THE DEVELOPMENT AND APPLICATION OF A NEUTRON SCINTILLATION SPECTROMETER

A Thesis
submitted in partial fulfilment of
the requirements for the degree of
Master of Science
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by
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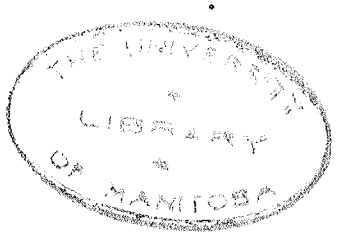
April, 1954.



A B S T R A C T.

"The Development and Application of the Neutron Scintillation Spectrometer."

C. P. Mitney

A neutron scintillation spectrometer using a Li I(Eu) crystal is described and is used to study the fast neutron spectrum of a Po-Be neutron source. In the spectrum so obtained features are identified at neutron energies of 3.60, 4.60, 5.55 and possibly at 7.1 Mev. During the course of the work observations with Cs I(Tl) crystals suggested that more attention should be given to this phosphor for gamma-ray spectroscopy.

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INTRODUCTION

Much work has been done at the University of Manitoba using a gamma-ray scintillation spectrometer[3,4,5,6] to study the gamma-ray spectra of radioactive substances. In most of this work a NaI(Tl) crystal has been used as the scintillation phosphor, but considerable work has also been done with liquid scintillators[6]. NaI(Tl) does not respond directly to neutrons but another crystal was recently obtained that does detect neutrons. This was LiI(Eu) which can detect and measure the energies of neutrons due to the reaction between neutrons and the lithium isotope of mass number 6

$$ {}_3Li^6 + {}_0n^1 \longrightarrow {}_2He^4 + {}_1H^3 + Q. $$

Q is the energy released in this reaction and it is found to have a value of 4.785 Mev.[1] The energy available for producing scintillations within the crystal is equal to the sum of this Q energy and the energy of the neutron.

It was proposed then to set up a neutron scintillation spectrometer using LiI(Eu) as the scintillation phosphor. This spectrometer was then to be used to study the energy spectrum of the fast neutrons from a Po - Be source. Since the decay constant for the light pulse in LiI(Eu) is several times longer than the 0.25 microsecond[28] constant for NaI(Tl), it became evident at the outset that certain modifications had to be made in the electronic circuitry which had been used at that time in the gamma-ray scintillation spectrometer. These modifications were carried out and a study of

a Po - Be neutron source was made.

A study was also made of a CsI and a CsI(Tl) crystal, each of which had been obtained after the modifications of the electronic circuitry had been made. They were initially compared with NaI(Tl). Then their operation at low temperatures (down to liquid nitrogen temperature) was studied. A comparison of the gamma-ray spectra of Cs^{137}, Zn^{65} and Ir^{192} as found with NaI(Tl) and with CsI(Tl) was made in an attempt to find out whether the ratio of the number of pulses thrown into the photoelectric peak to the number in the Compton peak was higher for CsI(Tl) than for NaI(Tl).

A brief study was made of a special-cathode photomultiplier tube to determine whether or not increasing the effective surface area of the cathode increased the pulse height for a given gamma-ray.

This thesis is divided into two parts, and these are:

A. The Electronic Development of the Neutron Scintillation Spectrometer.

B. The Application of the Neutron Scintillation Spectrometer to the Study of the Fast Neutron Spectrum of a Po - Be Neutron Source.

A. THE ELECTRONIC DEVELOPMENT OF THE NEUTRON SCINTILLATION SPECTROMETER.

A gamma-ray scintillation spectrometer measures gamma-ray energies by analyzing the scintillation pulses produced in a scintillating crystal or phosphor. (Discussions on the gamma-ray scintillation spectrometer and its applications may be found in a number of recent theses presented by physicists engaged in nuclear physics research at the University of Manitoba.[3,4,5,6]) A certain period of time is necessary for the majority of photons, caused by a gamma-ray, to be given out by a particular crystal. It is found that this period of time is several times longer for a LiI(Eu) crystal than for a NaI(Tl) crystal. Since the electronic equipment employed in this laboratory for a gamma-ray spectrometer was designed for use with NaI(Tl) crystals, it was found necessary to make certain modifications in the circuitry of certain parts of this electronic equipment in order to adapt it for use with a LiI(Eu) crystal. A suitable integrating circuit was introduced in the output stage of the photomultiplier tube in the cathode follower circuit, and the mixer stage of the differential discriminator was redesigned so that the discriminator could analyze pulses of relatively long rise time.

The modified cathode follower circuit was also used to study the characteristics of an unactivated cesium iodide crystal (CsI) and of a thallium activated cesium iodide crystal (CsI(Tl)). Results on the response of both crystals to gamma-radiation are given for operation at room

temperature and at liquid nitrogen temperature. A comparison of the gamma-ray spectra of Cs^{137}, Zn^{65}, Ir^{192} and Th as found with a CsI(Tl) crystal and a NaI(Tl) crystal is given.

This section will be subdivided into four parts, and these are:

1. Cathode Follower Modification.
2. A Differential Discriminator.
3. Experimental Results Obtained with a CsI(Tl) Crystal and a CsI Crystal.
4. A Short Report on the Characteristics of a Special-Cathode Photomultiplier Tube.

1. CATHODE FOLLOWER MODIFICATION

A standard cathode follower circuit[7] has been used in this laboratory in a gamma-ray scintillation spectrometer to provide a low output impedance device to pass the scintillation pulses from a photomultiplier tube to a linear amplifier. This cathode follower was intended for use with a NaI(Tl) crystal. In using this standard cathode follower circuit with a LiI(Eu) crystal, it was found that because of the fact that LiI(Eu) gives out less light over a longer period of time than does NaI(Tl), the output pulses from the cathode follower as displayed on a Cathode-ray oscilloscope were very ragged in shape in comparison with the smooth pulses obtained with NaI(Tl). The shapes of these pulses are shown in Fig. 3. Fig. 3(a) shows the pulses from NaI(Tl), and Fig. 3(b) shows the pulses from LiI(Eu). The decay constant for the light pulse in a NaI(Tl) crystal is about 0.25 microseconds.[28]

An oscillogram showing these pulses is given in Plate 1. The upper wave form is from NaI(Tl), the lower one is from LiI(Eu). The oscillogram was obtained by photographing the screen of the cathode ray tube of a Tektronix oscilloscope with an f/4.5 lens, Zeiss-Ikon camera using Ortho-X film. The cathode follower output pulses were fed from the linear amplifier (see the block diagram of Fig. 8) to the Y-deflection plates of the oscilloscope. The same sweep speed was used to obtain both pulses and so a direct comparison of rise times and durations of the two pulses is possible. The ragged form of the LiI pulses is not clearly evident due to the prolonged exposure time and the resultant smoothing-out effect. However, it is quite evident that the LiI pulses

VOLTAGE STABILIZATION POWER SUPPLY APK43

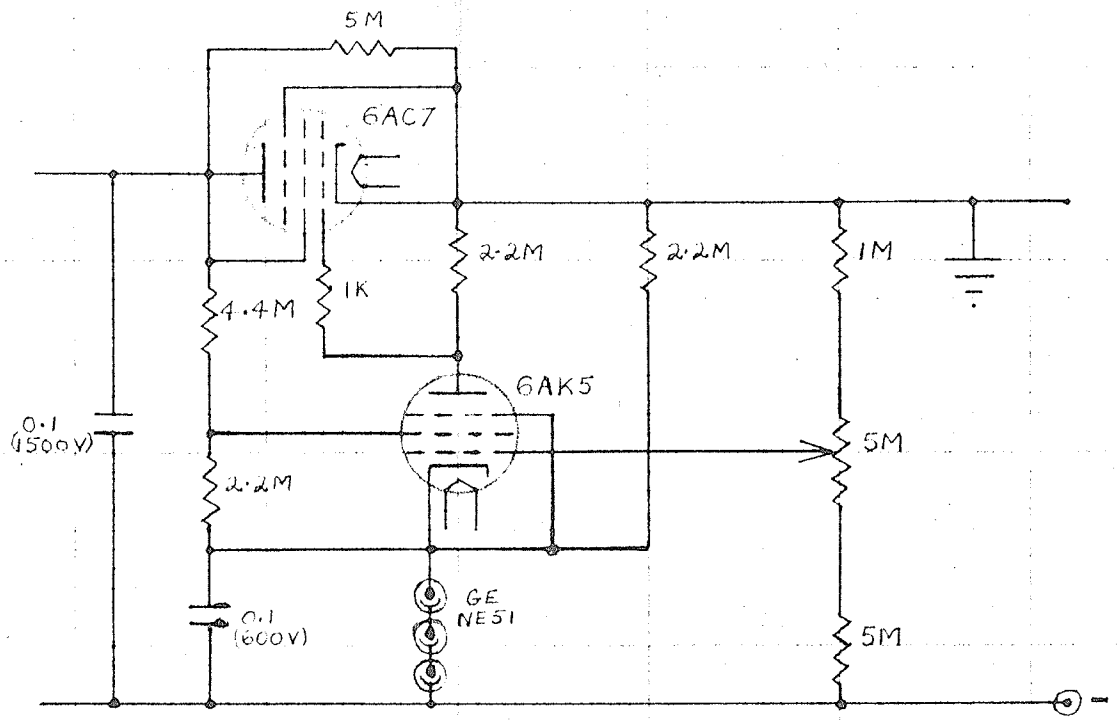


FIGURE 1

MODIFIED CATHODE FOLLOWER

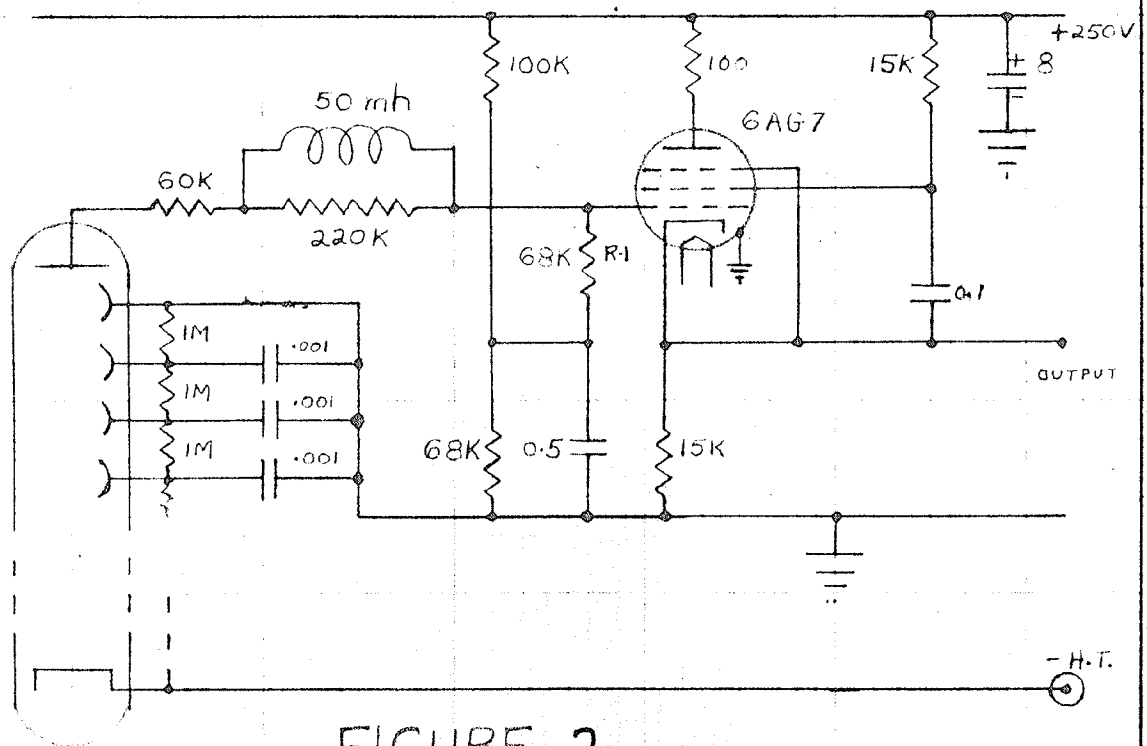


FIGURE 2

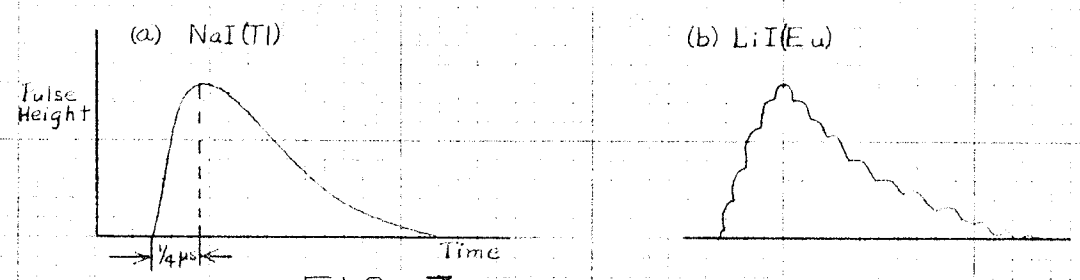
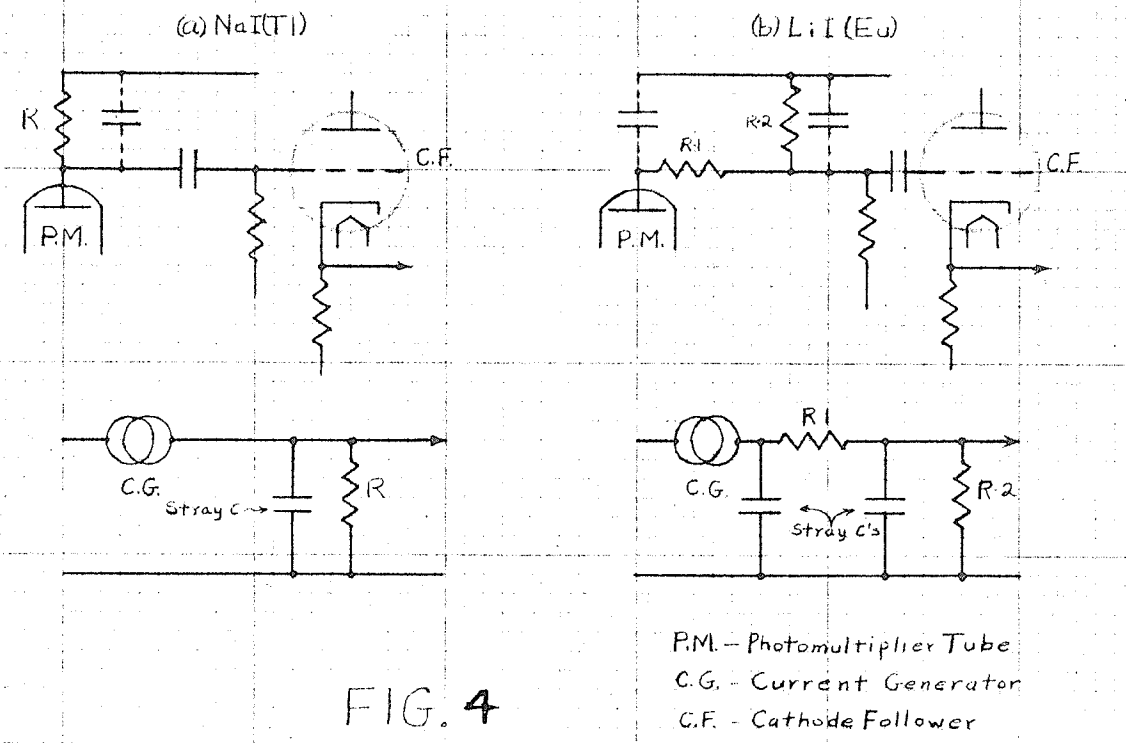


