Development of a
TOTAL ABSORPTION GAMMA RAY SCINTILLATION SPECTROMETER

A Thesis

Submitted to the

Faculty of Graduate Studies

UNIVERSITY OF MANITOBA

in partial fulfillment of the

requirements of the degree of

MASTER OF SCIENCE

by

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WINNIPEG, CANADA

August, 1956.

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PREFACE

The work presented in this thesis was carried out at the University of Manitoba during September 1954 - June 1956. It forms a part of a research program supported by the Defence Research Board of Canada.

The author wishes to express his most sincere gratitude to Dr. K.I. Roulston for his guiding interest, constant encouragement and invaluable discussions; to Dr. W.E. Turchinetz for many helpful suggestions and to Mr. C.J. Kubin for his part in mechanical construction of the equipment. Acknowledgement is also due for Miss. D. Obirek for accepting all typing work, and for Miss M. Guest for drawing the figures.

Financial assistance from the Defence Research Board of Canada is gratefully acknowledged. Without this help the project could not have been undertaken.

ABSTRACT

The development of a gamma-ray scintillation spectrometer is described in which use is made of a plastic phosphor as an anti-Compton shield. The performance of such a spectrometer is evaluated by studying the gamma-ray spectra of Cs^{137}, Zn^{65} and I^{131}. It is shown that the shield is effective in reducing the Compton portion of the gamma-ray spectra to about 35 per cent of its original value. The photo-peak as well as the internal conversion X-ray peak due to unassociated gamma-rays are left unreduced. Further applications of the spectrometer are suggested.

On the instrumentation side, a transistor anti-coincidence unit is used. All other electronic equipment used, with the exception of the scaler, was also either developed independently or entailed modification of existing units. A description of each is given.

CHAPTER 1.

INTRODUCTION

In the vast amount of knowledge accumulated to this day in physics one thing which is peculiarly missing is a completely satisfactory theory of the nucleus. The existing state of affairs in nuclear physics today is that there are a few islands of coherent knowledge in a sea of uncorrelated experimental facts. Such a state of affairs has once before existed, in the realm of atomic spectra. One would recall that a vast amount of experimental data first had to be accumulated before a satisfactory and consistent theory of atomic spectra could be propounded. Judging from the past experience it is hoped that given enough information about the nucleus, it will be possible to construct a satisfactory theory of the nucleus (B46).

One of several ways to study the nucleus is to examine the particles and radiations emitted by either naturally or artificially radioactive nuclei. The three most common radiations emitted by the nucleus are the alpha, beta and gamma radiations. The last named, gamma radiation, is known to, or more correctly, is hypothesised to arise from the transition of a nucleus from one energy state to another. The study of the energy levels in which different nuclei exist has been called ''nuclear spectroscopy''.

After beta-emission, or any nuclear interaction, the resulting nucleus is usually left in an excited state. In going to the ground state either directly or through successive steps, the nucleus emits one or more gamma rays. If between the excited

and ground state of the daughter nucleus (after beta-emission) there are in all "n" levels (including both the excited and the ground levels) and if transition to all the levels is probable, the number of gamma rays emitted will be $^{n}C_{2}$. These gamma rays provide a very suitable medium for nuclear spectroscopic studies.

The total absorption gamma-ray spectrometer, described in this thesis is a device based on scintillation technique. In such a spectrometer the self-coincident gamma lines tend to disappear. Thus, if the spectrometer is 100 per cent effective then in the spectrum obtained there will not be as many as $^{n}C_{2}$ gamma lines as mentioned in the preceding paragraph. Instead, the number of gamma rays observed will be equal to the number of levels to which the beta-transition takes place. The energy of such a gamma ray will be complementary to the beta-particle energy. The spectrometer, however, is not 100 per cent efficient; but still there is a clear indication which of the gamma rays correspond to the levels to which a beta transition has taken place. Since the self-coincident gamma lines mutually reduce each other, the spectrum obtained is somewhat simpler than the one obtained by an ordinary scintillation spectrometer. Further, such a spectrum also helps to estimate the nuclear energy levels and determine their cascade relationship more directly, precisely and easily than [redacted] by any other single nuclear spectroscopic technique.

CHAPTER 2.

SCINTILLATION SPECTROMETER

The scintillation technique was one of the earliest employed for detection of nuclear emanations. A scintillation screen was first used by Rutherford and his associates in 1903 as a detector of alpha particles. The principle was revived by Curran and Baker in 1944 with the addition of a photomultiplier tube for secondary detection (C44). This was the first simple form of the modern scintillation counter. In 1945 Blau and Dreyfus (B45) used a similar method to measure the alpha radiation intensity. The method was later developed by Kallmann (K47, K49) and by Coltman and Marshall (C47). They mainly used single crystals of various luminescent materials to produce the scintillation and subsequent electronic equipment for counting. For a survey of scintillators and also of the scintillation counter, the reader is referred to volumes by Curran (C53) and by Birks (B53). During the last nine years the scintillation counter and spectrometer have developed very rapidly. Presently it is the most used detection instrument in modern nuclear research. Some of the reasons for this are the following:-

(i) Because the photomultiplier tube is capable of detecting even extremely low intensity light flashes ($\sim 10^{-9}$ lumens), the scintillation counter is very sensitive.

(ii) As compared to some of the other techniques such as cloud chambers, magnetic focussing spectrometer and photographic emulsion, the scintillation method is more convenient to use for rapid survey.

(iii) Since the scintillation technique is more efficient than most of the others, weak source strengths (fractions of a microcurie) can be used.

(iv) It can be used for all radiations (electrons, protons, neutrons, alpha-particles, and gamma-rays) just by selecting the suitable scintillator.

(v) Scintillation counter has energy-selective properties in the range of 1 - 2 Kev to about 20 Mev. It can therefore be used both as a detector of radiations and also as a spectrometer.

(vi) Because the multiplication occurs in a vacuum rather than in a gas, the transit time of the secondary electrons is much less than the drift time of the ions in a Geiger Counter. Thus, if the scintillator is chosen to have a rapid decay, resolving times of the order of a few milli-microseconds can be obtained. It can, therefore, handle a high counting rate. This also makes it particularly suitable for fast coincidence experiments.

A more detailed description of the scintillation spectrometer is given elsewhere in the literature (R52, B55). Only a short description will be given here to bring up some important features which will be used later for the development of the total absorption spectrometer.

Essentially the scintillation spectrometer consists of a scintillating material which gives out flashes of light whenever a photon or any other nuclear particle interacts with it. The

scintillating material or scintillator is sometimes called ''phosphor'', although the actual process involved is ''fluorescence''. These flashes of light emitted by the scintillator are so minute (in intensity) and short lived that they are invisible to the naked eye. The scintillator, which frequently is a crystal, is therefore coupled directly or through a light pipe to a photo-multiplier tube. The purpose of the light pipe would be to cause a somewhat more uniform illumination of the photo-cathode surface of the multiplier tube more or less independent of position of origin of the scintillation in the phosphor. The light pipe is sometimes necessary to remove photo-multiplier tube from an unsuitable location (e.g. in a magnetic field). Figure 1, given below, shows the arrangement of the phosphor-photomultiplier tube assembly.

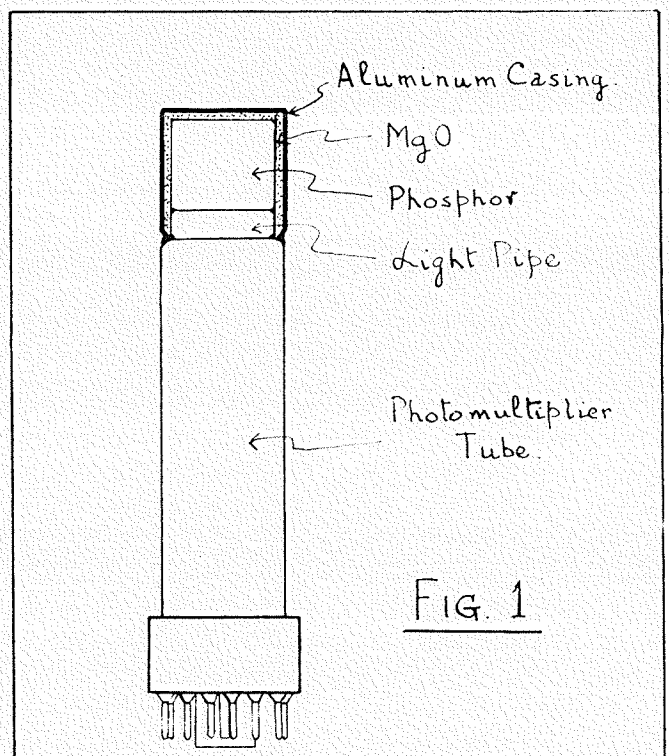
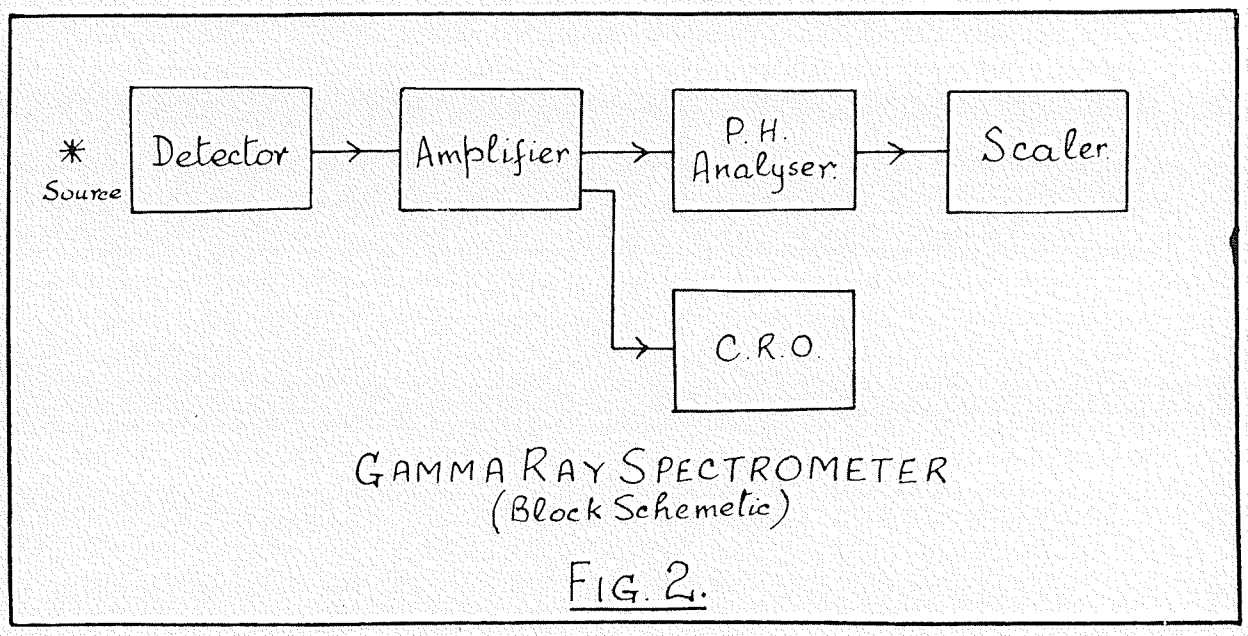


FIG. 1

PHOSPHOR PHOTOMULTIPLIER ASSEMBLY. (Schematic)

From the photomultiplier tube is finally obtained a voltage pulse whose amplitude (in volts) is directly proportional to the intensity of flash. This proportionality is linear only for low output (about one or two volts) from the photo-multiplier tube, unless the tube is designed to deliver large pulses. It is further subjected to statistical fluctuations.

