is due to the 2.75-Mev gamma ray[3] from Mg^{24}. The 1.02 Mev required for pair production is, of course, not recorded in the center crystal. The 0.35-Mev peak is due to the 1.37-Mev gamma ray from Mg^{24}. The peak at 0.70 Mev has not been identified. The total background observed was on the order of two counts per hour.

The counting efficiency of this pair spectrometer arrangement has not been measured.

V. FUTURE PLANS

It is planed in the future to add further coincidence components so that tubes 1 and 3 can also be used in the pair spectrometer. Faster coincidence circuits are planned for both modes of operation with parallel, comparatively slow electronic channels for pulse-height gating. The efficiencies of the Compton mode and the pair mode will be measured.

The efficiency of the side crystal pair coincidence detection will be measured as a function of crystal geometric arrangement by coincidence experiments.[2] A Na^{22} source is used in a geometry similar to that of Fig. 1. Na^{22} decays 90% of the time by positron emission, while 10% of the decays are by electron capture. These decays are followed by a 1.28-Mev gamma ray in Ne^{22}. The source is placed between the two side crystals; by pulse-height gating, only the 1.28-Mev gamma rays are counted in the center crystal. If N_{cr} are the counts in the center crystal due to 1.28-Mev gamma rays, S is the source strength, Ω_{cr} is the solid angle subtended at the center crystal, and e_{cr} is the counting efficiency of the 1.28-Mev gamma rays in

the center crystal, we have the relation

$$N_{cr} = S\,\Omega_{cr}\,e_{cr}$$

Events are also counted in which the oppositely directed 0.511-Mev gamma rays from the annihilation of the positron emitted by Na^{22} are in time-coincidence in opposite side crystals and are also in time-coincidence with the observation of the 1.28-Mev gamma rays in the center crystal. In this source the ratio of 1.28-Mev gamma rays to annihilation gamma rays is 1.11. If N_{tc} denotes the number of these triple coincidence events and if $p_{0.511}$ is the probability of coincident detection of the opposite 0.511-Mev gamma rays in opposite side crystals

$$N_{tc} = \frac{S\,\Omega_{cr}\,e_{cr}\,p_{0.511}}{1.11}$$

Then we have

$$p_{0.511} = 1.11\,\frac{N_{tc}}{N_{cr}}$$

Note that $p_{0.511}$ includes the factors for the coincidence counting efficiency of the side crystal pair and the solid angle subtended by the side crystal pair. This index, $p_{0.511}$, measured for various geometries, will be useful in optimizing the geometry of the pair spectrometer.

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3. P. M. Endt and C. M. Braams, Revs. Modern Phys. 29, 683 (1957).