FIG. 3



P.M. – Photomultiplier Tube
C.G. - Current Generator
C.F. - Cathode Follower

FIG. 4

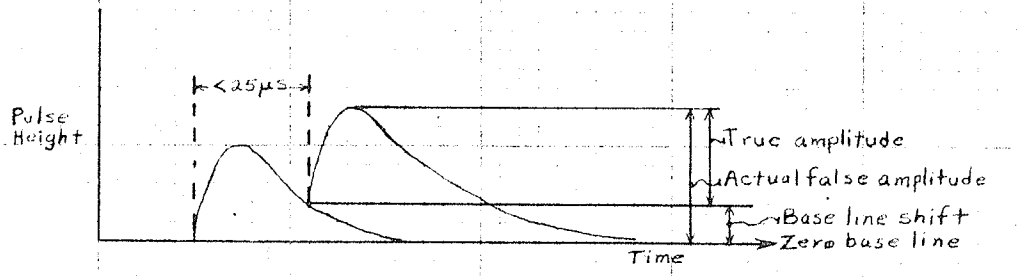


FIG. 5

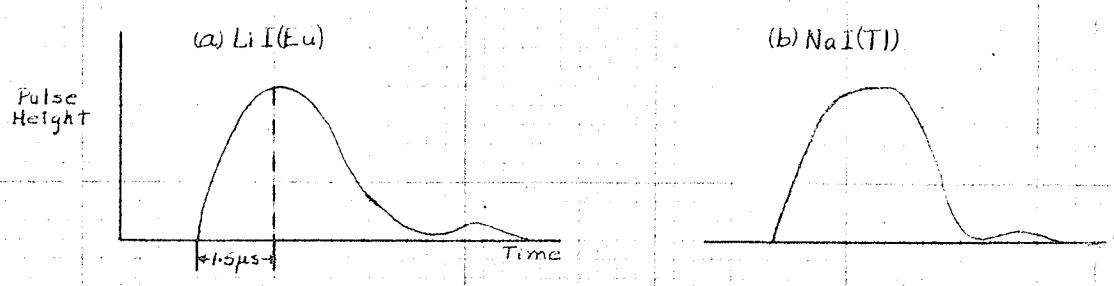


FIG. 6

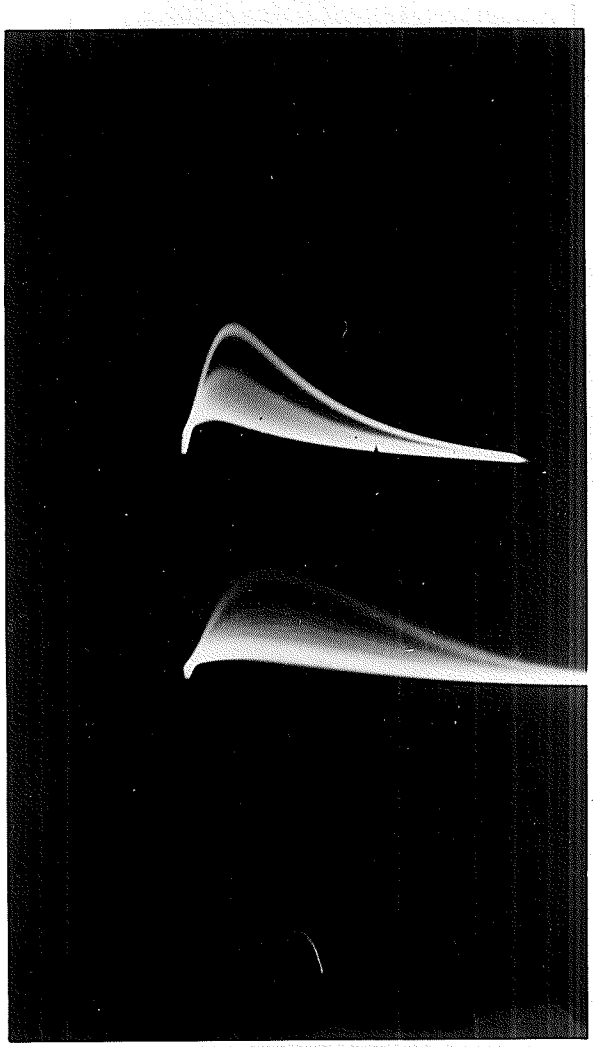


Plate 1.

Standard cathode follower output pulses for NaI(Tl) (top) and LiI(Eu) (bottom).

have a longer rise time (the time for the pulse to rise from 10 to 90% of its final value) and last longer than the NaI pulses. The resolution of the LiI crystal is considerably poorer than the resolution of the NaI. This is shown by comparing the broad line obtained for the 0.662 Mev. gamma-ray of Cs^{137} with LiI to the sharp line obtained with NaI. The vertical amplification for the LiI pulse is about 16 times that used for the NaI pulse.

An R-C integrating circuit was inserted in the output stage of the photomultiplier tube in order to smooth out these ragged pulses from LiI(Eu). Fig. 4(a) shows the output stage for use with a NaI(Tl) crystal and the equivalent circuit is shown below. Fig. 4(b) shows the output stage, with equivalent circuit, initially adapted for use with a LiI(Eu) crystal. The capacitors drawn in with broken lines indicate stray capacitances.

The output pulse from the modified circuit takes considerable time to decay. In this particular case the output pulse from the cathode follower lasted over 25 microseconds. As a result, accurate counting was not possible for pulses starting close together, i.e. for two or more pulses starting within this 25 microsecond period, due to a piling-up effect. This piling-up effect has the following result for two isolated pulses following each other in a manner such that the second starts before the first decays to zero amplitude. The second pulse starts, not at the zero base line, as did the first pulse, but at the D. C. level at which the decaying pulse exists at that instant. Thus, the second pulse has an amplitude

equal to its true amplitude plus the difference between the amplitude at which it started and the zero-amplitude base line. See Fig. 5 for a pictorial representation of this piling-up effect for two pulses.

In the particular problem at hand, that of counting fast neutrons from a Po - Be neutron source, it was found desirable to place the source within 20 cm. of the LiI(Eu) crystal in order to increase the counting rate. However, with the source this close, the piling-up effect became very pronounced and accurate counting became impossible, and so some means was sought to increase this counting rate without incurring inaccuracies due to a shifting base line from which the pulses started.

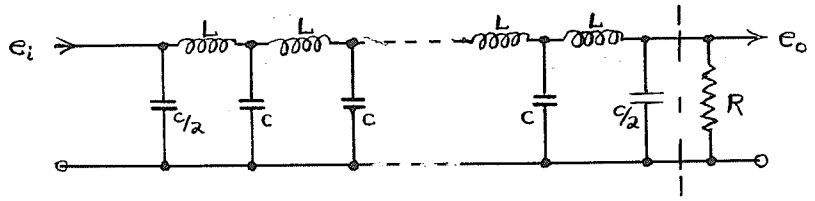
To do this, a different type of filter was employed in the output stage of the photomultiplier tube. A delay line*, consisting of a 50 millihenry inductor and stray capacitance, was used in place of R-1 (see the circuit diagram of Fig. 2). This inductor tended to slow down the rise time and speed up the decay time of the photomultiplier tube output pulse. This resulted in a nearly symmetrical output pulse being obtained from the cathode follower. A tendency of the cathode follower output pulse to give small damped oscillations was eliminated by inserting the correct value of resistance R of the circuit diagram of Fig. 2. This correct value of R combined with stray capacitances to give the correct terminating impedance for this delay line. The circuit digram of Fig. 2 shows the component values used in this modified cathode follower.

* A discussion of delay lines is given in Elmore and Sands

"Electronics".[29] The rise time (time taken for the delayed signal to rise from 10 to 90% of its final value in response to a step input signal) is represented very well by

$$T_R \doteqdot 1.1\ n^{1/3}\ (LC)^{1/2}$$

where n is the number of sections in the type of filter line illustrated below.



Here R = terminating impedance of line,

e_i = input voltage,

and e_o = output voltage.

For the delay line used in the modified cathode follower, the values for L and C were

$L \doteqdot 50$ mh and $C \doteqdot 40\ \mu\mu fd$ (stray capacitance).

Thus the rise time for this delay line would be

$$T_R \doteqdot 1.6\ \mu \text{ sec.}$$

This agrees well with the value of 1.5 μsec. obtained by measurement of the pulses displayed on the screen of an oscilloscope.

The decay time for light pulses from NaI(Tl) is about 0.25 microseconds[28] and for LiI(Eu) it is about 1 microsecond. Thus the input circuit of the modified cathode follower would not change the pulse height for a given gamma-ray as compared to that for NaI(Tl) since the circuit integrates the light pulse for approximately 1.5 microseconds.

The output pulses from the cathode follower now had the form illustrated in Fig. 6(a) for LiI(Eu). A small hump is evident in the decaying part of the pulse and it should be possible to eliminate this by adjusting the value of the terminating impedance of the delay line. These pulses had a rise time of about 1.5 microseconds and lasted about 7 microseconds. This was about one third of the duration of the pulses obtained with LiI(Eu) when using the R-C integrating circuit of Fig. 4(b). With the same modified cathode follower circuit, the output pulses for NaI(Tl) had a rise time of about 1.5 microseconds and a duration of about 5.5 microseconds with a flat portion at maximum amplitude as shown in Fig. 6(b). The standard cathode follower used with the gamma-ray spectrometer gave output pulses with NaI(Tl) that had a rise time of about 0.25 microseconds. Plate 2 is an oscillogram showing the output pulses from the modified cathode follower. The upper trace is that obtained from the output pulses for NaI(Tl) and the lower trace is for LiI(Eu) using, in both cases, a Cs^{137} source. The same sweep speed is used for both traces. It can be seen that NaI(Tl) gives considerably better resolution than does LiI(Eu).

It was noted that the pulses obtained with the inductor delay line from LiI(Eu) were not as smooth as those obtained with the R-C integrating circuit. Also, two pulses with the same amplitude had a tendency to occur with their peaks separated slightly, by about 0.1 microseconds at the most relative to the starting time. However, this did not seem to affect the amplitude resolution of the spectrometer. In

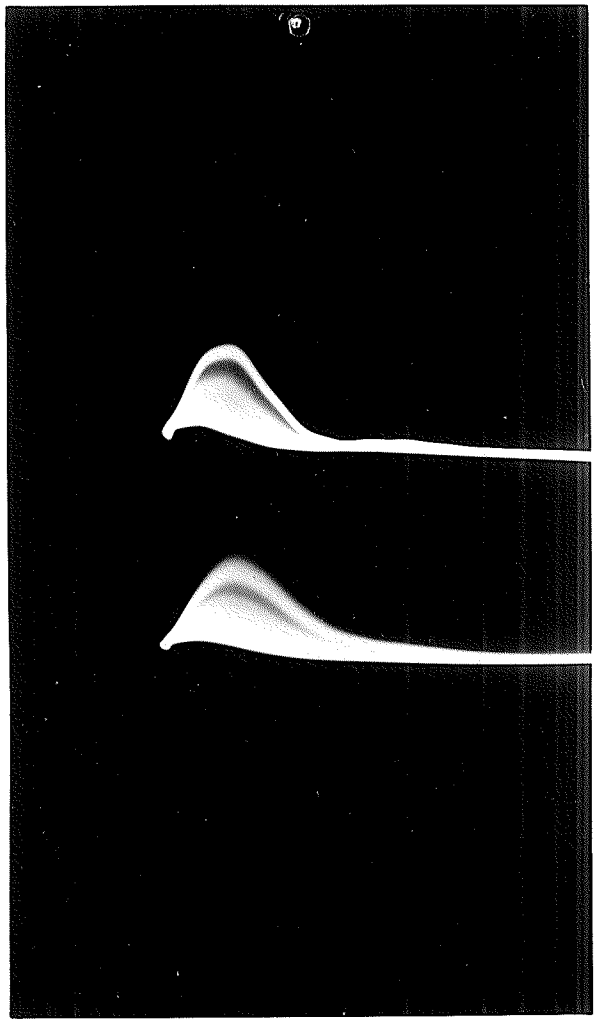


Plate 2.