The intensity of the light flash from the phosphor is in turn proportional to the amount of energy lost in the phosphor by the gamma ray photon. This proportionality is also subject to statistical fluctuations (R52). It is found to be linear from about 10 - 15 Kev up to about 20 Mev (B55) for sodium iodide (thallium activated) crystals, used with efficient optical reflectors. The linearity is impaired by an inefficient optical reflector or later by an unsatisfactory linear amplifier or pulse height analyser, which follow the photomultiplier tube. Linearity in other inorganic crystals such as lithium iodide (europium activated), cesium iodide, calcium tungstate and zinc sulphide (silver activated) is more or less the same as in sodium iodide (thallium activated) crystal. Organic scintillators have been found to be linear from about 100 Kev up to about 12 Mev (B55). Fig. 2 given below shows the block schematic diagram of a gamma-ray scintillation spectrometer.



GAMMA RAY SPECTROMETER
(Block Schemetic)

FIG. 2.

An analysis, after suitable amplification, of the voltage pulse output from the photomultiplier tube is an effective analysis of the gamma-ray striking the scintillator. If the counting rate in some voltage interval is plotted against the mean voltage of the interval, a pulse height distribution curve is obtained. The following would be the general features of such a curve obtained from a source of single gamma-ray of energy E. The energy E is less than 1.02 Mev and the source is not a positron emitter.

The counts corresponding to the absorption, in the phosphor, of total energy E of the gamma-ray photon will go to form a peak called the "photo-peak". This total absorption of gamma-ray energy can occur by either one single photoelectric interaction or by successive Compton collisions followed by a photoelectric interaction, with subsequent absorption of the X-rays following every photoelectric process. If the X-rays resulting from a photoelectric interaction are not reabsorbed in the crystal but escape from it, there will be other peaks (called escape peaks) at $E - E_K$, $E - E_L$, etc. where E_K, E_L, etc. are the binding energies of the K, L, etc. electronic shell assuming that the K electron was knocked out in the photoelectric process. Since E_K is small (a few Kev) as compared to the gamma-ray energy and E_L, etc. are even smaller, the escape peaks will fall within the width of the photo-peak and will alter the rising edge of the photo-peak from the symmetric gaussian shape. At gamma-ray energies less than 100 Kev and using NaI (Tl) crystal, because E_K involved is about 28 Kev, a second escape peak will be resolved whose mean pulse height

is proportional to $E - E_K$. Other peaks at $E - E_L$, etc. may also be resolved, but are less probable.

As well as the ''photo-peak'' there will be a broad ''Compton portion'' of the spectrum corresponding to those gamma-ray photons which, after losing a part of their energy by Compton process in the phosphor, manage to escape from it. This portion of the spectrum would have a Compton edge, clearly or badly defined, depending upon the resolution. The Compton edge will have the energy $E\left[1 + \frac{.511}{2E}\right]^{-1}$ Mev, which is the maximum energy loss in a single Compton collision (head on collision).

The radiations back-scattered from outside material will have a large probability of being totally absorbed in the crystal. This would give rise to a ''back-scattered peak'' in the spectrum. Its position will correspond to the energy of the back-scattered photon i.e. $E\left[1 + \frac{2E}{.511}\right]^{-1}$ Mev.

At low energies there will be a peak corresponding to the X-rays emitted by the daughter nucleus in the source of gamma-rays. These X-rays will arise due to internal conversion or due to K-capture if such is one of the modes of decay.

Fig. 3 shows the general shape of spectrum expected from a source of single gamma ray of energy E Mev. It is assumed that E is less than 1.02 Mev and the source is not a positron emitter. If E is greater than 1.02 Mev, there will be [redacted] peaks at E, (E - .511) and (E - 1.02) Mev corresponding respectively to the no escape, escape of one, and escape of both annihilation quanta. If the source is a positron emitter, there will be a peak at

0.511 Mev corresponding to the capture of one of the gamma rays due to positron annihilation.

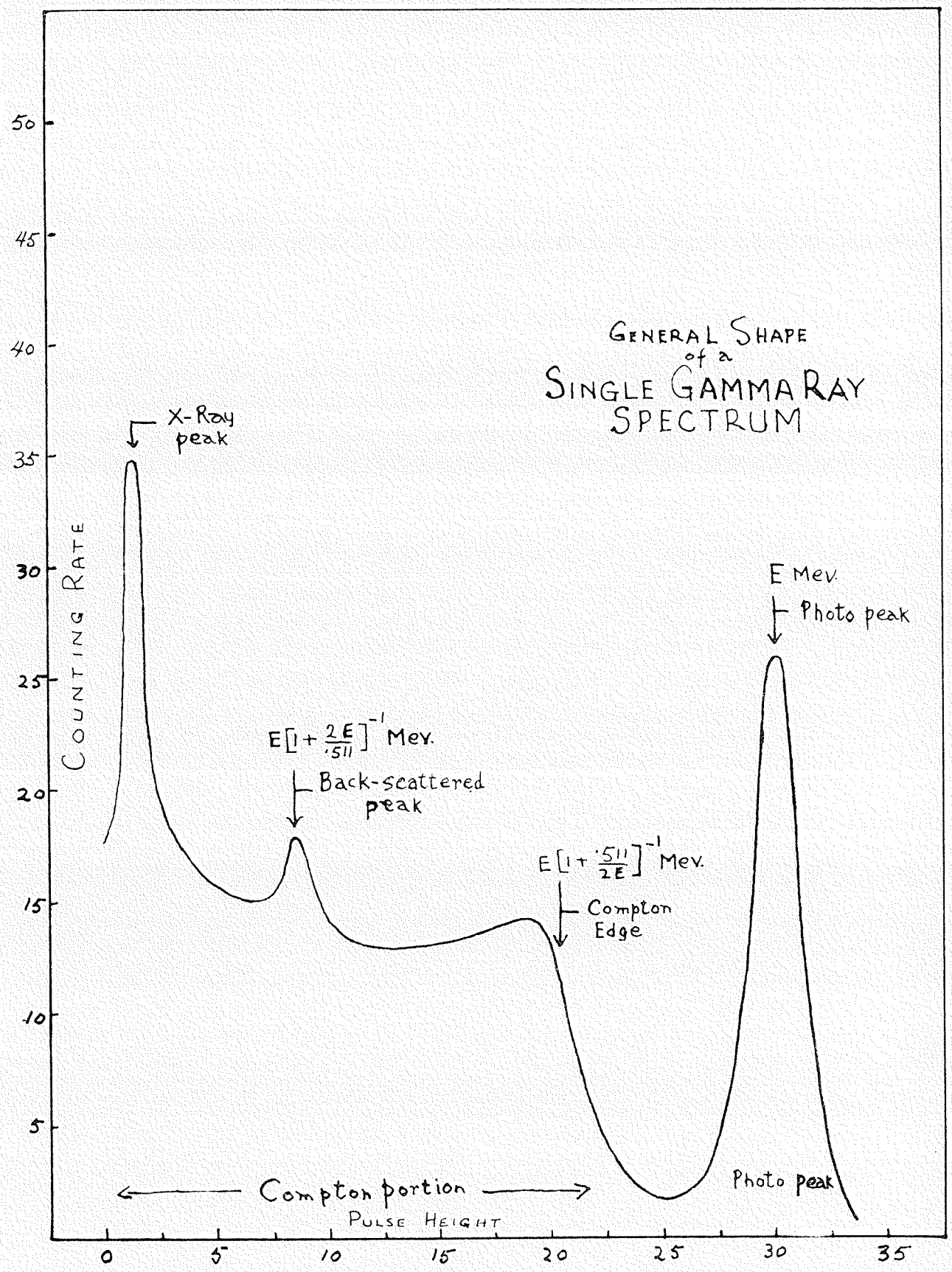

General Shape
of a
Single Gamma Ray
Spectrum
X-Ray peak
E Mev.
Photo peak
$E\left[1+\frac{2E}{.511}\right]^{-1}$ Mev.
Back-scattered peak
$E\left[1+\frac{.511}{2E}\right]^{-1}$ Mev.
Compton Edge
Photo peak
Compton portion
Counting Rate
Pulse Height
0
5
10
15
20
25
30
35
40
45
50

Fig. 3.

CHAPTER 3.

TOTAL ABSORPTION SPECTROMETER

3.1 SCHEME:-

Inspection of Fig. 3 will confirm that the most useful feature in the gamma-ray spectrum is its ''photo-peak''. If the source contains more than one gamma-ray, the resulting spectrum will be a superposition of several such curves as shown in Fig. 3. Such a complicated spectrum will be very difficult to interpret and some of the features may even be lost in the complex spectrum. This is specially so if the source studied has two rather close gamma-rays and if the one lower in energy is also weaker in intensity. The latter gamma-ray would probably be lost in the Compton portion of the more intense and higher energy gamma-ray. These considerations call for some way of reducing the Compton portion.

The method of using a large crystal in scintillation spectroscopy to reduce the Compton portion of the spectrum is well established (B55). The gamma-ray source is placed at the centre of a large NaI (Tl) crystal (for example, 4 inches diameter, 4 inches long) in a hole drilled along its axis. It is now obvious that most of the gamma-ray photons will give up all of their energy to the crystal because, the crystal being large, the probability of escape of a photon without interacting with the crystal is small. Also, the self-coincident gamma-rays will add up to give the total energy which is complementary to the beta particle energy. The advantage of using such a large crystal is that it not only reduces the Compton portion but also increases the size of the photo-peak. There are, however, some limitations

on the size of the crystal. Apart from the fact that large crystals are very expensive, it becomes increasingly difficult for the light flashes to come out of the crystal. Also, the light transmission properties do not remain uniform over all parts of the large crystal. Finally, the photomultiplier coupled with such a crystal has to have a large photo-cathode area which may not have uniform photo-sensitivity. These factors contribute to make the resolution poor and this is the main disadvantage of large crystal spectrometry.

On the other hand, small crystals are more desirable on some occasions, for example in angular correlation studies or high resolution spectroscopy. Resolution, is defined qualitatively as the ability to distinguish between two close gamma lines. Quantitatively it is defined as the ratio of the width of the photo-peak at half its height to the mean value of the centre of the peak, and is usually expressed as a percentage. The factors affecting the resolution are many, namely, the gamma-ray to light (low energy photon) conversion efficiency of the crystal, the light collection efficiency, that is, out of the total number of light photons originating in the crystal the fraction that does reach the photo-cathode and finally the efficiency of the photo-cathode surface of the photomultiplier to emit electrons for the incident light photons. The greatest proportionate statistical variations occur in the photoelectrons emitted by the photo-cathode of the multiplier tube (R52). For high resolution, therefore, the photo-cathode should have uniform sensitivity and this is obtained by employing the smallest possible photo-cathode area. This in turn calls for the use of small crystals. Incidently the light

collection efficiency is also better with small crystals than with the large ones. It is the design and construction of an instrument to accomplish a reduction in the Compton contribution while using small crystals that is the concern of this thesis. A brief summary of the essential idea follows, after which a detailed description of the instrument will be presented.