Modified cathode follower output pulses for NaI(Tl) (top) and LiI(Eu) (bottom).

actual operation, it was found possible to resolve the slow neutron peak without difficulty when about 10 cm. of paraffin was inserted between the crystal and the source. The source was about 20 cm. from the crystal. Since this gave a large slow neutron flux, apparently no serious piling-up effects now hampered accurate counting.

With this improvement in the operation of the cathode follower in order to get high counting rates, the limiting factor in the counting rate was then to be found in the long time constants of the mixer stage of the differential discriminator. The output pulses from this mixer stage had a duration of about 100 microseconds.

Later work with a CsI crystal and a CsI(Tl) crystal showed that these crystals also gave out scintillation pulses over a longer period of time than does a NaI(Tl) crystal, and that this period of time was comparable with that of a LiI(Eu) crystal. It was found that the modified cathode follower was well suited for operation with these CsI crystals. Experimental results with these crystals are given in a later section.

2. A DIFFERENTIAL DISCRIMINATOR

To explain the operation of the differential discriminator, the schematic diagram of which appears in Fig. 7, it can be considered as being composed of two parts:

(i) a pulse height discriminator, and

(ii) a differential or mixer stage.

The pulse height discriminator stage[8] consists of two Schmitt trigger circuits,[9] each with one sharp cut off, high-μ 6SH7 pentode and one sharp cut off, high-μ EF50 pentode, and a wire wound resistor chain to provide grid bias voltages.

In each trigger circuit the grids are biased so that the right hand tube (EF50) is normally conducting and the left hand tube (6SH7) is normally cut off. A positive signal of suitable magnitude impressed on the grid of the 6SH7 causes it to start to conduct. Because of the resultant drop in the plate potential of the 6SH7, a negative signal is fed to the grid of the EF50. This negative signal on the grid of the EF50 causes the common cathode potential to drop, hence more current passes through the 6SH7 and the effect is cumulative, giving rise to triggering, which causes a sudden transition to a second stable state. The 6SH7 is conducting and the EF50 is cut off in this second stable state. As the EF50 is being cut off, its plate potential rises to near 250 volts and a positive pulse can be obtained from this plate. Upon the removal of the positive signal from the grid of the 6SH7, the circuit will go through another regeneration condition and return to its normal stable state with the 6SH7

cut off and the EF50 conducting.

It is essential that the Schmitt trigger circuit be able to discriminate between varying amplitudes of positive input pulses. In order that it be able to do this, some means is necessary to adjust the grid bias voltage setting on the input tube to any preselected D. C. level, so that any pulses below this preselected level will not be able to trigger the Schmitt trigger circuit and cause it to go from its normal stable state to its second stable state. In this particular circuit, a wire wound resistor chain provides a means of applying a regularly variable bias voltage to the grids of the 6SH7 tubes. The pulse amplitude potentiometer P-1 gives a variable bias range from 0 to 100 volts. The voltage at the upper end of P-1 can be set at exactly 100 volts by means of the variable resistor R-1 (see Fig. 7).

In studying the spectrum of some radioactive source with a differential discriminator, it must be possible to scan the scintillation output pulses from the cathode follower at regular intervals in order to obtain a distribution curve. Usually these regular intervals consist of the pulse distribution between two preselected D. C. levels. If the lower level is set at V_o (say) and the upper level at $V_o + dV$, then only pulses falling within the 'gate' of width dV, between V_o and $V_o + dV$, must be counted. Any pulses below V_o or above $V_o + dV$ must be discarded by the differential discriminator without any resultant pulses that can be counted appearing at the discriminator output.

DIFFERENTIAL DISCRIMINATOR

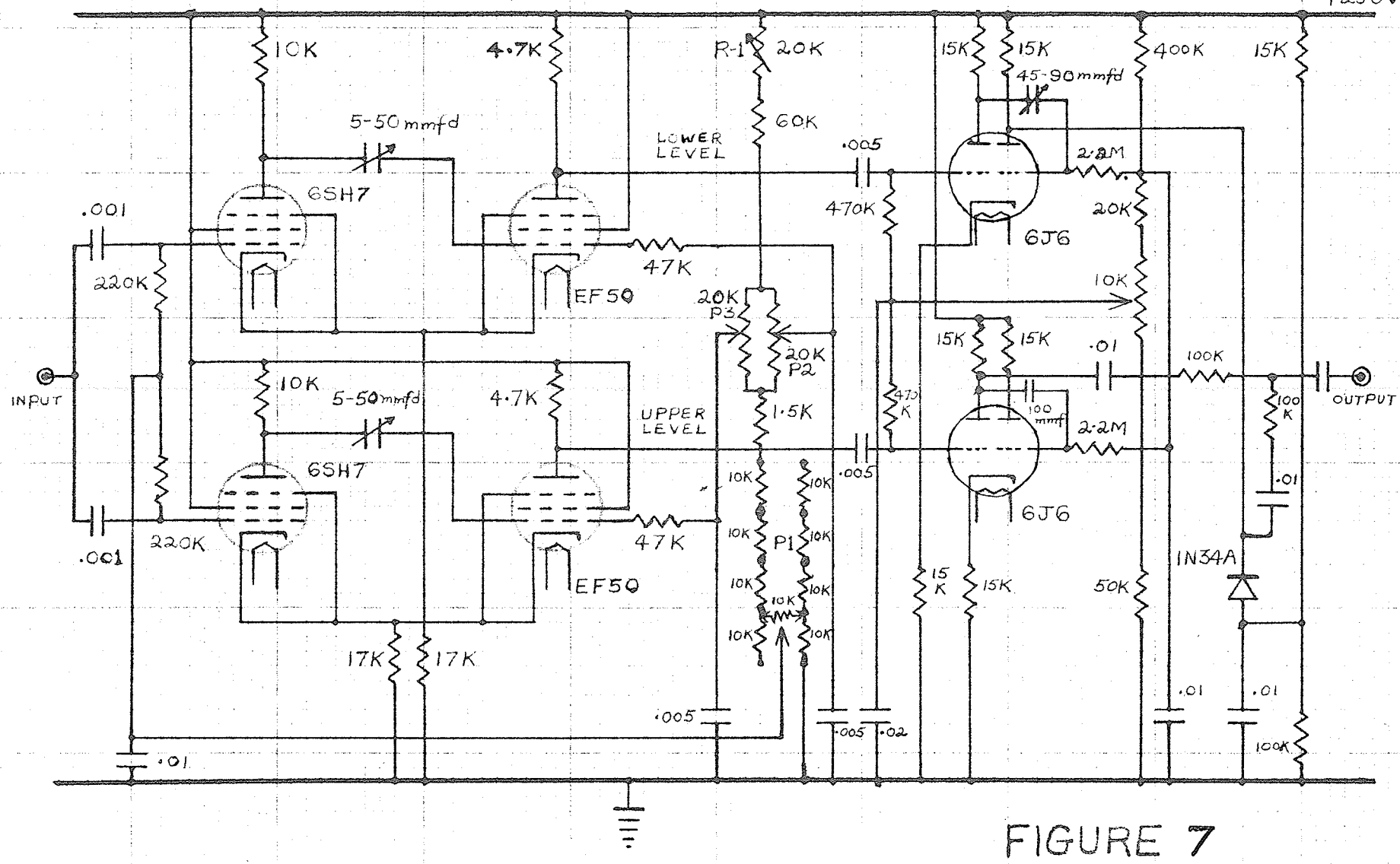


FIGURE 7

Several adjustments have to be made in this particular circuit before a given gate width can be selected. With no input signal and with the pulse amplitude potentiometer P-1 set at zero reading, the 'ZERO SET' potentiometer P-2 must be adjusted to give a grid bias voltage on the lower level EF50 just below that necessary for free running, when the Schmitt trigger circuit resembles a multivibrator. Then the 'GATE SET' potentiometer P-3 must be similarly adjusted for the upper level. Ideally, after these two adjustments have been made, the grids of the two EF50 tubes will be at the same D. C. level, giving zero gate width. Any desired gate width from 0 to 20 volts can then be selected, with the potentiometer P-3, by moving the sliding contact from the zero position through a voltage equal to the desired gate width.

The pulse amplitude potentiometer P-1 sets the bias voltage on the grids of the 6SH7 tubes. Suppose that a positive input pulse is impressed upon these grids. If the pulse lies within the chosen gate, it will trigger the lower level trigger circuit but not the upper level one. Thus a positive pulse would be sent out only from the lower level to the mixer stage of the differential discriminator. If the input pulse lies outside the chosen gate and above the upper level, it will trigger both the lower and upper level trigger circuits, and this will result in a positive pulse being sent out from both the lower and upper levels to the mixer stage. A pulse below both levels will trigger neither level.

The analysis of the scintillation pulses from a LiI(Eu) crystal is somewhat different than the analysis of pulses from a NaI(Tl) crystal, due to the fact that the light pulse duration in LiI(Eu) is several times longer than in NaI(Tl). As a result, an appreciable spacing in time (of the order of a few tenths of a microsecond) occurs in the start of the trigger pulses from the two levels of the pulse height discriminator when both levels are triggered by a given input pulse. This difference presents a problem in the design of the mixer stage. The function of the mixer stage is to give no output pulse when pulses arrive from both levels of the pulse height discriminator, and to give a positive output pulse when a pulse arrives only from the lower level. This cancellation for the case of pulses arriving from both levels is accomplished by first changing the phase of the upper level pulse and then performing an addition of the two pulses in the output of the mixer stage. To get complete cancellation, both pulses must be of identical shape and must start at the same time. If the cathode follower output pulses had an infinitely fast rise time, the trigger output pulses from both levels of the discriminator stage would start at exactly the same time and this cancellation process could be performed easily.

However, in the actual case at hand, the lower level pulse must be delayed in a suitable manner because of the fact that the upper level pulse starts slightly later than the lower level one. Also, the discriminator trigger circuits give output pulses whose lengths are dependent upon the bias

voltages. As a result, the discriminator output pulses must be reshaped because of their variable length and because of their different starting times. This reshaping is done in the mixer stage. The trigger output pulses from the mixer stage are considerably longer than those from the discriminator stage, being about 100 microseconds long as compared to less than 10 microseconds. These mixer stage output pulses have a comparatively fast rise time and so they must be sent through an R-C combination to give them a slower rise time before the cancellation can take place.

Let us now consider the actual mixer stage circuit used. It consists of two 6J6 double triodes acting as Schmitt trigger circuits, two wire wound resistor chains, and a IN34A diode. In each double triode trigger circuit, the bias voltages are adjusted so that the left hand sides are normally cut off and the right hand sides are normally conducting. The right hand plate of the lower level 6J6 is kept near a fixed potential by means of the IN34A diode and the resistance chain composed of R-2 and R-3. This ensures that the positive output pulse from this trigger circuit will always be less than a certain amplitude as determined by the values of R-2 and R-3.

If a positive input pulse comes from the lower level of the discriminator stage, it triggers the lower level trigger circuit of the mixer stage and a positive square wave pulse is sent out from the right hand plate. This pulse is then reshaped, by a combination of a 100 K ohm resistor

and shunt capacity at the end of this resistor, so as to have a slower rise time when it arrives at the output condenser. A similar negative pulse arrives at the output condenser when the upper level is triggered. The positive pulse can be made to have a length slightly shorter than that of the negative pulse by means of the variable condenser C-1. This is to ensure that there be no possibility of a resultant positive pulse after the addition takes place. If only the lower level is triggered, the resultant output pulse is positive and can be used to operate a scalar. It was found, in practice, that a resultant negative pulse was obtained from the differential discriminator when both upper and lower levels were triggered. This was of no importance since the scalar used to count these pulses operated only on positive input pulses.

The neutron scintillation spectrometer was ready for operation after the differential discriminator was ready for use and the cathode follower modification was carried out. A block diagram of the spectrometer is given in Fig. 8. The amplified cathode follower pulses were fed both to the cathode ray oscilloscope and to the differential discriminator. These pulses were displayed on the screen of the oscilloscope in order to observe the shapes of the pulses and to measure the rise times and durations of these pulses. Fig. 1 shows the schematic diagram of the voltage stabilization circuit added to the power supply which gave the high negative voltage for the cathode of the photomultiplier tube.