A small crystal is coupled with a small photomultiplier tube and is used in the usual manner to study the gamma-ray spectrum. The whole crystal-multiplier tube assembly is then surrounded by a large scintillator. The source is placed between the small crystal and large scintillator (See arrangement in Fig. 4). Whenever a gamma photon after suffering a Compton collision in the small crystal is scattered out of the crystal, it may be detected in the large scintillator. Thus if the output from the large scintillator is used in anti-coincidence with the output from the small crystal, the Compton counts are cancelled out. On the other hand, no counts occur in the large scintillator which are time-correlated with counts in the photo-peak, except for chance coincidences. The resulting spectrum, therefore, has the same size of photo-peak as obtained without using the large scintillator in anti-coincidence; but has a reduced Compton portion. Because of its action, the large scintillator used in this manner is called an ''anti-Compton Shield''.

Such a spectrometer using a cluster of NaI (Tl) crystals as an anti-Compton shield has been described by Albert (A53). The photographs shown in the literature [redacted] are excellent but no

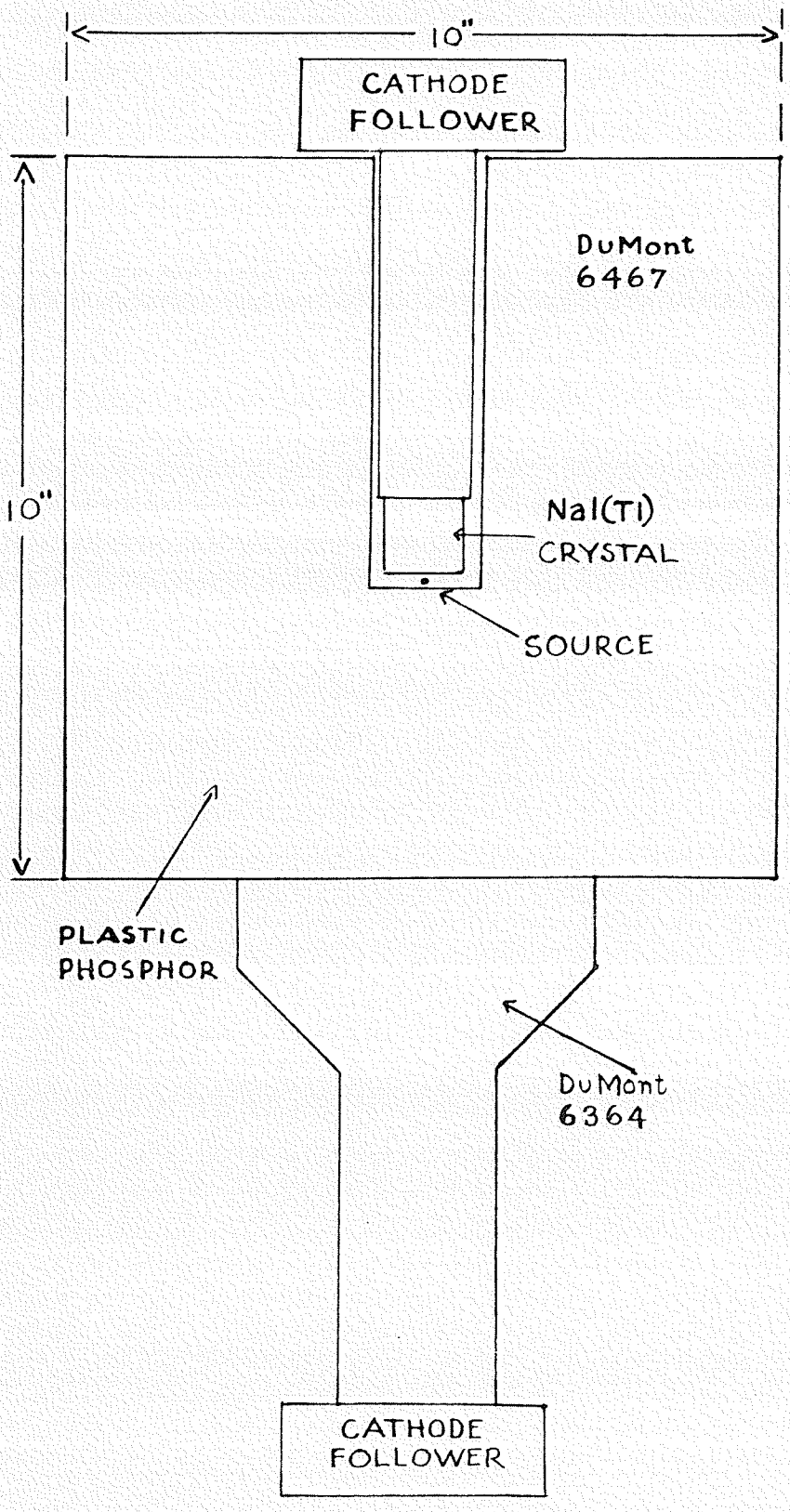

10"
CATHODE FOLLOWER
DuMont 6467
10"
NaI(Tl) CRYSTAL
SOURCE
PLASTIC PHOSPHOR
DuMont 6364
CATHODE FOLLOWER

FIG. 4.

pulse-height distribution curve is given. It is difficult to estimate the reduction caused in the Compton portion. Since large plastic phosphors have become available, it seemed desirable to investigate their performance as an anti-Compton shield.

Following the above mentioned idea, a total absorption spectrometer was designed using a one inch by one inch cylindrical crystal of sodium iodide activated by about one per cent of thallium iodide. The crystal was coupled optically to a one inch photomultiplier tube (DuMont 6467) which was made light tight with black plastic tape. This assembly was then inserted in a hole, about 1 1/2 inch in diameter, bored approximately half way down the axis of a large plastic scintillator in the shape of a 10 inches by 10 inches cylinder. The plastic phosphor was surrounded by a layer of cellucotton dusted with magnesium oxide ~~heavily~~ to act as an optical reflector. It was important to ensure a good light collection efficiency from the plastic. For this reason tests were made on a piece of small (one inch by one inch cylinder) plastic phosphor for relative efficiency of the various optical reflectors. The result is shown in the following table (page16 which indicates that the cellucotton dusted ~~heavily~~ with magnesium oxide powder is the best of all. For the same reason, that is, better efficiency for light collection, the large plastic phosphor was viewed by two 5 inches photomultiplier tubes (DuMont 6364) through suitable holes in the covering layer at the bottom end of the cylinder. The whole assembly was housed in a light-tight box. Plate 1 is a photograph of the arrangement shown schematically in Fig. 4.

Relative Efficiency of the Optical Reflectors Used for the Plastic Phosphor:-

Reflector Used	Counts per second
No reflector	0.5
Aluminum foil	6.3
Tissue paper	13.4
Bond paper	14.7
Bond paper (thick)	36.1
Cellucotton	63.9
Cellucotton dusted with MgO	77.3

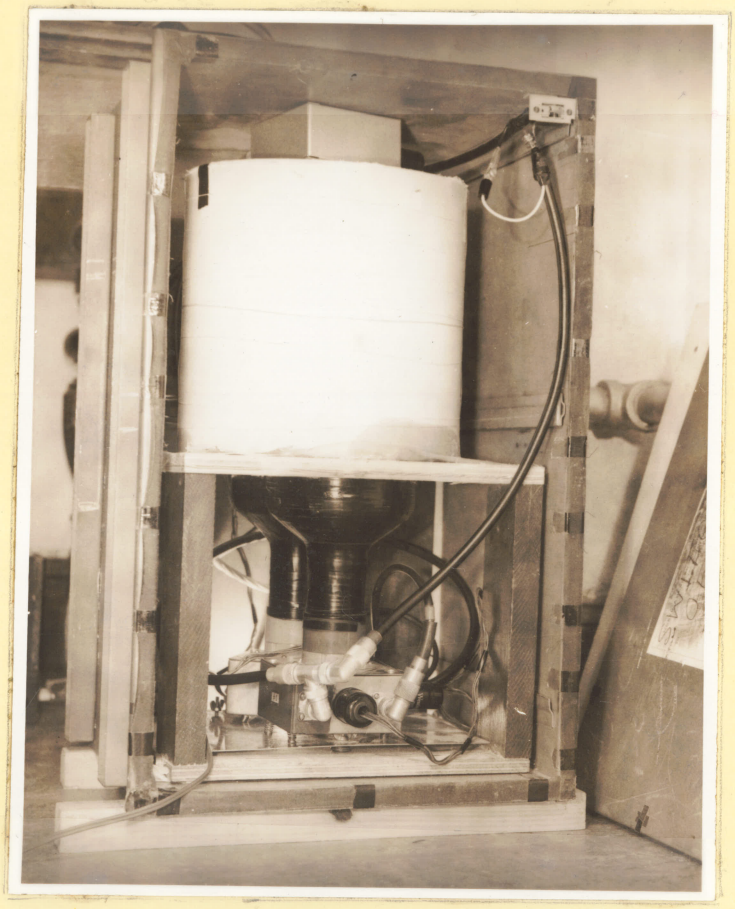


Plate 1

DETECTOR HEADS.

The source of gamma-rays could be placed close to the NaI (Tl) crystal in two different ways. These are shown in Fig. 5 as source positions A and B.*

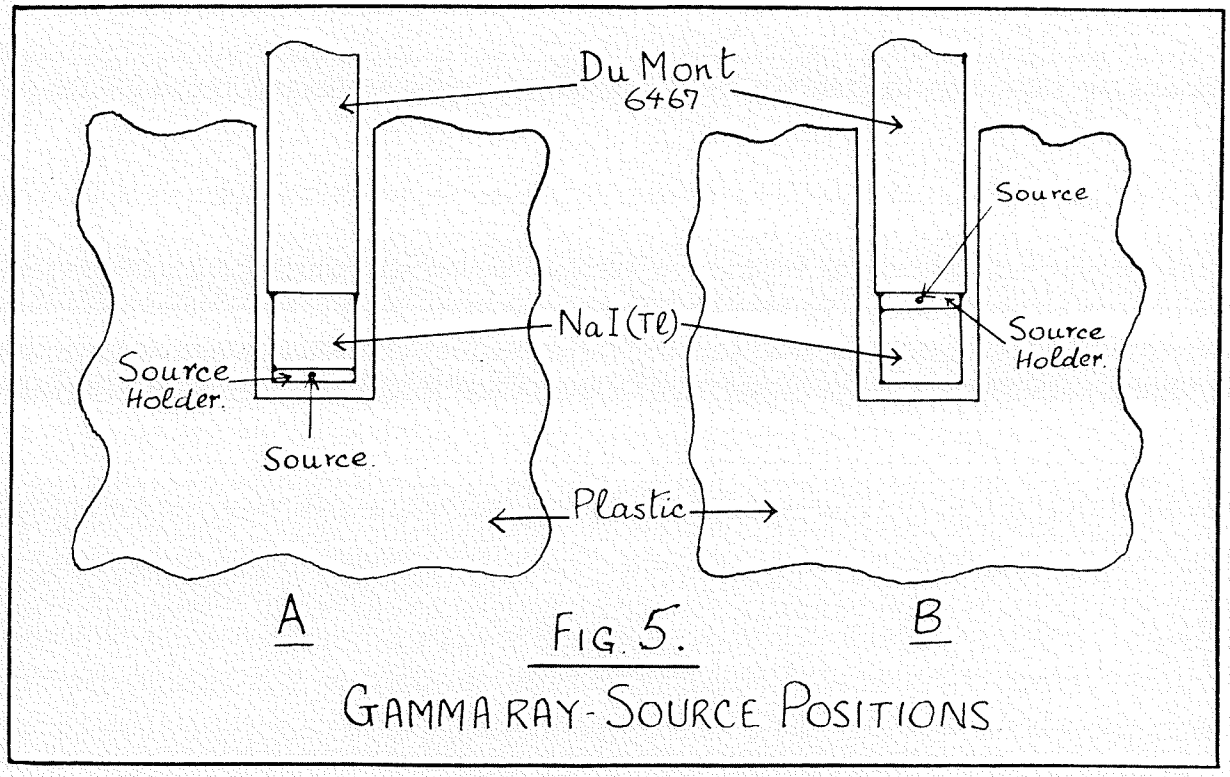


FIG. 5.
GAMMA RAY-SOURCE POSITIONS

A complete electronic schematic of the spectrometer, excepting power supplies, is shown in Fig. 6. The pulses from the NaI (Tl) channel are amplified in a low gain amplifier (about 50 times) of conventional design and are passed to a pulse height analyser. The analyser consists of a double discriminator unit containing conventional trigger discriminator circuits and a transistor anti-coincidence mixing circuit.