BLOCK DIAGRAM

NEUTRON SCINTILLATION SPECTROMETER

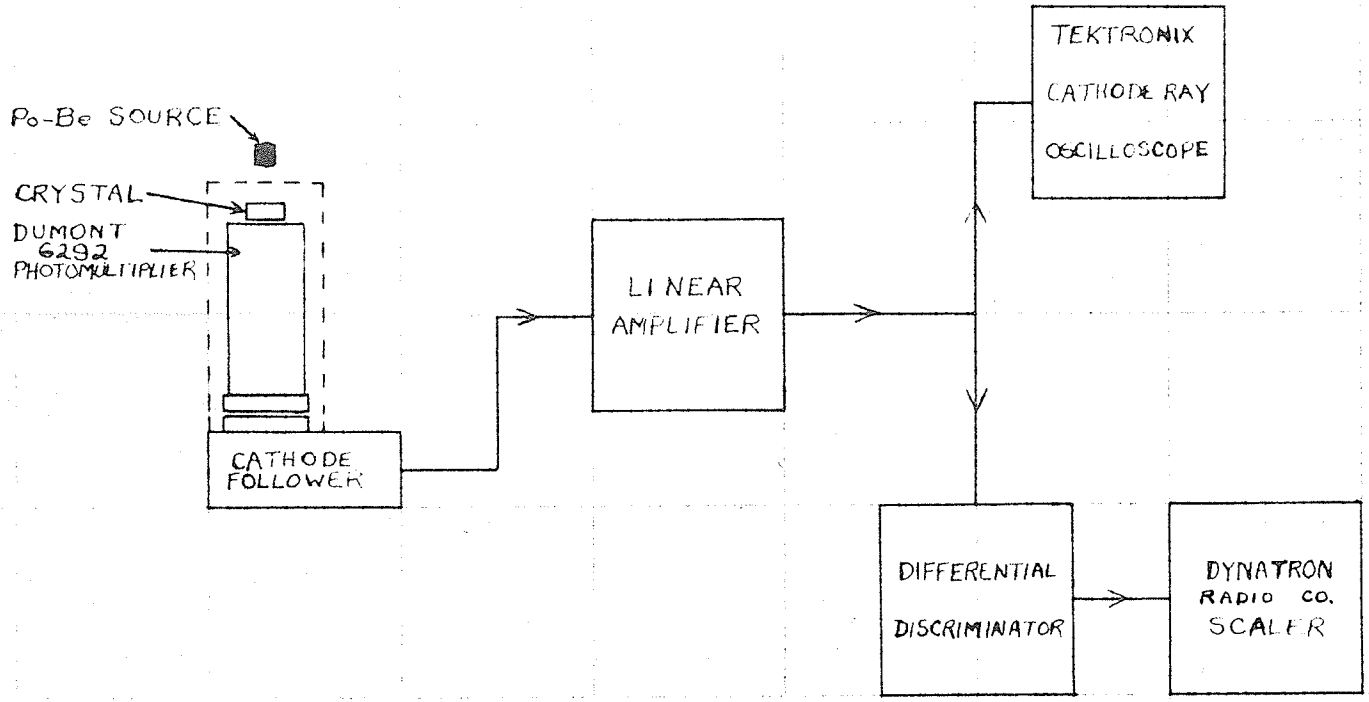


FIG. 8

3. EXPERIMENTAL RESULTS OBTAINED WITH A CsI(Tl) CRYSTAL AND A CsI CRYSTAL.

Interesting results on CsI have been reported by Hahn and Rossel.[10] In this crystal, the time taken for the emission of the light is considerably longer than for NaI(Tl). It therefore seemed opportune to carry out tests with the equipment as set up for LiI(Eu).

Crystals of CsI and CsI(Tl) were available. These crystals were each one inch in diameter and half an inch high. Comparisons were made with a NaI(Tl) crystal one inch in diameter by one inch high. CsI is considerably heavier than NaI, the densities being 4.51 and 3.67, respectively. The atomic numbers of the constituents in NaI are 11 and 53, respectively, so that the importance of the I far outweighs the importance of Na in the production of secondary electrons within the crystal. However, in CsI the atomic numbers of the constituents are 55 and 53, respectively, so that both the Cs and the I are important in the scintillation process. It would, therefore, be expected that the photoelectric effect would be more pronounced as compared with the Compton effect in CsI than in NaI. This is of importance if it is desirable to reduce the Compton effect in favor of the photoelectric effect as much as possible within a given crystal. In this respect, evidence in favor of the CsI(Tl) over the NaI(Tl) has been found for the spectra of Cs^{137} and Zn^{65}.

The CsI crystals used were not mounted. No special

precautions had to be taken to seal them from the atmosphere, since unlike NaI, CsI is not hygroscopic, and moisture present in the atmosphere does not cause it to deteriorate. The following method was used to mount the CsI crystals on the light-sensitive cathode of a Dumont 6292 photomultiplier tube. A cylindrical lucite ring, having a diameter of about one quarter of an inch greater than the diameter of the crystal, was fixed to the phototube cathode with vacuum pump grease. The crystal was then placed within this lucite ring and on the cathode. A silicone grease was used to ensure good optical contact between the cathode and the crystal. A diffuse reflector, of MgO powder, was then packed between the lucite ring and the crystal to a depth of nearly one inch to reduce to a minimum the loss of light from the crystal through crystal faces other than that next to the cathode. The crystal and phototube were then ready for counting purposes.

Preliminary trials, using the modified cathode follower, were made with NaI(Tl), CsI(Tl) and CsI to find the pulse height and resolution obtained with these crystals for the 0.662 Mev gamma-ray from Cs^{137}. The CsI had the face next to the cathode polished but the CsI(Tl) did not. Pulse heights and resolutions obtained were

(i) for NaI(Tl) - 96 volts and 8.5%,

(ii) for CsI(Tl) - 35.6 volts and 12%, and

(iii) for CsI - 10 volts and 25%.

One face of the CsI(Tl) crystal was then polished and it was remounted

on the phototube with this polished surface next to the cathode. An increase in pulse height to 42 volts was obtained and the resolution was found to be 10%. This stresses the importance of having a highly polished surface on that face of the crystal next to the cathode of the phototube in order to have maximum light transmission efficiency through this face.

The amplified output pulses from the cathode follower were displayed on the screen of a Tektronix oscilloscope for the three crystals. A Cs^{137} source was used. Plate 3 is the oscillogram obtained using the same sweep speed but different vertical amplifications for each crystal. The wave form trace at the top of the photograph is for CsI(Tl); the one in the middle is for NaI(Tl); and the one at the bottom is for CsI. It can be seen that good resolution was obtained with CsI(Tl) and NaI(Tl), but very poor resolution was obtained with CsI for the Cs^{137} gamma-ray. If the wave forms shown in Plate 3 for NaI(Tl) and CsI(Tl) are compared with those shown in Plate 2 for NaI(Tl) and LiI(Eu), it can be seen that CsI(Tl) and LiI(Eu) give similar cathode follower output pulses. This is due to the fact that the time taken for the emission of light is approximately the same for these crystals. At room temperature CsI is slower than all these other three crystals in emitting light pulses. Further modification of the output stage of the phototube, with the introduction of longer delay times, would be necessary if the CsI was to be used at room temperature. The output pulses for CsI were very ragged in shape (see Fig. 3(b)

for the actual shape), but this is not evident in the photograph because of the long exposure time necessary to obtain an appreciable darkening of the negative.

After these preliminary tests with CsI and CsI(Tl) were completed, the effect of temperature on the light output of these crystals was studied. Hahn and Rossel[10] found that CsI at 100° K gave a pulse height for the 0.662 Mev. gamma-ray of Cs^{137} about twice that given by NaI(Tl) at room temperature. Dry ice was used as a cooling agent for the preliminary trials. It was put in a paper container which was placed on the lucite ring surrounding the crystal. A dewar flask was then placed over the dry ice and crystal to ensure that dry ice temperature (-57° C.) would be maintained for an appreciable time. A decrease in pulse height with decreasing temperature was noted for both CsI(Tl) and CsI. Evidence that the pulse height for CsI reached a minimum and then began to increase with decreasing temperature, near dry ice temperature, indicated that lower temperatures were desirable; and so liquid nitrogen was used for further tests.

The apparatus illustrated in Fig. 9 was constructed for this purpose. MgO powder was first put in the brass cup, then the CsI crystal was put in place and held firmly by a rubber 'O' ring. The polished surface of the crystal protruded above the brass cup just enough to allow the phototube to be lowered on to the crystal. The brass cylinder and cup were placed in the Dewar flask at the bottom of which was a cushion of loose insulation material.

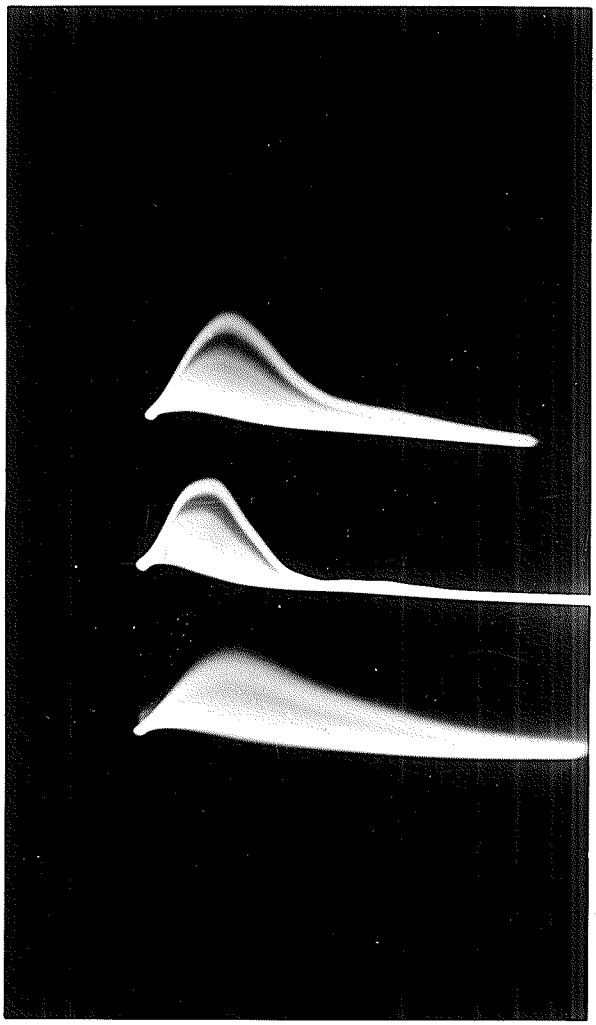
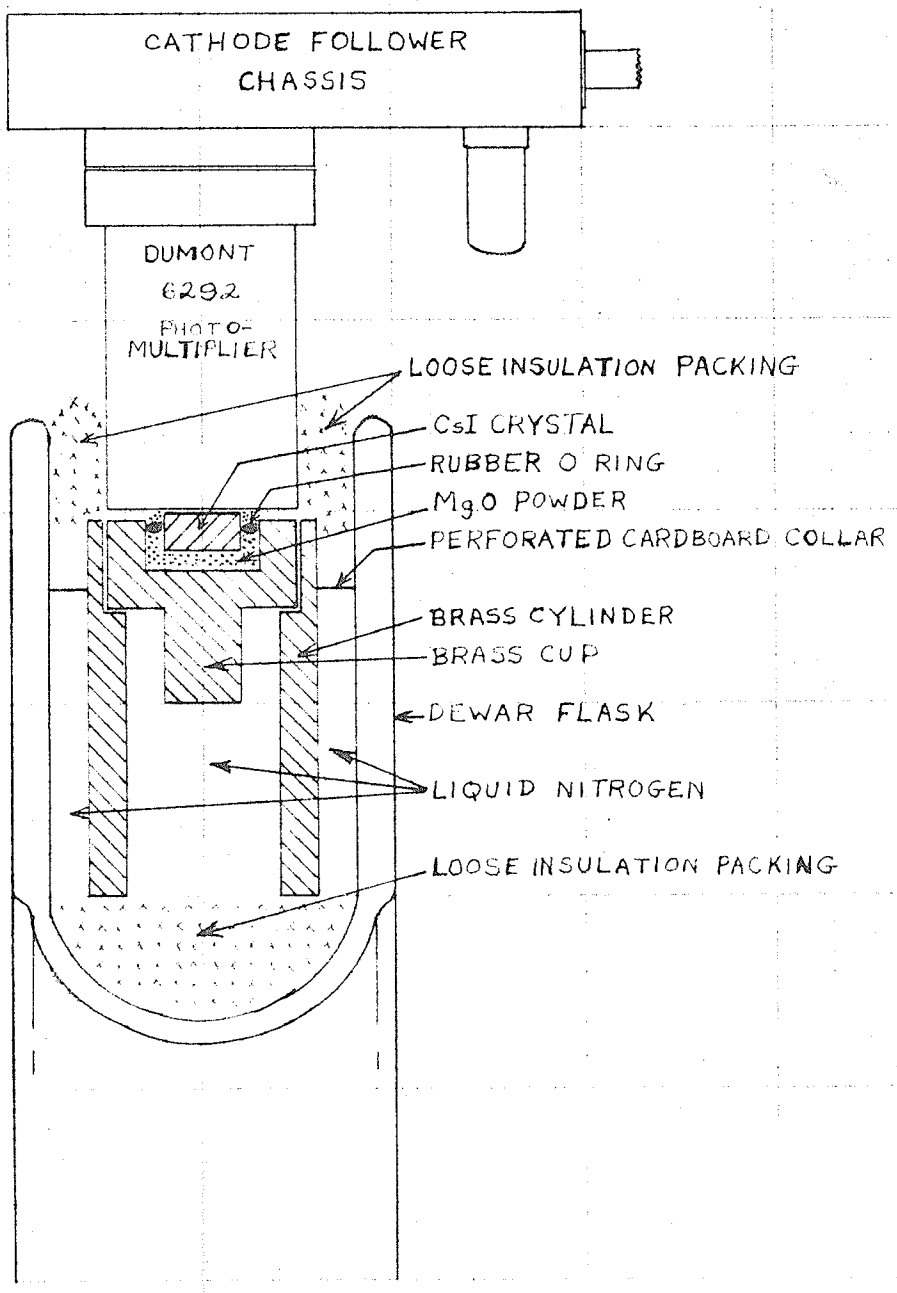


Plate 3.

Modified cathode follower output pulses for CsI(Tl) (top), NaI(Tl) (center) and CsI (bottom).

FIG. 9

LOW TEMPERATURE APPARATUS



The Dewar flask was placed, along with the phototube and cathode follower, in a light tight box. The phototube was suspended in such a manner that it could be lowered easily on to the crystal which was completely within the flask. Insulation material was then packed between the Dewar flask and the phototube. The liquid nitrogen was slowly poured into the Dewar flask through a glass funnel until the liquid reached the level of the brass cup. The crystal was separated from the brass cup by about a quarter of an inch of MgO, and so it was possible that it did not quite reach liquid nitrogen temperature (-196° C.). However, since the liquid nitrogen filled the Dewar flask to the level of the brass cup, and since this amount of liquid did not boil away entirely for at least 5 hours, it was considered that a temperature very near -196° C. was reached by the crystal.

The amplified cathode follower output pulses due to a Cs^{137} source were displayed on the oscilloscope for both CsI crystals at room temperature. The trace on the screen was inked in to allow for visual observations of any changes that might occur in the pulse height and pulse width as the crystal temperature decreased. The pulse height and resolution for the Cs^{137} gamma-ray were also obtained with the differential discriminator and the scalar. Liquid nitrogen was not added until these operations were completed.

At room temperature CsI gave a pulse height of 10 volts and a resolution of 25% for the Cs^{137} gamma-ray. The half-height width (the width of the pulses at one-half their

maximum amplitude) of the cathode follower output pulses was approximately 8 microseconds. The pulse height at first decreased with decreasing temperature to a minimum of 5.5 volts; then it rose rapidly with a further decrease in temperature to a maximum of 80 volts. Meanwhile, the half-height width of the pulses had decreased to approximately 3.5 microseconds. The resolution obtained at liquid nitrogen temperature was 12.5%, which was considerably better than the room temperature resolution of 25%. NaI(Tl) at room temperature gave a pulse height of 96 volts and a resolution of 8.5% for the Cs^{137} gamma-ray. Thus the ratio of the CsI pulse height at liquid nitrogen temperature to the NaI(Tl) pulse height at room temperature was 1 : 1.2. This differs from the ratio of 2 : 1 obtained by Hahn and Rossel.[10] Possibly the integrating circuitry employed in the two sets of experiments was ~~markedly~~ different.

Quite different results were obtained for CsI(Tl). At room temperature it gave a pulse height of 42 volts and a resolution of 10% for the Cs^{137} gamma-ray. There was a continual decrease of pulse height with decreasing temperature until the pulse disappeared completely into the base line on the oscilloscope screen.

(A temporary change in the characteristic operation of the photomultiplier tube resulted from the large temperature change it underwent. The number of noise pulses up to a pulse height of approximately 3 volts had shown a marked increase when the phototube was used immediately after it had returned to room temperature. However, these low level

noise pulses decreased considerably in number after approximately one day's operation, and the phototube appeared to regain its normal characteristics.)

Since the pulse height from CsI(Tl) decreased with decreasing temperature, it seemed reasonable to assume that it would increase with increasing temperature for at least a short range of temperature above 20° C. This assumption was tested by placing an oven, which was capable of maintaining a temperature of 50° C., over the crystal. A time interval of over two hours was allowed for the crystal to reach a stable temperature of approximately 50° C. It was found that a 3.5% increase in pulse height occurred, but no appreciable change occurred in the resolution. No change was noticeable in the pulse height for CsI at 50° C. This was due in part to the ragged shape of the cathode follower pulses which eliminated any possibility of observing a small change even if it were present.

Table I shows the values obtained for the pulse height and resolution for the Cs^{137} gamma-ray with the four crystals - NaI(Tl), CsI(Tl), LiI(Eu) and CsI. The pulse height ratio given in the last column is based on the pulse height given for the Cs^{137} gamma-ray by NaI(Tl) as a standard. It is the ratio of the pulse height obtained with a given crystal to the pulse height obtained with NaI(Tl).

Fig. 10, which gives the gamma-ray energy calibration curve for CsI(Tl), shows that a linear relation exists between pulse height and energy for this crystal in this region of energies.

TABLE I

A Comparison of Four Crystals Using the 0.662 Mev. Gamma Ray of Cs^{137}

Crystal		Pulse Height (Volts)	Resolution	Pulse Height Ratio
Type	Temperature			
NaI(Tl)	Room Temp.	96	8.5%	1
CsI(Tl)	"	42	10%	0.44
LiI(Eu)	"	6.7	18%	0.07
CsI	"	10	25%	0.10
CsI	Liquid Nitrogen temperature	80	12.5%	0.83

$$\text{Pulse Height Ratio} = \frac{(\text{Pulse height from given crystal})}{(\text{Pulse height from NaI(Tl)} \quad)}$$

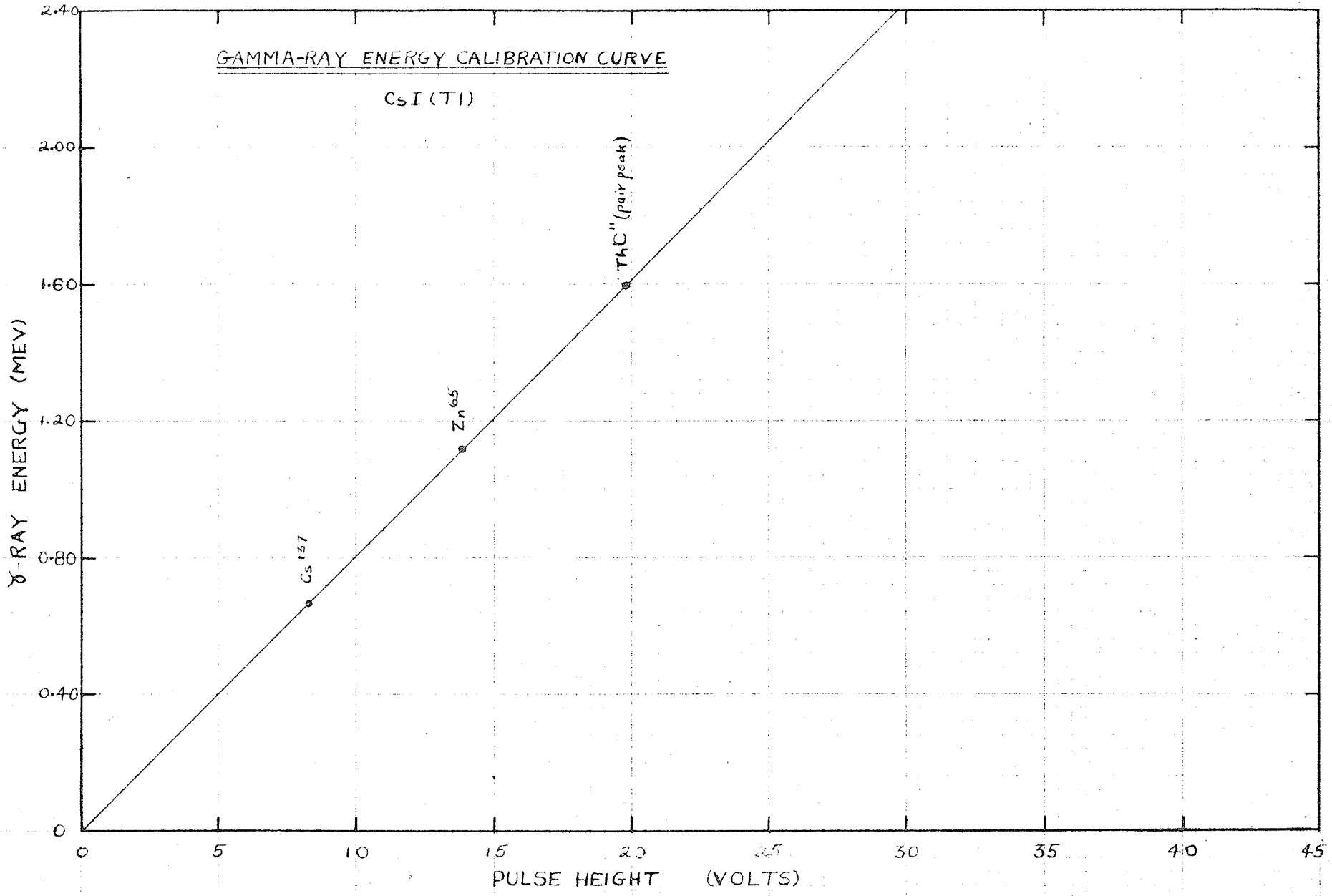

GAMMA-RAY ENERGY CALIBRATION CURVE
CsI (Tl)
γ-RAY ENERGY (MEV)
2.40
2.00
1.60
1.20
0.80
0.40
0
Cs 137
Zn 65
"ThC" (pair peak)
0
5
10
15
20
25
30
35
40
45
PULSE HEIGHT (VOLTS)

FIG. 10

Maeder and Wintersteiger[11] have published a paper in which they have considered the importance of the photoelectric and Compton effects in the absorption of gamma-rays in a NaI(Tl) crystal; they have considered a monochromatic as well as a complex gamma-ray spectrum.

In order to compare the ratios of the absorption of gamma-rays by the photoelectric effect to the absorption by the Compton effect in NaI(Tl) and CsI(Tl), the spectra of three radioactive sources were obtained with both crystals. Exactly the same geometry and the same negative high voltage on the cathode of the phototube were used for each crystal for a given source. Corrections for background radiations were applied in all cases. In each case the CsI(Tl) curve was normalized to give the same counting rate and pulse height as given by NaI(Tl) for the most prominent photopeak of the given source.

The two curves obtained for Cs^{137} are given in Fig. 11. The CsI(Tl) curve was normalized to make the 0.662 Mev. gamma-ray peak correspond in position and height to the same photopeak as given by NaI(Tl); both have this photopeak at a pulse height of 25 volts in Fig. 11. A comparison of the areas of the 0.662 Mev. photopeak and the area of the region between 9 and 19 volts shows that the ratio of the photoelectric to the Compton effect is slightly higher for CsI(Tl). This ratio would be more in favor of CsI(Tl) if the crystals had the same volumes; here the NaI(Tl) had twice the volume of the CsI(Tl) crystal.

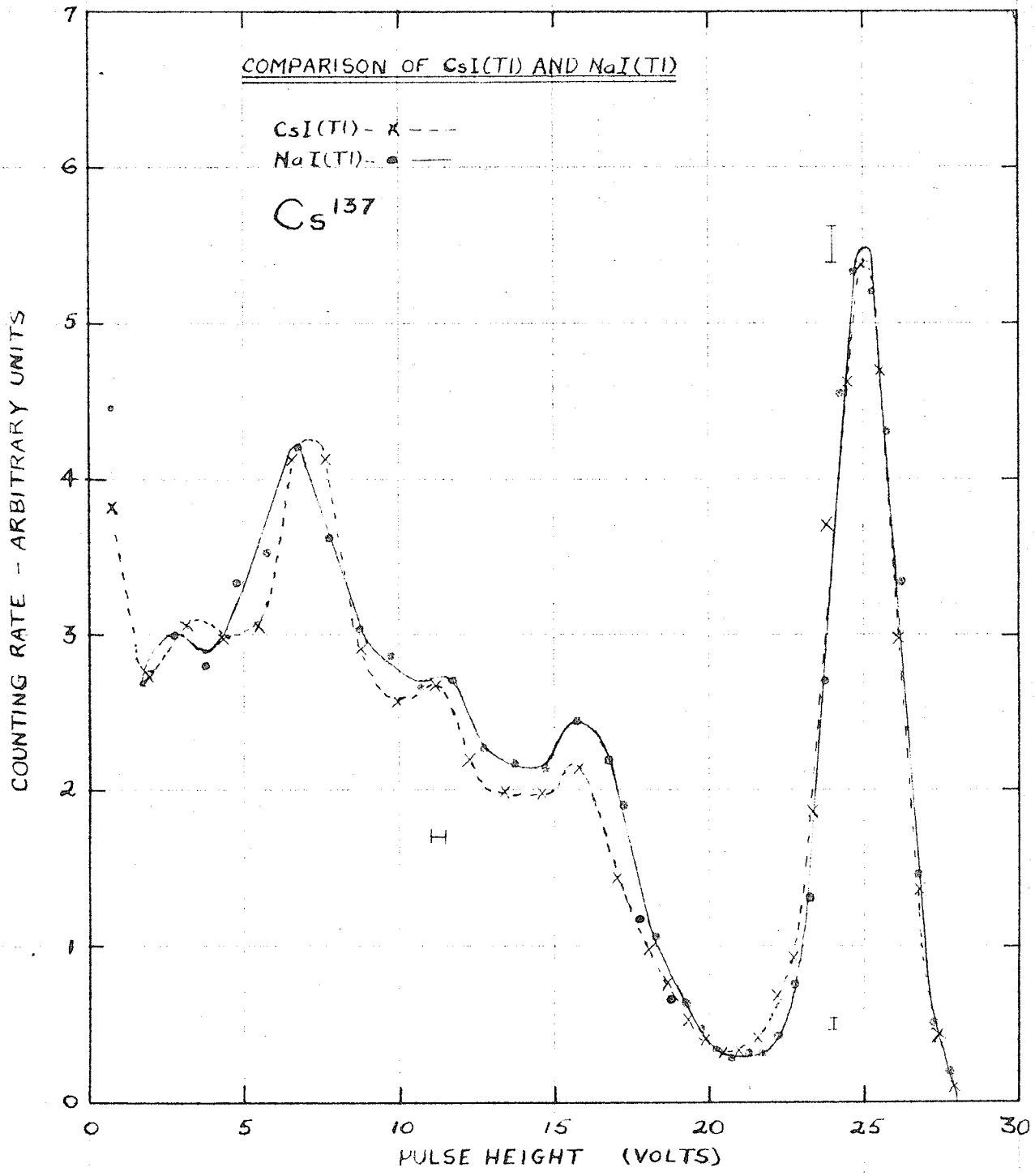

COMPARISON OF CsI(Tl) AND NaI(Tl)
CsI(Tl) - x ---
NaI(Tl) - • ——
Cs 137
COUNTING RATE - ARBITRARY UNITS
PULSE HEIGHT (VOLTS)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30