The plastic phosphor pulses are passed to a high gain amplifier (Atomic Instruments, Inc., Model 204C) modified to give a good overload response. The discriminator on this amplifier

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* This will be referred to in a later section.

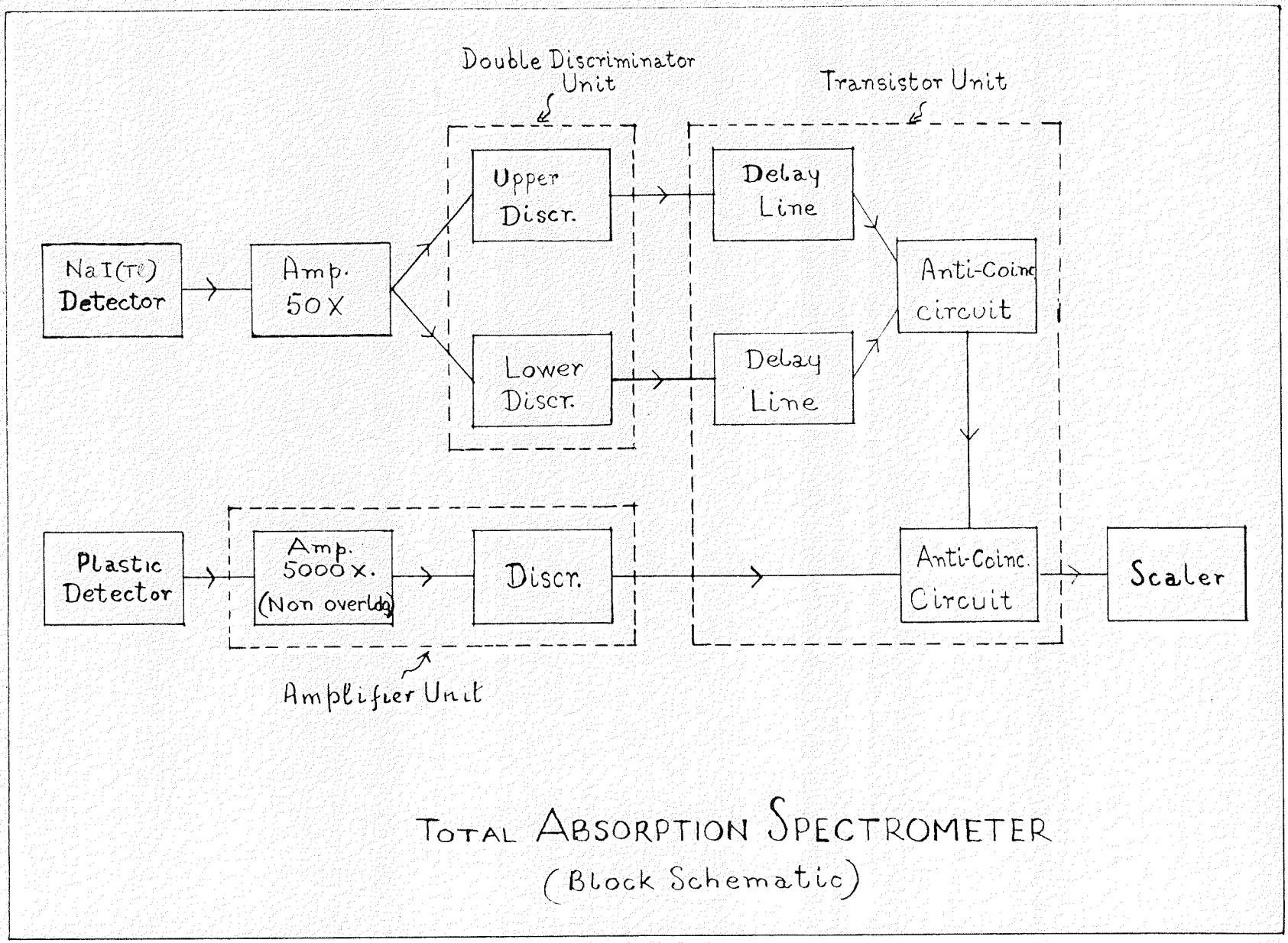
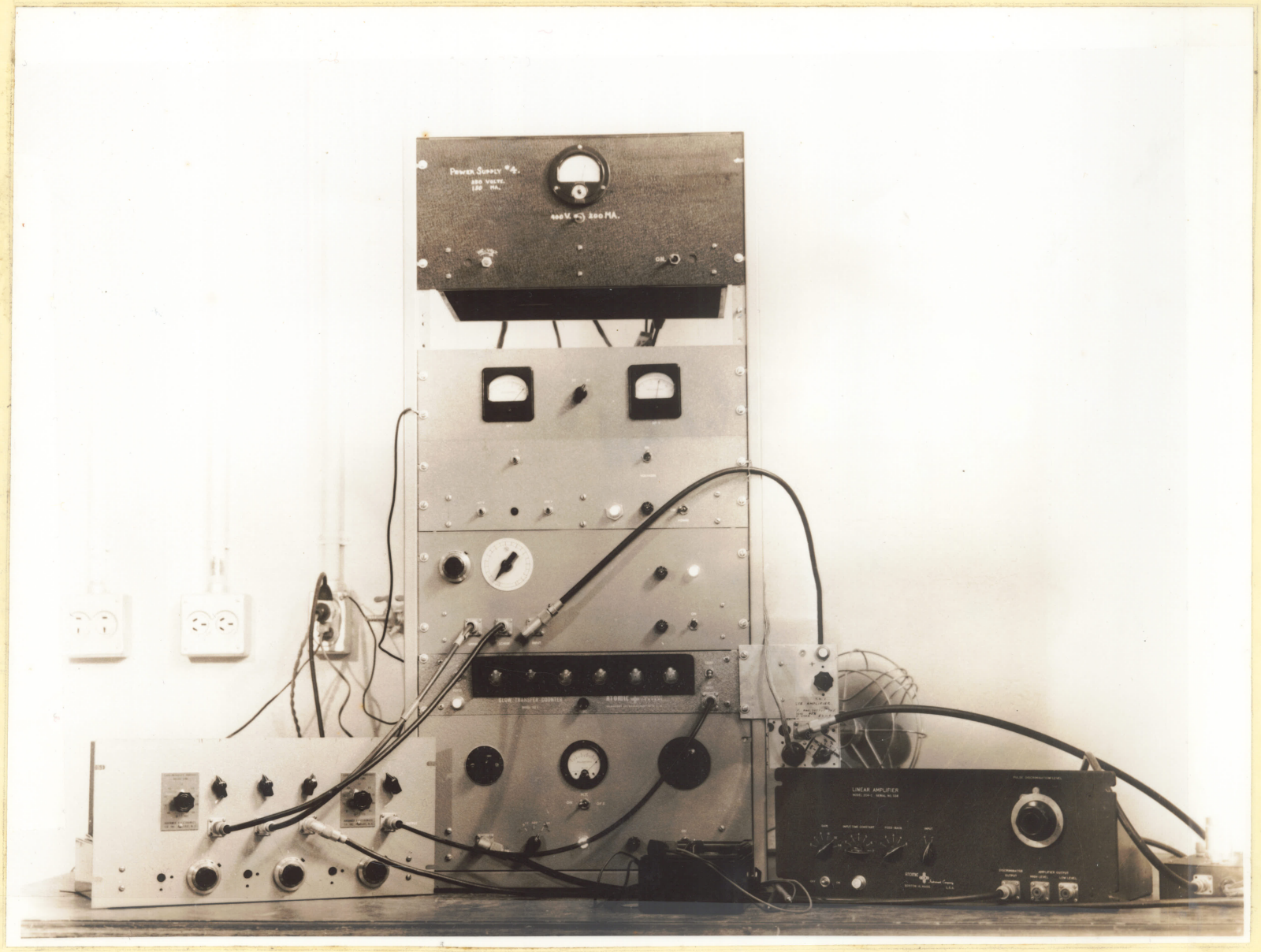


Fig. 6

TOTAL ABSORPTION SPECTROMETER
(Block Schematic)

was modified to give an output pulse of about one microsecond duration independent of the input pulse amplitude above the trigger level. This output is put in anti-coincidence with the analyser output. A photograph of the complete instrument is shown in plate 2.

A description of each electronic unit will now be given.



TOTAL ABSORPTION GAMMA-RAY SPECTROMETER

3.2 POWER SUPPLIES:-

The Atomic Instruments Model 204 C Linear Amplifier used to amplify plastic pulses had its own power supply. The scaler (Atomic Instruments Model 200) and the cathode ray oscilloscope (Tektronix Model 511AD) also had their own power supplies.

A standard stabilized power supply designed and built in this laboratory was used to supply power to the low gain amplifier, double discriminator and pulse generator units often used for testing purposes. The power supply is of conventional design and uses VR150 tube for reference. It is designed to deliver 150 milliamperes at 175-300 d.c. stabilized positive volts and a total of about 14 amperes at 6.3 a.c. volts from two separate filament wirings.

At first the same power supply unit was used to supply power to the cathode followers in the detector heads. There is, however, a danger that the pulses from the analyser section may be fed back, through the common power supply unit, to the plastic section and because of the high gain amplifier on this section, may give rise to misleading results. In earlier tests this difficulty was met and soon realized. In addition to inserting good decoupling devices at proper places in all electronic units, a separate power supply was employed to deliver power to cathode followers in the detector heads. With proper decoupling no interference was detected between the cathode followers on the two sections. This separate power supply unit was also designed and built in this laboratory and is similar to one described before but uses battery reference.