FIG. 11

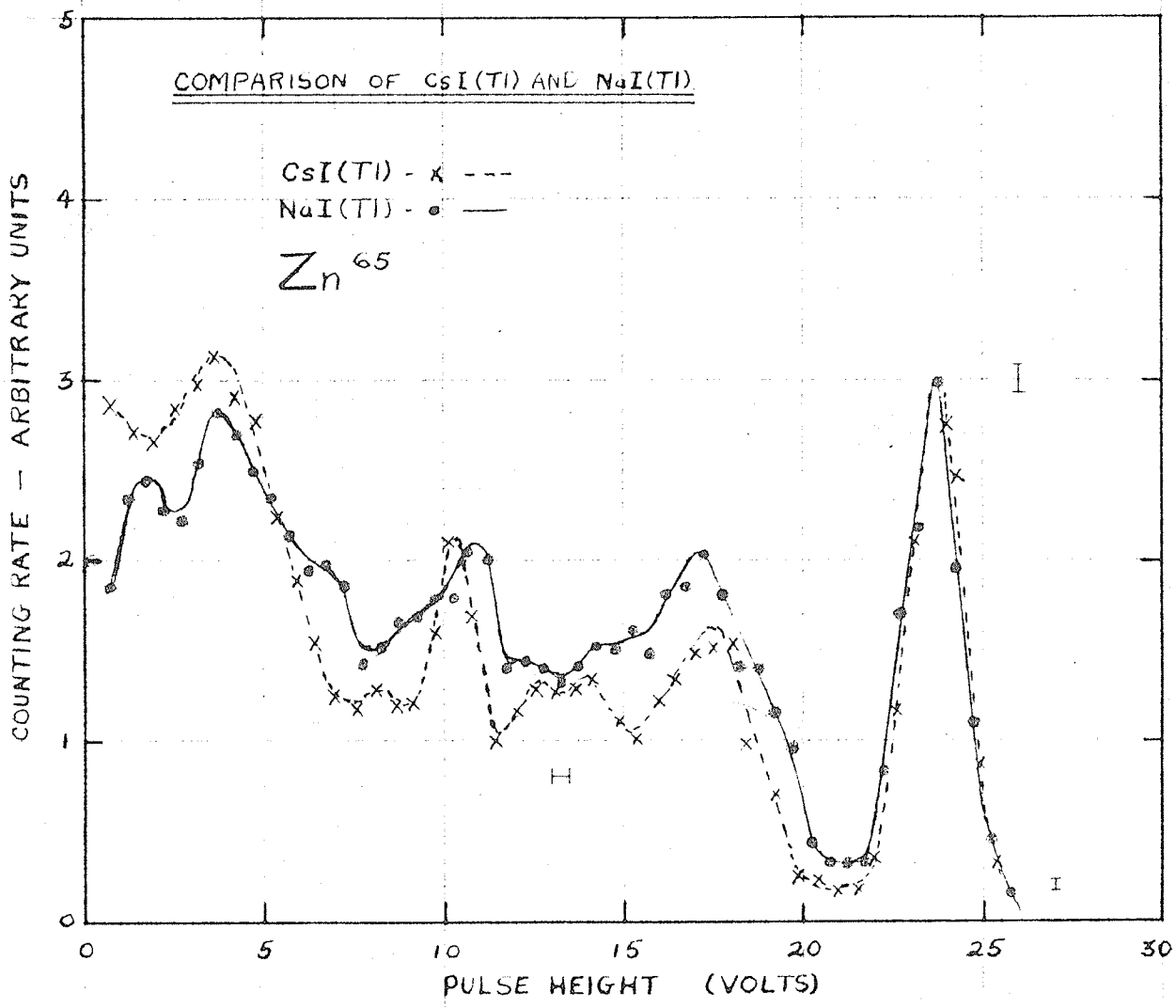

COMPARISON OF CsI(Tl) AND NaI(Tl)
CsI(Tl) - x ---
NaI(Tl) - • ——
Zn 65
COUNTING RATE — ARBITRARY UNITS
PULSE HEIGHT (VOLTS)
0
1
2
3
4
5
0
5
10
15
20
25
30
H
I
I

FIG. 12

The spectra obtained for Zn^{65} are given in Fig. 12. The 1.12 Mev. gamma-ray photopeak occurs at a pulse height of 23.8 volts. The peak-to-trough ratio for this photopeak is definitely higher for the CsI(Tl) crystal and, as can be seen by comparing areas in the region to the right of a pulse height of 5 volts, the photoelectric to Compton ratio is considerably higher for the CsI(Tl) crystal than it is for the NaI(Tl) crystal. A considerably larger number of pulses is thrown into the region between 5 and 22 volts by the NaI(Tl) crystal than by the CsI(Tl). Again the results obtained with CsI(Tl) would have been better if a larger crystal had been used.

The spectrum obtained for Ir^{192} with NaI(Tl) is almost identical with that obtained with CsI(Tl) as can be seen in Fig. 13. The prominent photopeak at a pulse height of 20 volts has an energy of about 310 kev. The photoelectric effect is much more important than the Compton effect at these low gamma-ray energies. Because of this, it seems reasonable to suppose that the number of pulses given out by both crystals is due largely to the absorption of the gamma-radiation by the photoelectric effect; if this is the case, then the two curves would be expected to be very similar. The Th source used to obtain the spectra given in Fig. 14 contained a trace of uranium ore. Composite spectra of Th and Ra were obtained as a result, and so no attempt was made to compare these curves in detail.

In summing up, it would seem that CsI(Tl) has at least

two distinct advantages over NaI(Tl) as a phosphor for a gamma-ray scintillation spectrometer. The chief advantage is that CsI(Tl) is non-hygroscopic, which means that no special precautions need be taken to prevent moisture contamination of the crystal. The second advantage of CsI(Tl) arises from the fact that a larger number of pulses is thrown into the photoelectric peak than into the Compton peak. It is unfortunate that no large CsI(Tl) crystals are available at the present time.

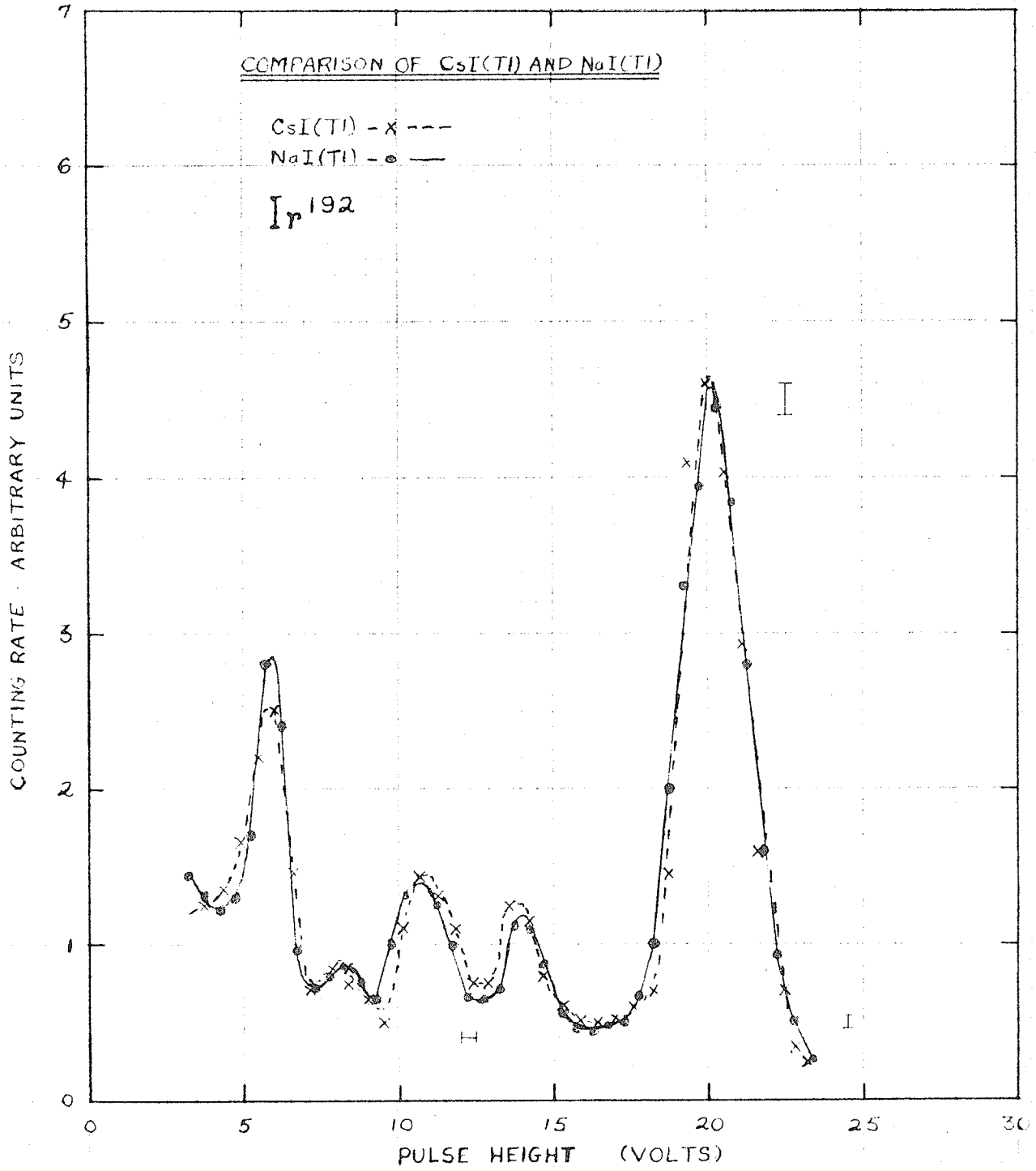

COMPARISON OF CsI(Tl) AND NaI(Tl)
CsI(Tl) - x ---
NaI(Tl) - o ——
Ir 192
COUNTING RATE - ARBITRARY UNITS
PULSE HEIGHT (VOLTS)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30

FIG. 13

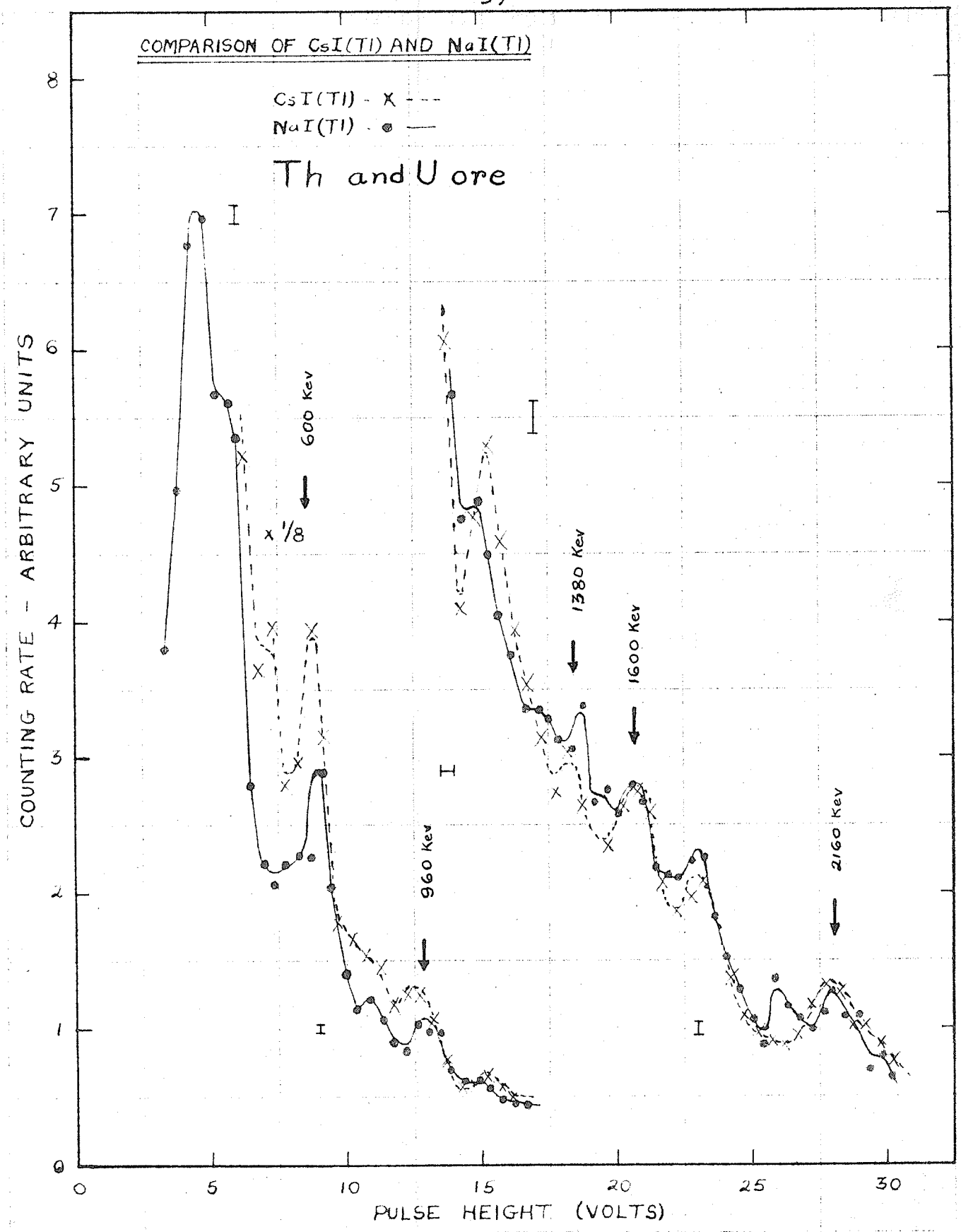

COMPARISON OF CsI(Tl) AND NaI(Tl)
CsI(Tl) - X ---
NaI(Tl) - ● ——
Th and U ore
COUNTING RATE - ARBITRARY UNITS
PULSE HEIGHT (VOLTS)
600 Kev
960 Kev
1380 Kev
1600 Kev
2160 Kev
x 1/8
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
30

FIG. 14

4. SPECIAL-CATHODE PHOTOMULTIPLIER TUBE.

To investigate methods of improving the cathode efficiency of a phototube, the Dumont Laboratories constructed a 6292 tube with half of the cathode window etched on the inside. The whole window was coated in the usual manner.

The tube was tested in the following manner:- A smooth piece of silver foil was placed over one-half of the cathode window in order to test the other half. This made it possible to place a one inch diameter NaI(Tl) crystal on that half of the window under study without having part of the crystal overhanging the edge of the phototube. Any light striking the silver foil had an excellent chance of being reflected back into the crystal so that it could eventually reach the unmasked half of the cathode window. A Cs^{137} source was used and the position of the 0.662 Mev. gamma ray photopeak was found for three positions of the crystal.

When the crystal covered only the etched-glass portion of the window, a pulse height of 25 volts was obtained, with a resolution of 11.2%. When the crystal covered only the clear-glass portion of the window, a pulse height of 28 volts was obtained, with a resolution of 9.7%. The pulse height obtained when the crystal was equally on the etched- and the clear-glass portion of the cathode window was 33 volts, with a resolution of 9.7%. Assuming an otherwise uniform cathode window, it would appear from these results that the increase in the surface area of the etched-glass window over the area of the clear-glass window does not produce an increase in pulse height as might be expected.

B. THE APPLICATION OF THE NEUTRON SCINTILLATION SPECTROMETER TO THE STUDY OF THE FAST NEUTRON SPECTRUM OF A Po - Be NEUTRON SOURCE.

The detection of neutrons[12, 13] depends on secondary effects, due to the fact that the neutron possesses zero net charge, and hence cannot be detected directly by the usual methods for alpha- and beta-particles. The neutron cannot directly cause ionization in a G.M. tube, in an ionization chamber, or in a proportional counter; it cannot of itself produce tracks in a cloud chamber or in a photographic emulsion; it cannot directly produce scintillation photons in the crystal of a scintillation counter; nor can it be deflected in an electric or a magnetic field. There are several nuclear interactions[14] involving neutrons which make their detection possible, and some of these are (1) the absorption of a neutron by a nucleus with the resultant formation of a radioactive nucleus, (2) the absorption of a neutron by a nucleus followed by the emission of a fast charged particle, (3) elastic scattering from a light nucleus such as the nucleus of a hydrogen or a helium atom, and (4) the absorption of the neutron by a nucleus with fission of the compound nucleus so formed.

In case (1), the decay of the radioactive nucleus can be studied by observing the decay products (such as alpha- or beta-particles, or gamma-rays) with suitable detectors. After information is obtained on the original nucleus and on the product nucleus, the reaction can be identified, in

some simple cases at least, from theoretical considerations. For the interaction of type (2), a proportional counter or an ionization chamber filled with BF_3 gas can be used to detect the fast charged particle. In such a boron counter, the alpha-particles produced in the reaction B^{10} (n, α) Li^7 cause the ionization necessary for the counter to operate. One method of detection applicable to the interaction of type (4) is to use a photographic emulsion containing the fissionable material. The density of the tracks produced is a measure of the intensity of the neutron. A second method of detection involves the use of an ionization chamber which incorporates the fissionable material. Several types of detectors based on elastic scattering have been used for the nuclear interaction of type (3). Elliot et al[15] have used a scintillation spectrometer employing an anthracene crystal to study the fast neutrons from a Po - Be neutron source. This spectrometer uses the recoil proton pulse amplitude principle that has been described by Owen et al.[16] A proton-recoil proportional counter which can operate in fairly strong gamma-ray backgrounds has been described by Frisch[17]. Dr. B. G. Whitmore and Wm. Baker[18], working at the University of Manitoba, have used a photographic emulsion technique, involving the measurement of recoil proton tracks, to study the energy spectrum of neutrons from Po - Be.

In the experiment described here, a neutron scintillation spectrometer was used to detect the fast neutrons from a Po - Be source. The neutrons are produced in the follow-

ing exoergic reaction

$$_4Be^9 + {}_2He^4 \longrightarrow {}_6C^{12} + {}_0n^1 + Q .$$

Q is found to have a value of 5.65 Mev. from a consideration of the mass values of reactants and products using the relation[19,20]

$$Q = 931.16 \left[M(X) + m(x) - M(Y) - m(y) \right] c^2 \text{ (Mev)},$$

where M(X) = mass of Be^9,

m(x) = mass of He^4,

M(Y) = mass of C^{12},

and m(y) = mass of a neutron.

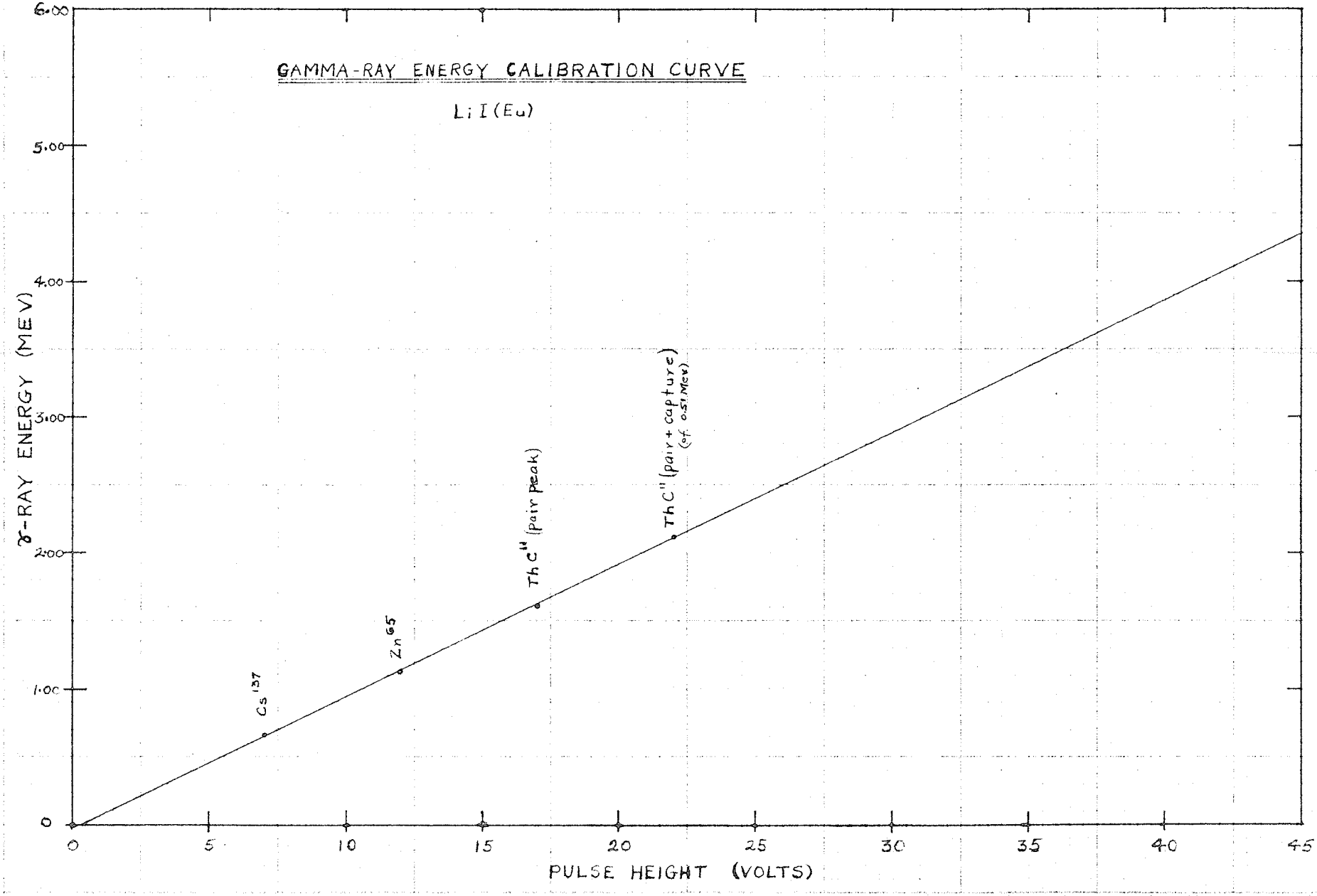
The alpha-particles necessary to produce this reaction come from Po and have an energy of 5.30 Mev. The neutrons produced are found to have an energy range from about 11 Mev. down to zero. This energy spread is due to two causes[21]: (1) The C^{12} nucleus may in some cases be left in an excited state with the result that the outgoing neutron has less energy. For monoenergetic incident alpha-particles, the possibility arises of obtaining groups in the spectrum of the outgoing neutrons. Each group would correspond to an excited level in the C^{12} nucleus. Pringle, Roulston and Standil[22] made a study of the gamma-rays from $Be^9(\alpha,n)$ using a gamma-ray scintillation spectrometer. Summaries[23,30] have been made of the available evidence (up to 1952) for the existence of levels in C^{12}. (2) The Be target has a finite thickness and there is a good chance of the Po alpha-particles losing much of their energy before interacting with a Be^9 nucleus. And

so, even if the ground state of C^{12} results from every interaction, there is still a possibility of a spread in the energies of the outgoing neutrons due to the possible spread in the energies of the Po alpha-particles from 5.30 Mev. to zero.

The scintillation phosphor used was a LiI(Eu) crystal. Normal Li is made up of 7.4% Li^6 and 92.6% Li^7. Li^6 is the isotope involved in the detection of neutrons due to the reaction $Li^6(n, \alpha)$ H^3. The crystal was a cylinder having a diameter of 3/4 inch and a depth of 3/4 inch. It was mounted in a moisture-proof container with a glass plate cemented to the light-transmitting face. The crystal was not perfectly colourless but had a slight pinkish hue. LiI is more hygroscopic and chemically more unstable than NaI. It undergoes hydrolysis and oxidation in the presence of the slightest trace of water and oxygen. As a result, free iodine is liberated, thus giving the crystal a brown discoloration. LiI is perfectly transparent when carefully prepared. The addition of Eu can cause color centers which can be minimized by careful heat treatment. Schenck and Neiler[24] found some improvement in pulse height after applying this heat treatment to LiI(Eu).

The LiI(Eu) crystal was used with a Dumont 6292 phototube. A silicone grease was placed between the phototube cathode and the light-transmitting face of the crystal to ensure good optical contact. The phototube was then used in all cases with the modified cathode follower circuit. The Po - Be source, in the form of a cylinder approximately

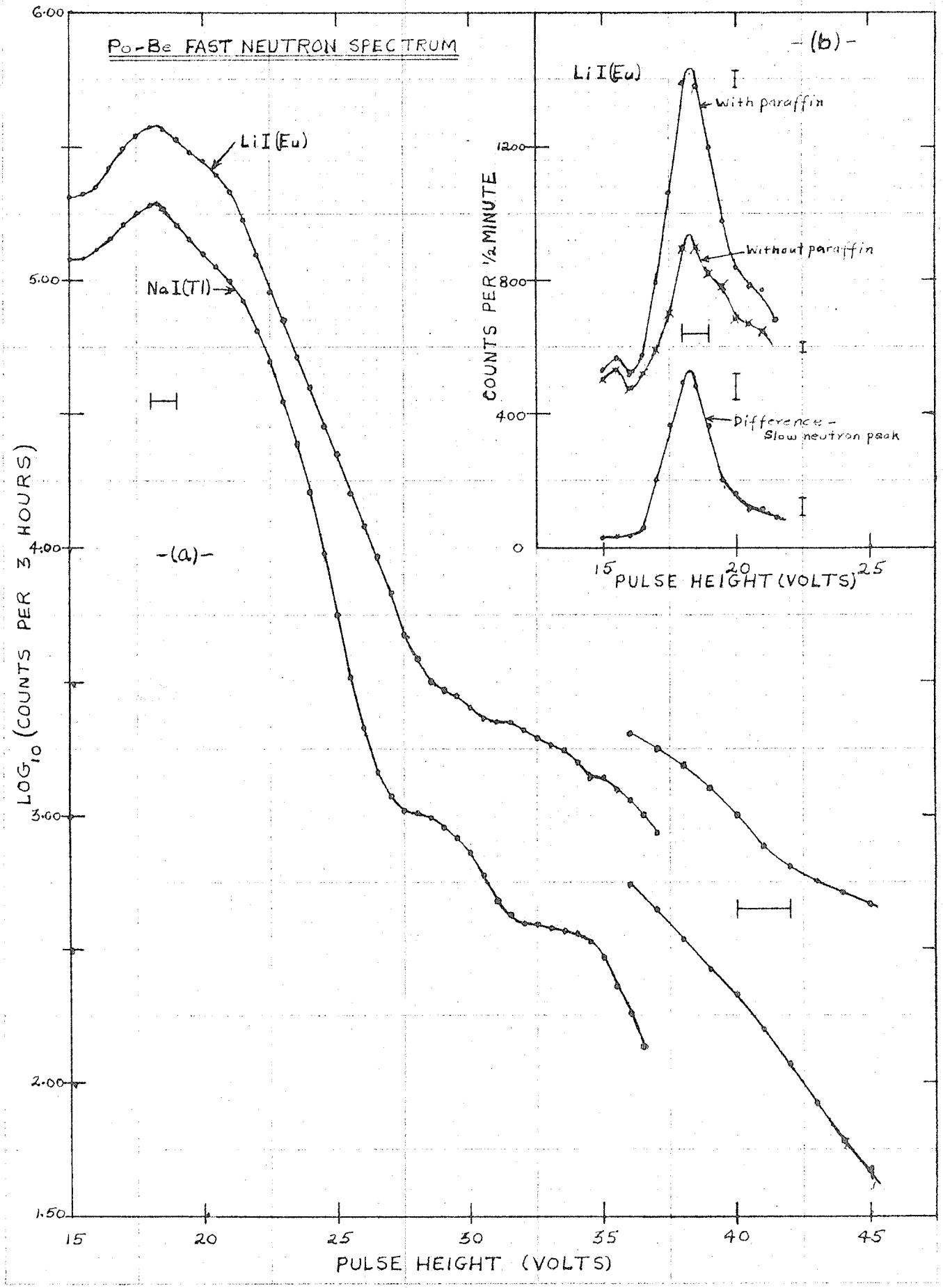
FIGURE 15


GAMMA-RAY ENERGY CALIBRATION CURVE
LiI(Eu)
γ-RAY ENERGY (MEV)
6.00
5.00
4.00
3.00
2.00
1.00
0
0
5
10
15
20
25
30
35
40
45
PULSE HEIGHT (VOLTS)
Cs 137
Zn 65
ThC'' (pair peak)
ThC'' (pair + capture)
(of 0.51 MeV)

1/2 inch in diameter and 1 inch in depth, was placed on the cover of the light-tight box containing the phototube and crystal. The source was handled with a set of tongs having an arm approximately 9 feet in length. By using these tongs, one could safely handle this comparatively 'hot' source without fear of getting too close to it. The source, when obtained from the Oak Ridge National Laboratory, had a strength of 5 curies. The half-life of the Po - Be source is wholly dependent on the 128-day half-life of Po. It was estimated that the source had a strength of about 2 curies midway through the experiment.