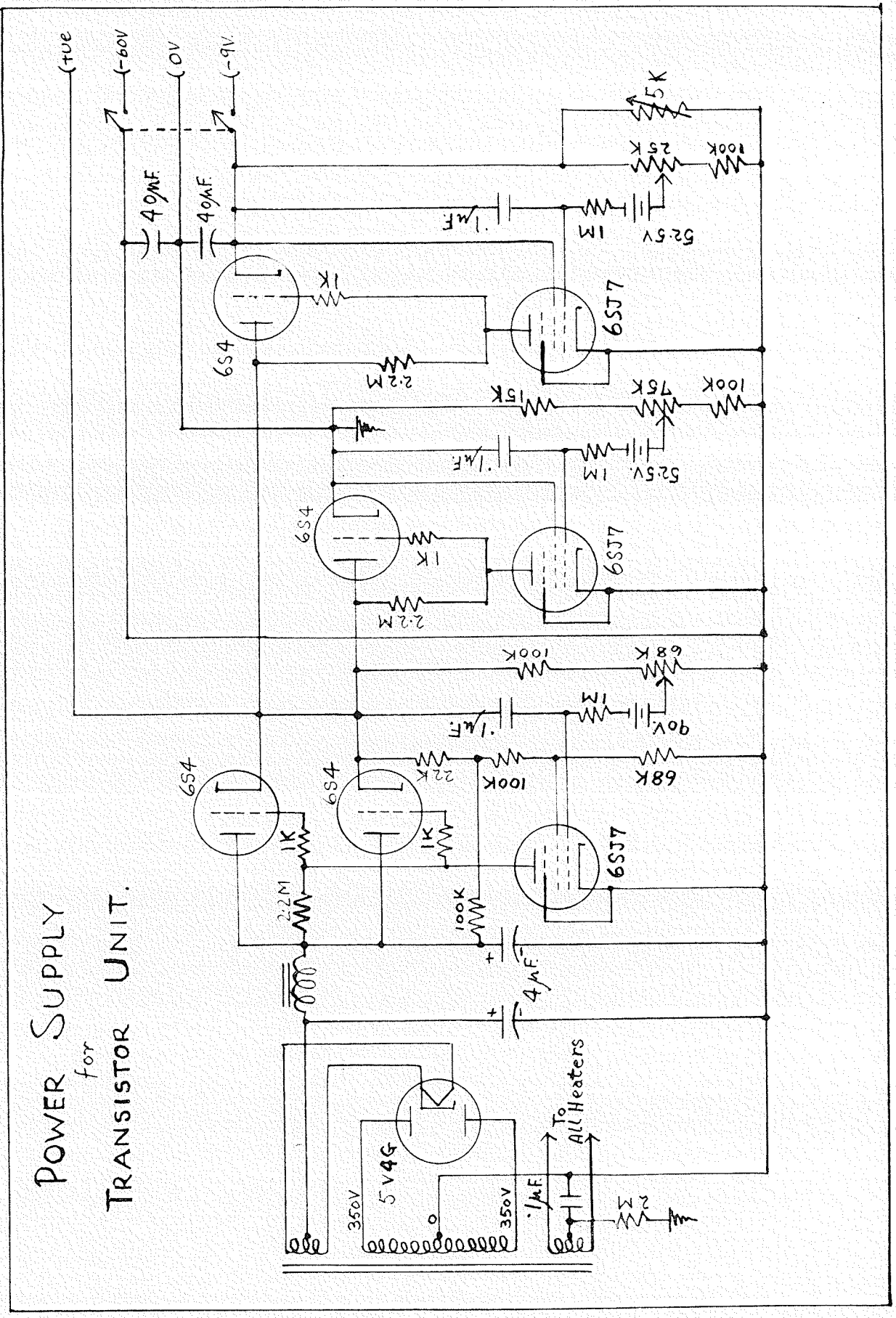

POWER SUPPLY
for
TRANSISTOR UNIT.
(+ve
(-60V
(0V
(-9V.
40MF.
40MF.
5K
25K
100K
1M
.1MF.
52.5V.
6S4
1K
2.2M
6SJ7
15K
75K
68K
90V.
22K
2.2M1
100K
4MF.
5V4G
350V
350V
.1MF.
To All Heaters
2M

FIG. 7

The power supply for transistor anti-coincidence unit was originally designed in this laboratory by Pollock (P55). In his design there were four outputs, namely, 100 volts positive for pulse height selection (discrimination) of positive pulses, 100 volts negative for discrimination of negative pulses, 67 1/2 volts negative for collector supply and 9 volts negative for emitter supply. For use in this spectrometer the design of the power supply was modified to give greater stability in collector and emitter supply voltages. The collector supply was changed to 60 volts negative to ensure safe operation of the transistors. The circuit in its present modified form is given in Fig. 7. Nine volts negative for emitter supply are obtained as the difference between a stabilized 51 volt supply section and a stabilized 60 volt supply section which also supplies the collector voltage. Both these sections are run from a stabilized 250 volts line which is obtained from 115 volts a.c. mains supply after transformer-rectifier-filter circuits. No 100 volts positive and negative supply was incorporated, because if required, the discrimination (pulse height selection) of both positive and negative pulses can be achieved by using the existing 250 d.c. positive voltage.

The 250 volts line is stabilized against both input voltage variations and output current variations. For an input voltage change from 90 - 130 volts the output voltage change is less than one volt (first increase and then decrease) most of which is due to cathode temperature variation. There is no noticeable variation in the output for an input change from about

105 - 115 volts. Against load variations of 0.2 milliamperes to 80 milliamperes, the output voltage changes by less than 0.2 volts.

Both the 60 volts and 51 volts sections are stabilized against a load variation of one to 50 milliamperes. Under normal conditions of load variations (no load to full load) the 60 volt supply section automatically stays in this working range. Because of the negative polarity of the nine volts supply, the 51 volts section does not draw any current unless an artificial load is put across it. A 5000 ohms potentiometer is used for this purpose whose setting will depend quite critically upon the number of transistors used (i.e. the load current drawn) in the transistor unit. In the present arrangement, only two transistors were used for anti-coincidence mixing and it was possible to obtain a setting of this potentiometer at which the output remained stabilized under load variations from zero to full load.

Because the 60 volts and 51 volts sections are run from a stabilized supply, no noticeable effects of mains voltage fluctuations are observed. If the mains voltage is varied from about 90 to 130 volts, a slight variation (less than one volt) appears in the 60 volts negative output due to cathode temperature change. The corresponding change in the negative nine volts output is undetectable because the change in 51 volts line is almost exactly balanced out by the change in 60 volt line.

It is known (R52) that a 1 per cent change in the voltage applied to a photomultiplier of ten stages will cause a change of about 7 per cent in the gain of the photomultiplier. This demands

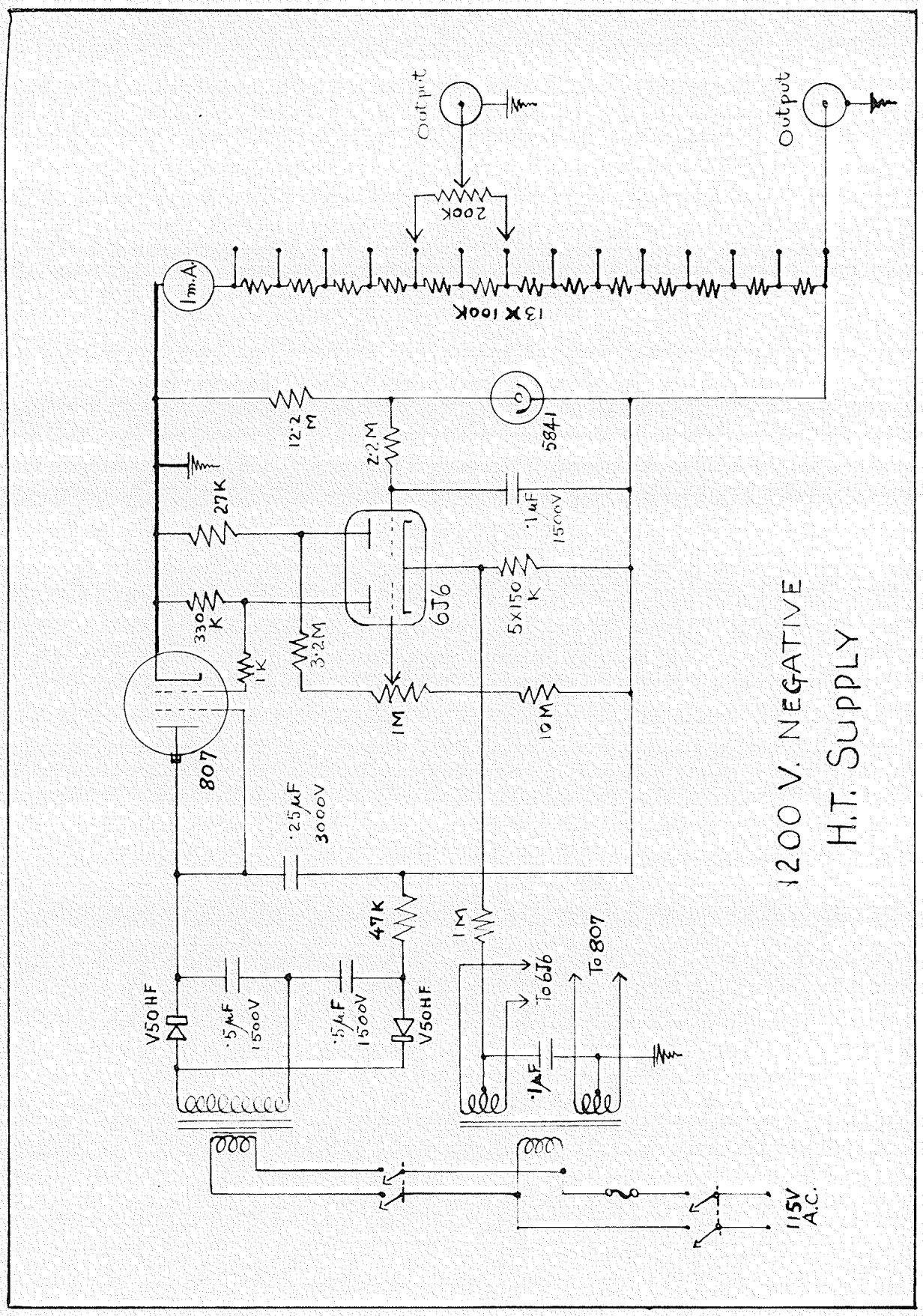
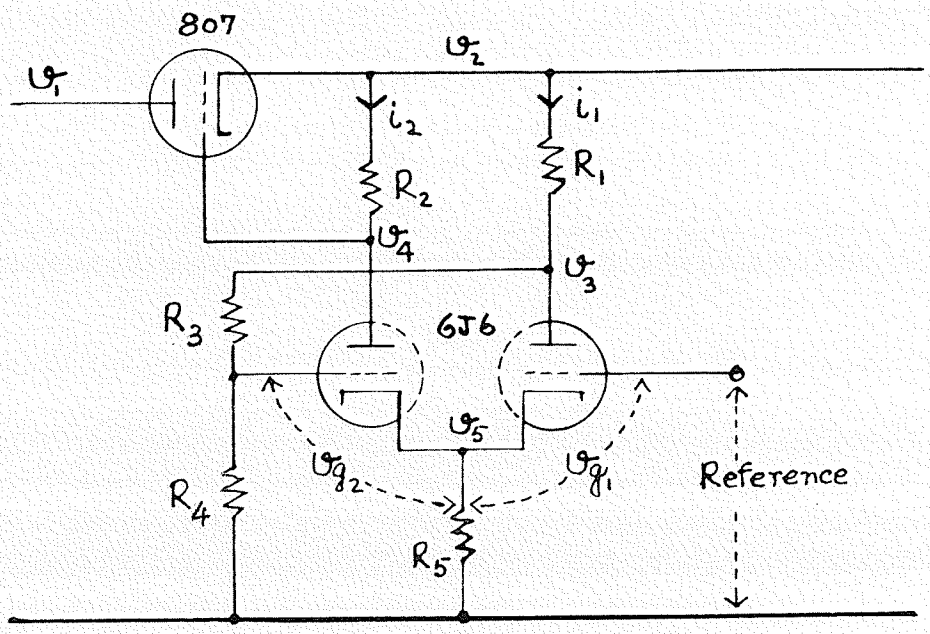

1200 V. NEGATIVE
H.T. SUPPLY
Output
Output
200K
1m.A.
13 X 100K
12·2 M
2·2M
5841
27K
·1μF 1500V
330 K
1K
3·2M
6J6
5X150 K
1M
10M
807
·25μF 3000V
47K
1M
V50HF
·5μF 1500V
·5μF 1500V
V50HF
To 6J6
To 807
·1μF
115V A.C.

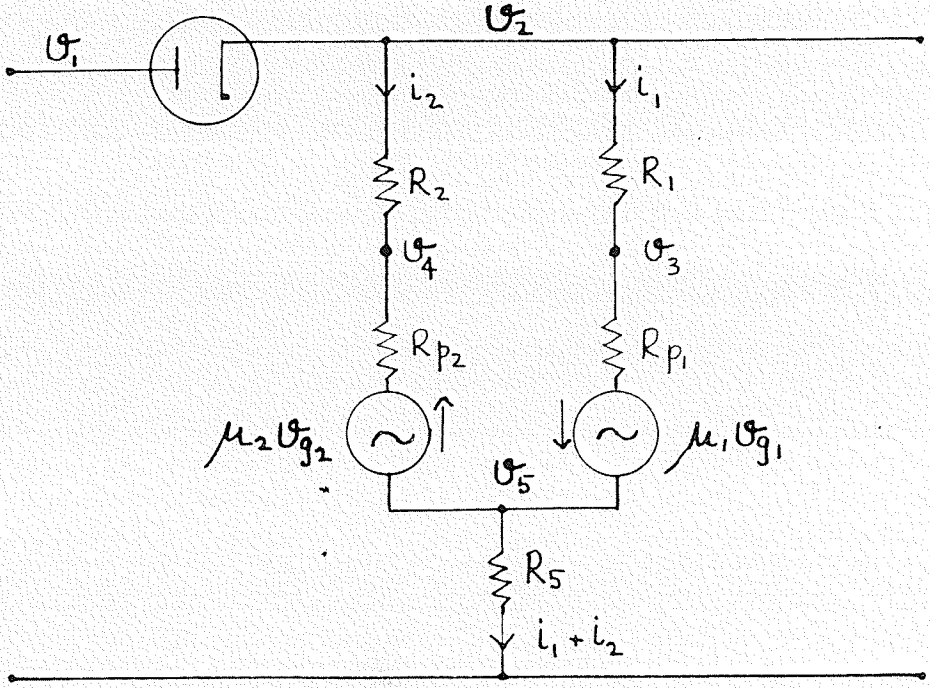
FIG. 8

a high order of regulation in the H.T. Supply. Further, because of the high voltage involved, it becomes more convenient to employ a voltage supply of negative polarity because it avoids the use of high voltage capacitors at the output stage. These considerations led to the design of a moderately highly stabilized 1200 volts negative H.T. Supply unit of simple design, whose circuit is given in Fig. 8. The 900 volts regulator used as a reference is a sub-miniature corona regulator tube Victoreen type 5841. The transformer is followed by a voltage doubler circuit employing two selenium rectifiers International type V.50.HF. The stabilizer circuit, following the filter circuit, consists of a tube type 807 series regulator and a twin triode type 6J6 used as a difference amplifier. Across the output of the stabilizer is connected a potential divider arrangement. The final output voltage can thus be varied at will. A separate outlet for full H.T. voltage is also provided. The circuit can easily be adapted to supply positive voltage by simply grounding the negative line instead of the positive and providing a capacitor between the positive line and the left hand grid of the 6J6 tube (Fig. 8). Then the filament transformers will also have to have high voltage insulation. At the time of writing this thesis the H.T. Supply has actually been so arranged that it can be switched to give positive or negative voltage output.

For the purpose of simple analysis of the stabilizer circuit an equivalent circuit is drawn in Fig. 9B. Suppose a voltage change V_1 at the input of the stabilizer causes a voltage change V_2 in the output. Let the voltage change V_2



(A) STABILIZER CIRCUIT



(B) EQUIVALENT CIRCUIT

FIG. 9

cause current changes of i_1 and i_2 in the right and left hand side respectively of the difference amplifier. These changes along with others are indicated at their respective points in the stabilizer circuit (Fig. 9A) and also in the equivalent circuit diagram (Fig. 9B). Rp is the plate impedance, μ the amplification factor and V_g the change in the grid voltage. Subscripts 1 and 2 refer to the right and left hand sections, respectively, of the 6J6 twin triode. Since the reference voltage is applied to the right hand side grid, $V_{g_1} = -V_5$. A fraction $\frac{R_4}{R_3 + R_4}$ of the voltage change V_3 will appear at the left hand grid because of the voltage divider ratio (Fig. 9A).

$$V_{g_1} = -V_5 \quad ; \quad V_{g_2} = \frac{R_4 V_3}{R_3 + R_4} - V_5$$

Using these values of V_{g_1} and V_{g_2}, the following five independent equations can be written:-

$$V_3 = V_2 - R_1 i_1 \qquad \text{(i)}$$

$$V_4 = V_2 - R_2 i_2 \qquad \text{(ii)}$$

$$V_5 = (i_1 + i_2) R_5 \qquad \text{(iii)}$$

$$V_2 - V_5 - \mu_1 V_5 = i_1 (R_1 + Rp_1) \qquad \text{(iv)}$$

$$V_2 - V_5 + \mu_2 \left(\frac{R_4 V_3}{R_3 + R_4} - V_5 \right) = i_2 (R_2 + Rp_2) \qquad \text{(v)}$$

If μ be the amplification factor of the tube type 807 series regulator, we can write

$$\mu = \frac{V_1 - V_2}{R_2 i_2}$$

From the last equation we proceed to evaluate the stabilization factor $\frac{V_1}{V_2}$. This leaves only i_1, i_2, V_3, V_4 and V_5 as the unknowns which can be eliminated by the help of above five equations. After a little algebra the condition for perfect (100%) stability, i.e. stabilization factor infinity, is obtained as:-

$$\left\{R_2 + Rp_2 + R_5 (\mu_2 + 1)\right\} \left\{R_1 + Rp_1 + R_5 (\mu_1 + 1)\right\} = R_5 (\mu_1 + 1) \left\{R_5 (\mu_2 + 1) + \mu_2 \frac{R_1 R_4}{R_3 + R_4}\right\}$$

$$\text{or } (R_1 + Rp_1) \left\{R_2 + Rp_2 + R_5 (\mu_2 + 1)\right\} = R_5 (\mu_1 + 1)\left\{\mu_2 \frac{R_1 R_4}{R_3 + R_4} - R_2 - Rp_2\right\}$$

The actual values of components in the circuit were chosen for best operation. These values when substituted in the above formula seemed to satisfy approximately the condition of perfect stability. An exact check is difficult to make because the exact values of μ_1, μ_2, Rp_1 and Rp_2 under actual operating conditions of the tube are difficult to determine.

Extensive tests on the H.T. Supply were made and its operation determined. It has been in use, off and on, for more than a year and through this period its operation has been quite satisfactory, except that the 6J6 tube twice developed a leakage between grid and cathode. This is probably caused by the application of excessive high voltages during the brief periods of switching the power supply on and off. The remedy could be a separate switch for the H.T. line so that the high voltage could be switched on after switching on the heaters and reverse the order when switching off.

Curves were drawn showing the operation of the H.T. unit. The change in output voltage against the variation in input voltage is shown in Fig. 10. A long term stability against drift was determined and the result is shown in Fig. 11. Total ripple content in the output of the unit is less than 0.09 volt, most of which could have been picked up in the measuring probe.

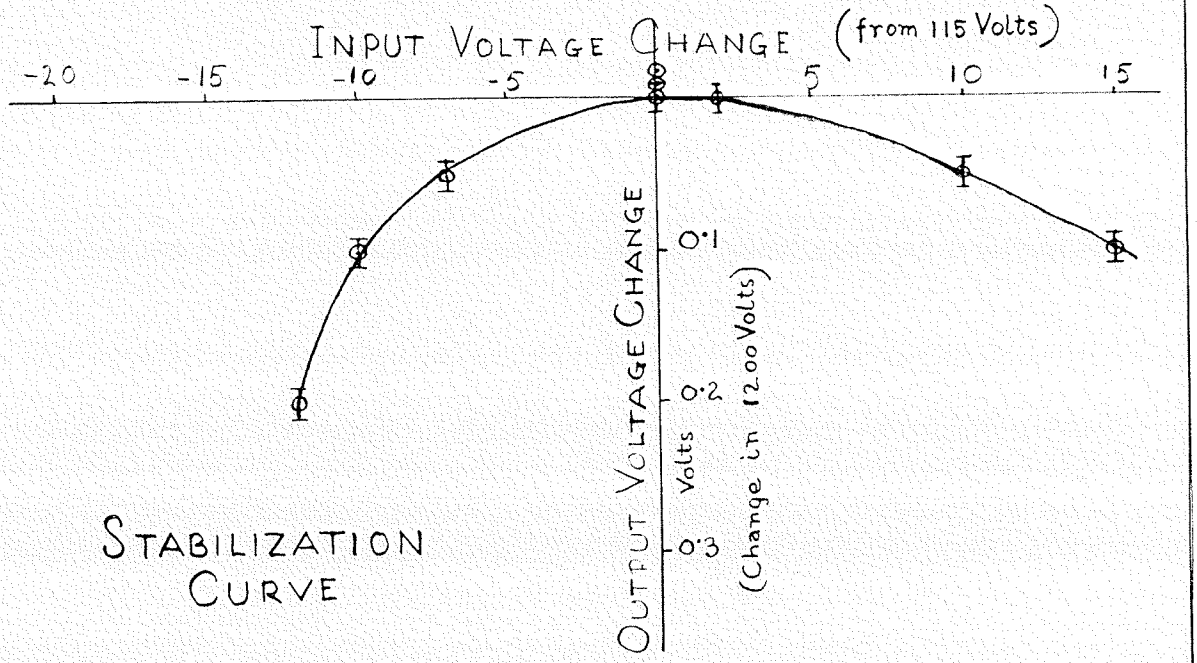

INPUT VOLTAGE CHANGE (from 115 Volts)
-20
-15
-10
-5
5
10
15
0·1
0·2
0·3
OUTPUT VOLTAGE CHANGE
Volts
(Change in 12.00 Volts)
STABILIZATION CURVE

FIG. 10.