The LiI(Eu) crystal was initially calibrated for gamma-ray energies using the following sources - Cs^{137} (0.662 Mev.), Zn^{65} (1.12 Mev.), and Th (1.60 and 2.11 Mev.). It was found to have a linear energy relation for gamma-rays in this range of energies, as can be seen by the straight line graph of Fig. 15. In obtaining the LiI(Eu) spectrum for the Po - Be neutron source, one minute counts were taken up to a pulse height of 23 volts, thirty minute counts up to 25 volts, and three hour counts up to 37 volts. These counts were taken at half-volt steps with a one-volt gate. Three hour counts were taken at one-volt steps with a two-volt gate from a pulse height of 35 to 47 volts. Fig. 16(a) shows the spectrum obtained with LiI(Eu) after corrections were applied. The gate width used is indicated on the graph by a horizontal line with vertical bars at each end. The corrections applied arose from instrumental drift. A careful watch was maintained on the position of the gamma-ray

FIGURE 16

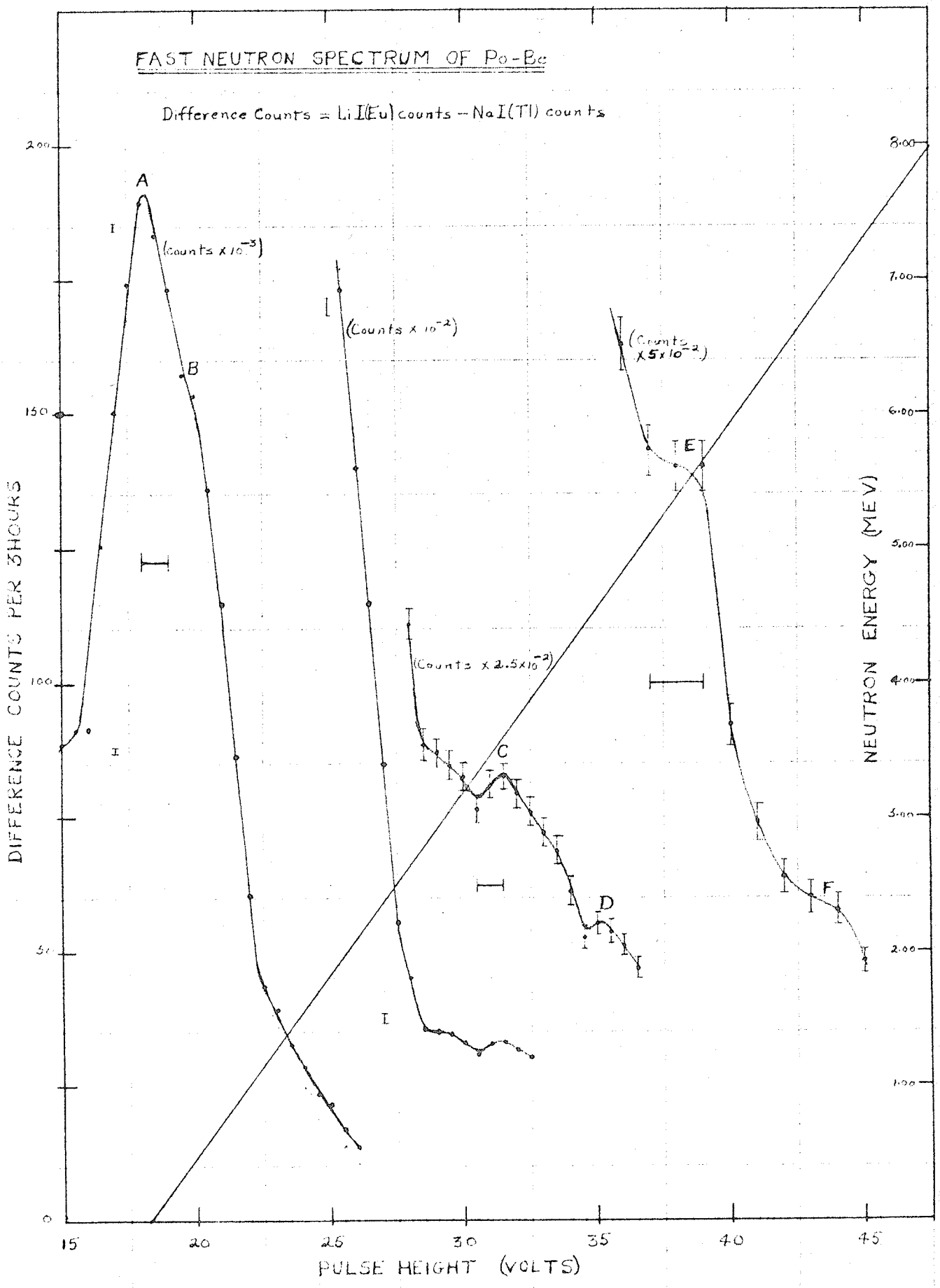

Po-Be FAST NEUTRON SPECTRUM
LiI(Eu)
NaI(Tl)
-(a)-
LOG10 (COUNTS PER 3 HOURS)
6.00
5.00
4.00
3.00
2.00
1.50
15
20
25
30
35
40
45
PULSE HEIGHT (VOLTS)
-(b)-
LiI(Eu)
with paraffin
without paraffin
Difference - Slow neutron peak
COUNTS PER ½ MINUTE
1200
800
400
0
15
20
25
PULSE HEIGHT (VOLTS)

peak at 18.3 volts to spot any drift in order that the point obtained could be corrected if drift did occur. Any appreciable drift during an overnight count could not be spotted. During the course of six days, no drift greater than 2.25% was noticed in the gamma-ray peak at 18.3 volts, and it was during this period that the counts used in drawing the curve of Fig. 16(a) were obtained.

The position of the slow-neutron peak had to be found accurately in order to get a neutron energy calibration curve. Counts were taken in the region of the gamma-ray peak with and without paraffin between the source and the LiI(Eu) crystal. The 'no-paraffin' curve was then subtracted from the 'paraffin' curve to give the slow neutron peak shown in Fig. 16(b). A straight line was drawn passing through two points on an energy (in Mev.) vs. pulse height (in volts) graph. The first point had a zero ordinate and an abscissa of 0.3 volts, which was the zero point of the differential discriminator. The second point had an ordinate of 4.80 Mev., the Q value of the reaction $Li^6(n, \alpha)\ H^3$, and an abscissa equal to the pulse height of the slow neutron peak. The neutron energy calibration curve was obtained by drawing a straight line (assuming a linear energy relation[2]) with the same slope as the above line and passing through the point with zero energy and pulse height equal to that obtained for the slow neutron peak. This calibration curve is given in Fig. 17 with the neutron energy scale as the right-hand ordinates.

Since LiI(Eu) is also an efficient detector of gamma-rays,

FIG. 17


FAST NEUTRON SPECTRUM OF Po-Be
Difference Counts = LiI(Eu) counts – NaI(Tl) counts
A
B
C
D
E
F
(Counts x 10⁻³)
(Counts x 10⁻²)
(Counts x 5 x 10⁻²)
(Counts x 2.5 x 10⁻²)
DIFFERENCE COUNTS PER 3 HOURS
NEUTRON ENERGY (MEV)
PULSE HEIGHT (VOLTS)
0
50
100
150
200
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
15
20
25
30
35
40
45

the Po - Be neutron spectrum found with this crystal is due not only to neutrons but also to gamma-rays produced in the reaction $Be^{9}(\alpha,n)\ C^{12}$. These gamma-rays arise from the de-excitation of excited levels of the C^{12} nucleus. NaI(Tl) was used to determine the shape of this gamma-ray spectrum. The light output of this crystal had to be cut down with a grid cut from black paper because the pulse height obtained with NaI(Tl) for a given gamma-ray photopeak was 14.3 times higher than with LiI(Eu) (see Table I). The gamma-ray energy vs. pulse height calibration curve for NaI(Tl) was made to correspond exactly with that for LiI(Eu), as shown in Fig. 15, by means of this grid. This meant that these two crystals would then give the same resolution for a given gamma-ray photopeak. This was a necessary feature if a Po - Be gamma-ray spectrum that could be subtracted from the LiI(Eu) neutron-plus-gamma-ray spectrum was to be obtained with NaI(Tl).

Upon studying the Po - Be source with NaI(Tl), it was confirmed that the prominent feature obtained with LiI(Eu) at a pulse height of 18.3 volts was due chiefly to gamma-radiation, and was in fact the pair-production peak for the C^{12} gamma-ray having an energy of 4.45 Mev. It is found, by using Fig. 15, that this pulse height corresponds to an energy of 3.42 Mev., which gives a value of 4.44 Mev. for this C^{12} gamma-ray, (N.B. Since the calibration curve of Fig. 15 was obtained with the amplifier set at full gain, and since the Po - Be spectrum was obtained with the amplifier set at half gain, the gamma-ray energy scale reading must be

doubled to give the correct value in this case.).

NaI(Tl) gave higher counting rates than LiI(Eu) chiefly because of the larger volume of the NaI(Tl) crystal. A normalization factor had to be applied to the NaI(Tl) curve to give the same counting rates for gamma-radiation for both crystals in order that only the neutron counting rate would be left after the curves were subtracted. This factor was obtained from a consideration of the masses and atomic weights of the constituents of the two crystals. The final LiI(Eu) and NaI(Tl) curves are shown in Fig. 16(a). The great similarity in the shapes of the two curves in the neighbourhood of the pair-production peak for the 4.45 Mev. gamma-ray of C^{12} indicates that slow neutrons produced no detectable modification in the LiI(Eu) curve. Of course, this was not true when paraffin was placed between the source and the LiI(Eu) crystal to greatly increase the number of slow neutrons as can be seen in Fig. 16(b).

The neutron energy spectrum of Po - Be was obtained by subtracting the NaI(Tl) curve from the LiI(Eu) curve. Fig. 17 shows the curve obtained after a cross section correction had been applied. Since no data were available for the neutron cross section variation with energy of Li^6 for neutrons of energy greater than 1 Mev., the 1/v law[25], where v is the velocity of incident neutrons, wasapplied to give this difference curve. The neutron energy calibration curve is also included in Fig. 17.

In Fig. 17, feature A is the slow neutron peak.

Feature B seems to be due to the resonance peak at about 0.3 Mev. in the neutron cross section curve of Li^6. Features C, D and E are pronounced maxima having energies of $3.6 \pm .2$, $4.6 \pm .2$ and $5.5 \pm .2$ Mev., respectively. A doubtful maximum is suggested at an energy of $7.1 \pm .3$ Mev. at F. Table II compares the values of the neutron energy maxima obtained in this experiment with values obtained by other workers. The methods used by Whitmore and Baker and by Elliot et al were mentioned earlier in the discussion on neutron detection. Gursky et al[26] employed a variable absorption proportional counter arrangement to get their results. Neiler et al[27] also used the Li^6 (n, α) H^3 reaction in LiI(Eu) in their experiment.

TABLE II

Energy Spectrum of Neutrons from a Po - Be Source.

(Energy in Mev.)

Feature (Fig.17)	Present Work	Whitmore and Baker[18]	Elliot et al[15]	Gursky et al[26]	Neiler et al[27]
-	-	1.2 (D)	1.8 (D)	-	2.3
C	3.6	3.2	3.6	3.2	3.6
D	4.6	4.8	4.5 (D)	4.6	5.0
E	5.5	5.8 (D)	5.5	5.5	-
F	7.1	7.7	8.2 (D)	-	-
-	-	9.7 (D)	9.4 (D)	-	-
-	-	-	-	-	16.7

(D - doubtful)

CONCLUSION

A neutron scintillation spectrometer was used to study the fast neutron spectrum of a Po - Be neutron source. This spectrometer detected and measured the energies of neutrons with a europium activated lithium iodide crystal (LiI(Eu)) due to the exoergic reaction $Li^6(n, \alpha) H^3$ which has a Q of 4.785 Mev.[1] A linear relation[2] was assumed between the neutron energy and the amount of light given out by the crystal, and from this a calibration curve for neutron energies was obtained.

The LiI(Eu) crystal used in this spectrometer was also an efficient detector of gamma-rays. A thallium activated sodium iodide crystal (NaI(Tl)), which does not respond to neutrons, was used to find the gamma-ray distribution curve for the Po - Be source. After suitable corrections were applied to this NaI(Tl) curve, it was subtracted from the LiI(Eu) curve to give the fast neutron energy spectrum of Po - Be.

In the fast neutron energy spectrum of Po - Be obtained with this spectrometer, maxima were obtained at energies of 3.6, 4.6 and 5.5 Mev. There was also evidence suggesting a maximum at 7.1 Mev.

The output pulses from three crystals - LiI(Eu), CsI(Tl) and CsI, were compared with NaI(Tl). Tests were made on the pulse height change with changing temperature from CsI and CsI(Tl). Both crystals were lowered to liquid nitrogen

temperature. At liquid nitrogen temperature CsI gave a pulse height 8 times larger than that at room temperature. A comparison was made of the spectra obtained with CsI(Tl) and NaI(Tl) for Cs^{137}, Zn^{65} and Ir^{192}.

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