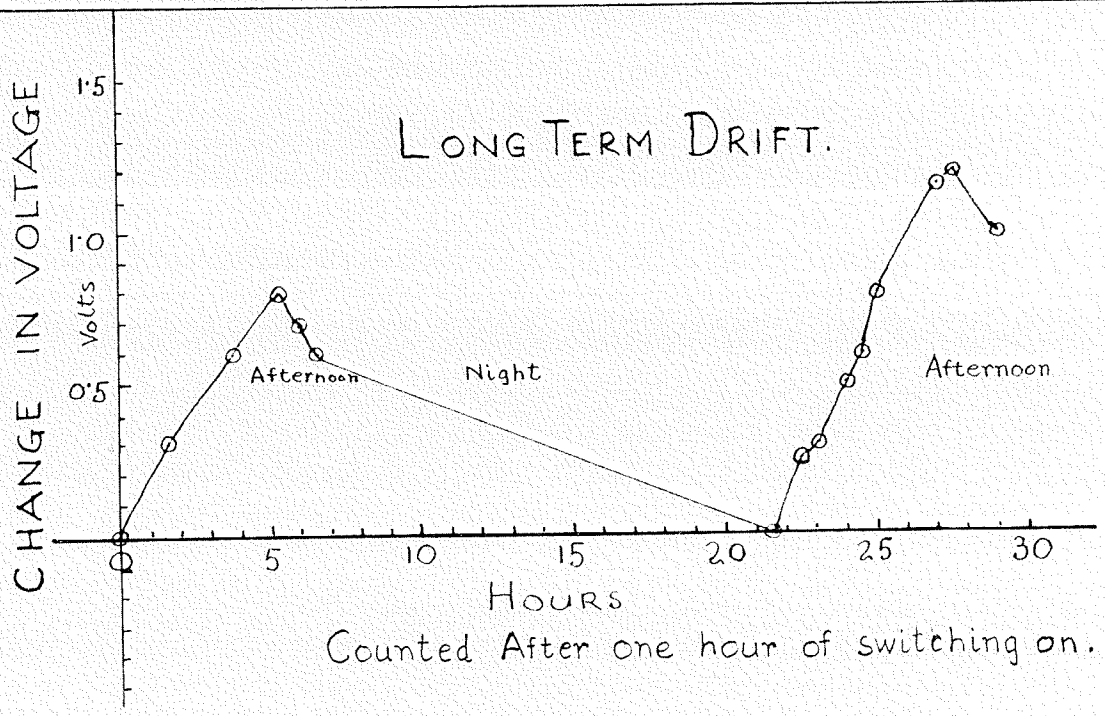

LONG TERM DRIFT.
CHANGE IN VOLTAGE
Volts
1·5
1·0
0·5
Afternoon
Night
Afternoon
0
5
10
15
20
25
30
HOURS
Counted After one hour of switching on.

FIG. 11.

3.3 DETECTOR HEADS:-

A potential divider was used to supply proper voltage to the various stages of the photomultiplier. Further, because of the low input impedance of the linear amplifier used to amplify the photomultiplier output, it was necessary to feed the pulses from the photomultiplier through a cathode follower to minimize the loss of amplitude. The voltage-divider network along with the cathode follower was housed very close to the photomultiplier tube base-socket in a small (4'' x 4'' x 2'') metal box. This unit is referred to as the detector head.

The photomultipliers used were: one 1'' DuMont type 6467 for NaI (Tl) crystal and two 5'' DuMont type 6364 for the plastic scintillator. DuMont type 6467 has an internally connected shield for best focussing of the photoelectrons on the first dynode. DuMont type 6364 has a shield which is connected to an external point in the tube base. For best focussing this externally connected shield has to be attached to some potential between cathode and first dynode. The two DuMont type 6364's used were arbitrarily labelled No. 1 and No. 2, and best shield potential for each was determined. A plot of photomultiplier output against shield potential while all other potentials are kept constant is shown for each tube in Fig. 12.

The outputs from the detector heads were taken to their respective amplifiers. As mentioned before, the plastic phosphor was viewed by two photomultipliers and so the outputs had to be added before passing on to the amplifier. For proper mixing it

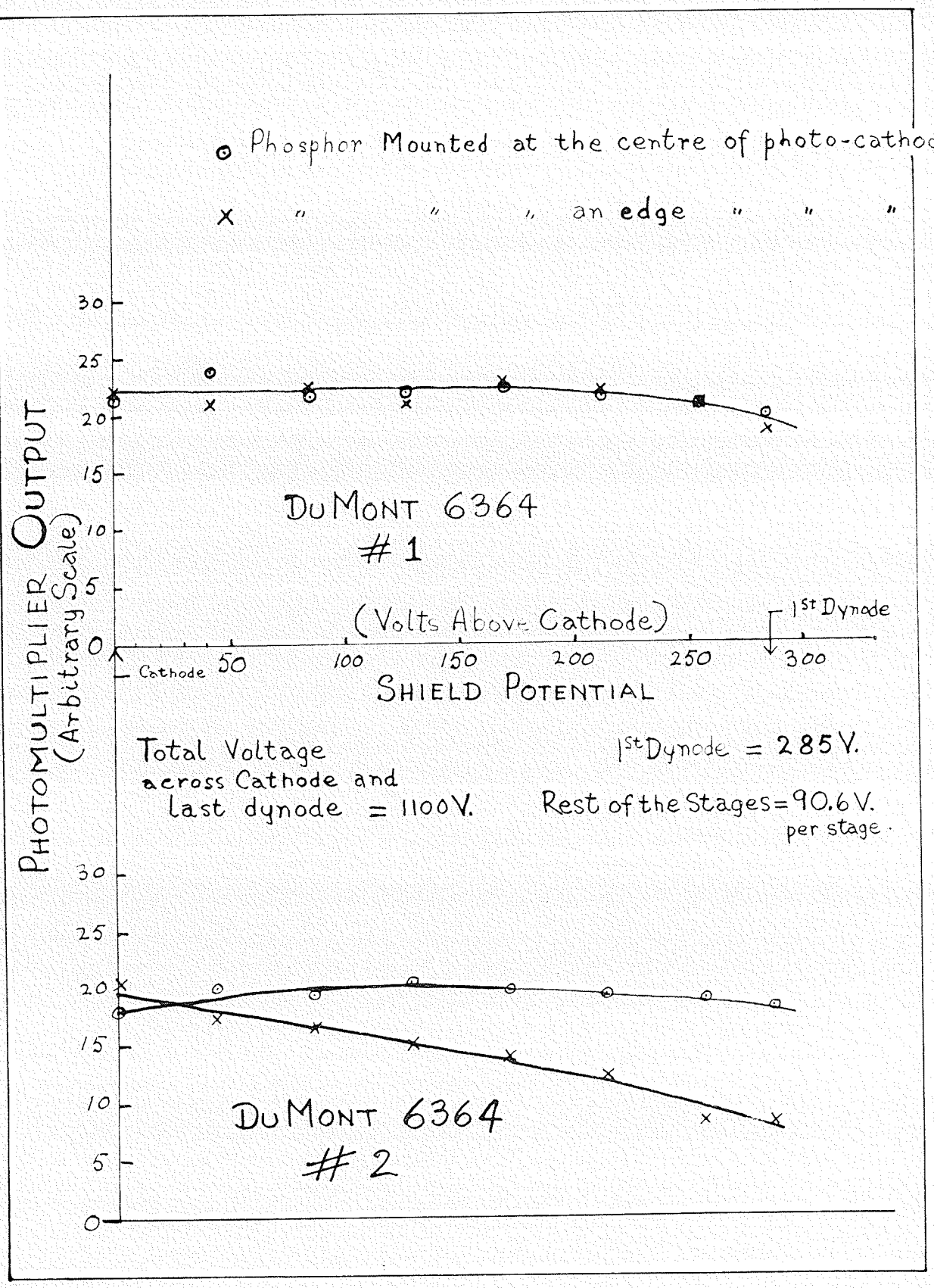
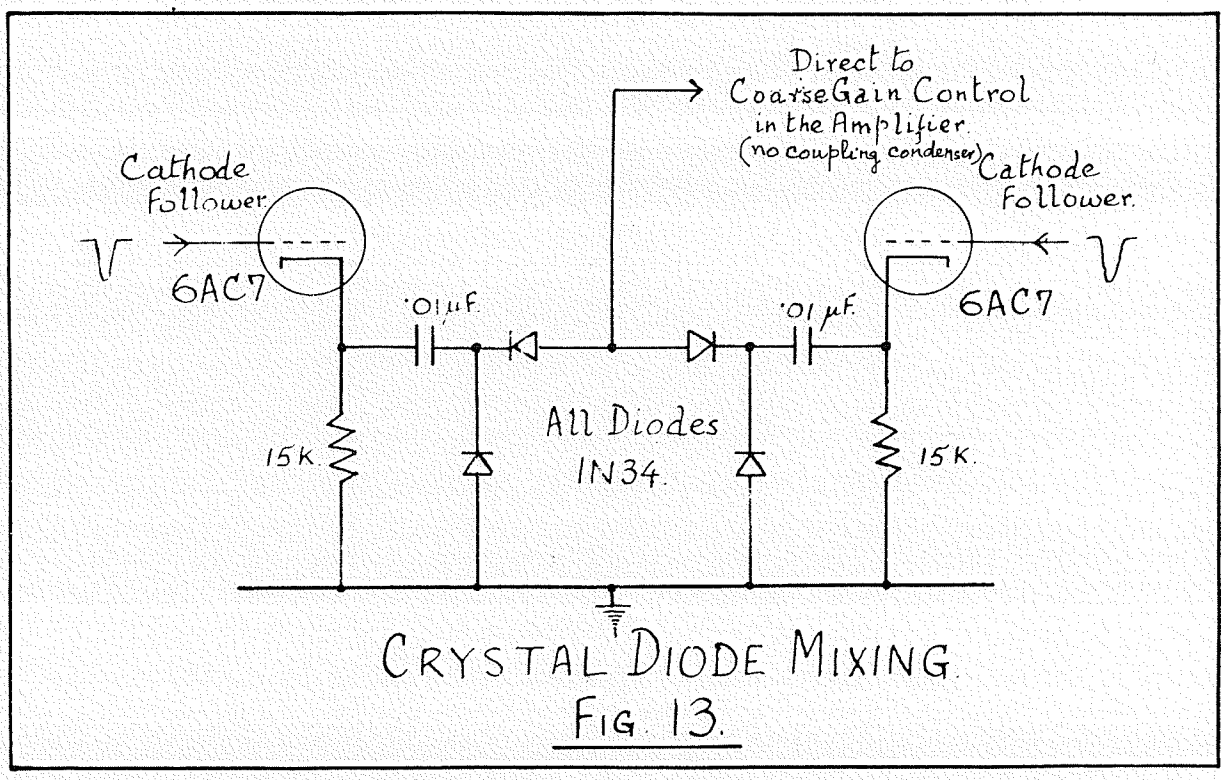

⊙ Phosphor Mounted at the centre of photo-cathode
× " " " an edge " " "
PHOTOMULTIPLIER OUTPUT (Arbitrary Scale)
30
25
20
15
10
5
0
DUMONT 6364
#1
(Volts Above Cathode)
1st Dynode
Cathode
50
100
150
200
250
300
SHIELD POTENTIAL
Total Voltage across Cathode and last dynode = 1100V.
1st Dynode = 285 V.
Rest of the Stages = 90.6 V. per stage.
DUMONT 6364
#2

FIG. 12

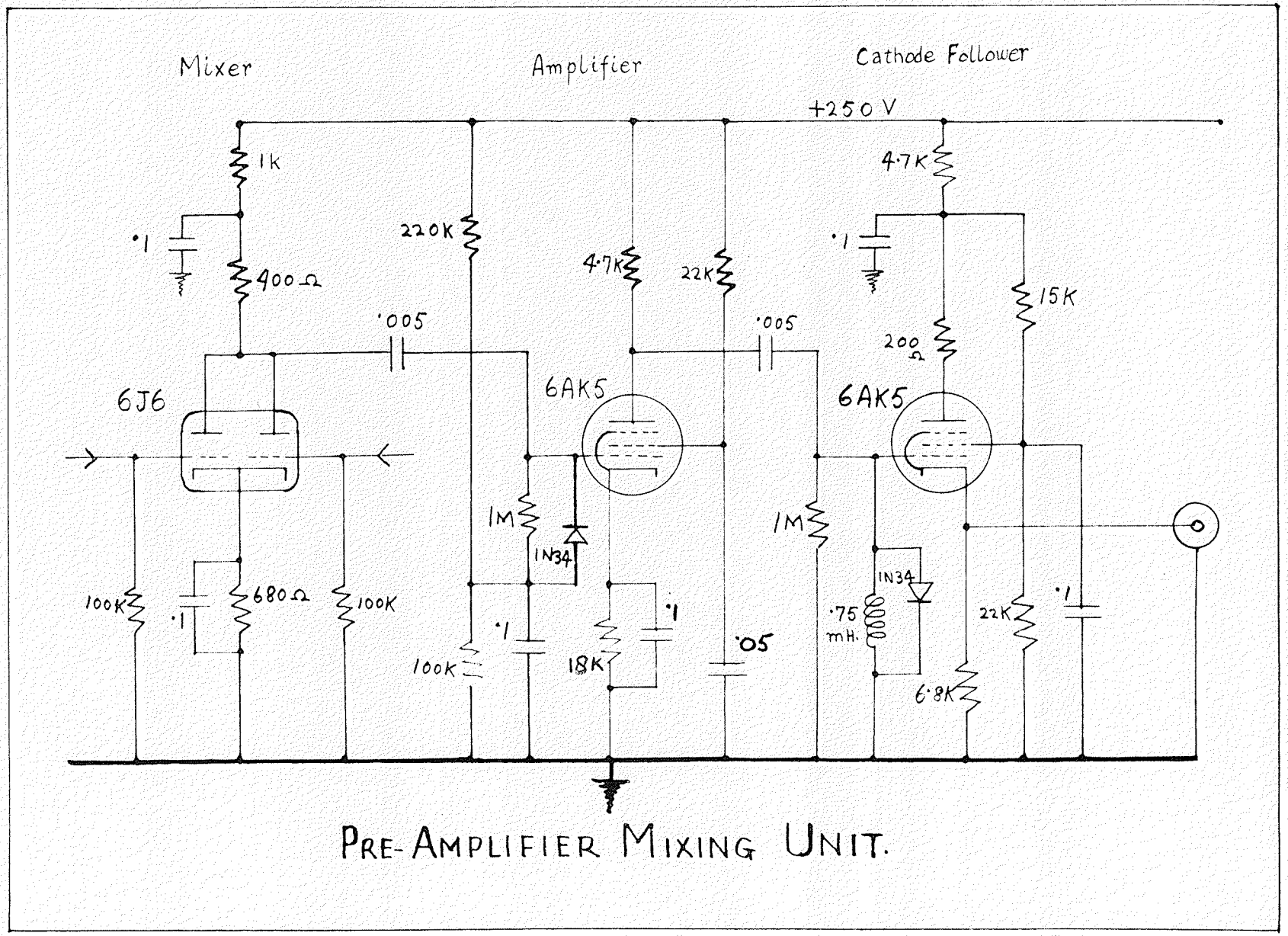
was necessary to match (equalize) the two photomultiplier outputs. Matching was achieved by adjusting the H.T. voltages across the two photomultipliers. In earlier tests a simple form of mixing was done by the help of crystal diodes inserted into the detector heads. The circuit arrangement for those crystal diodes is shown in Fig. 13 given below.



CRYSTAL DIODE MIXING.
FIG. 13.

This mixing was, however, not perfect because of the losses in the diodes. The signal level at the photomultiplier output being low (of the order of 10 millivolts), these losses are quite serious. For this reason a simple pre-amplifier mixing unit was designed whose circuit is given in Fig. 14. The circuit utilizes a twin triode tube type 6J6 for mixing the output of the two detector heads on the plastic scintillator. The mixer is followed by a single stage amplifier employing a pentode tube

type 6AK5. The output, which is negative, is taken through a 6AK5 cathode follower. The unit is designed for limited output so that over-loading of the first stage in the amplifier which follows cannot occur. In addition to mixing the output of the two photomultipliers on the plastic, the unit has the extra advantage of amplifying the pulses before passing them on to an amplifier. A very important side-feature is that the electronic noise pulses from the two photomultipliers are not added since they are not correlated to one another while the plastic pulses are. This greatly improves the signal to noise ratio.



PRE-AMPLIFIER MIXING UNIT.

FIG. 14

3.4 AMPLIFIERS:-

For the NaI (Tl) pulses an amplifier of simple design and small amplification was used. This amplifier, whose design is substantially the same as the latter portion of the Atomic Instruments Model 204C amplifier, was built in this laboratory.

As far as the total absorption spectrometer is concerned, the useful pulses from the plastic consist of only those due to absorption in the plastic of Compton scattered gamma-ray photons from the NaI (Tl) crystal. All other pulses which are not caused by Compton effect in the crystal are not useful in the sense that they do not help to reduce the Compton portion of the spectrum. There are three different sources of these so-called ''useless'' pulses:-

(i) Pulses due to absorption in plastic of gamma-photons direct from the source.

(ii) Pulses due to cosmic rays. Since the plastic represents quite a large cross-section, the cosmic ray pulses are large in size and number. In fact the same plastic phosphor which was used in this investigation as an anti-Compton shield was tested by Gagne (G56) for cosmic ray detection.

(iii) Pulses due to back-ground radioactivity.

Thus the useful pulses from the plastic are only a small fraction of the total plastic pulses. It was estimated experimentally that in every hundred pulses from the plastic there were only about two useful pulses.

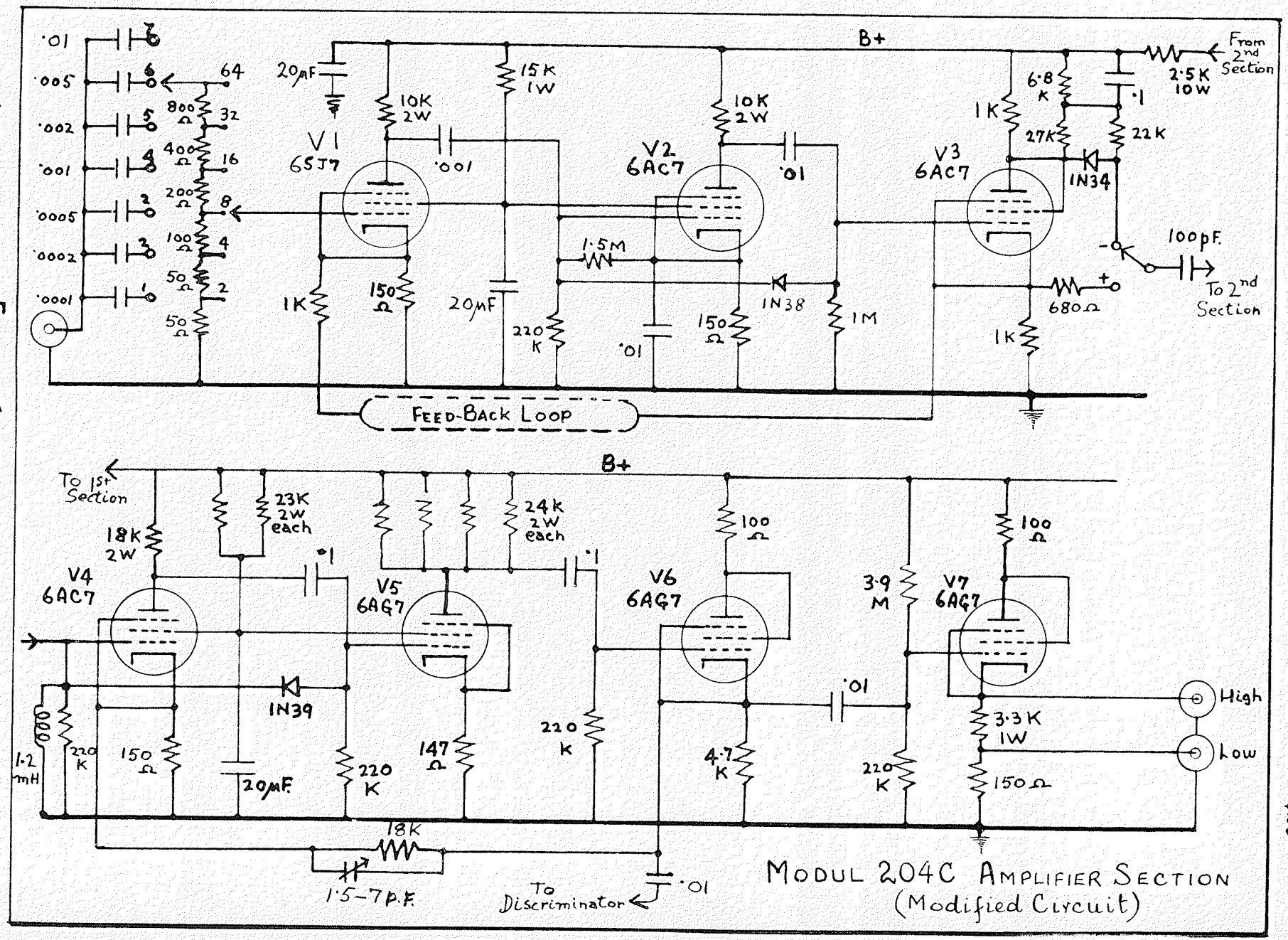
This very small number of useful pulses as compared to the total number of pulses, however, does not present very serious difficulties. It simply results in a rather high accidental rate which imposes a limitation to the gamma-ray source intensity to about one microcurie maximum. The main difficulty arises from the fact that the useful pulses are at much lower level (voltage) than the so-called ''useless'' pulses. This is because all the useful pulses are caused by the gamma-photons which have already lost a part of their energy to the NaI (Tl) crystal. Because the useful pulses are at very low level, a high gain amplifier (about 5000 times) is required. At the same time the large pulses should not cause any trouble in the amplifier. In an ordinary amplifier with high amplification, an input pulse greater than a certain maximum will normally cause grid currents to flow at the grids where the signal has positive polarity. For larger inputs, the undershoots of the differentiated pulses may be so large as to draw grid current at grids where the signal polarity is negative. Once the grid current is drawn, the coupling condenser between the two tubes is charged which changes the grid potential of the second tube. This shifted d.c. level decays toward its normal level at a very slow exponential rate because the charged coupling condenser has to discharge through the plate load of the first and grid leak of the second tube , both of which are high resistors. During this time the amplifier is partially cut off and is even dead to those pulses whose amplitude is less than the shift in the d.c. level beyond cut off. The amplifier on the plastic side,

therefore, must have, in addition to an amplification of about 5000 times, excellent non-over-loading characteristics. In both, the pre-amplifier mixer and the non-overloading amplifier the large pulses from the plastic are limited in amplitude for the benefit of small pulses.

The amplifier used for amplifying the plastic pulses was the Atomic Instruments Model 204C. Modifications were made primarily according to a paper by F.I. Magee, P.R. Bell and W.H. Jordan (M51) to give improved over-load response. In this paper use is made of what the above named authors call ''amplified diode'' for clipping the pulse undershoots at a number of places. They have suggested inserting a coupling network between the coarse gain control and the first grid of the amplifier to give the clipping diode a coupling capacitor upon which to act. For the present purpose the undershoot caused by the differentiation in this coupling network was causing trouble. Therefore, after making sure that the output from the pre-amplifier mixing unit preceding the amplifier, did not cause over-loading of the first grid in the amplifier, the coupling network and its associated clipping ''amplified diode'' were dispensed with. Since the back resistance of the diodes shunt the amplifier, the unfed back gain is considerably reduced. To compensate for this effect in the first section of the amplifier (stages before differentiation) it is suggested in the above mentioned article to place a resistor (R67 in their diagram) of 3.3 Meg ohms across alternate grids. This provides a small positive feedback and thus compensates for the loss in gain.

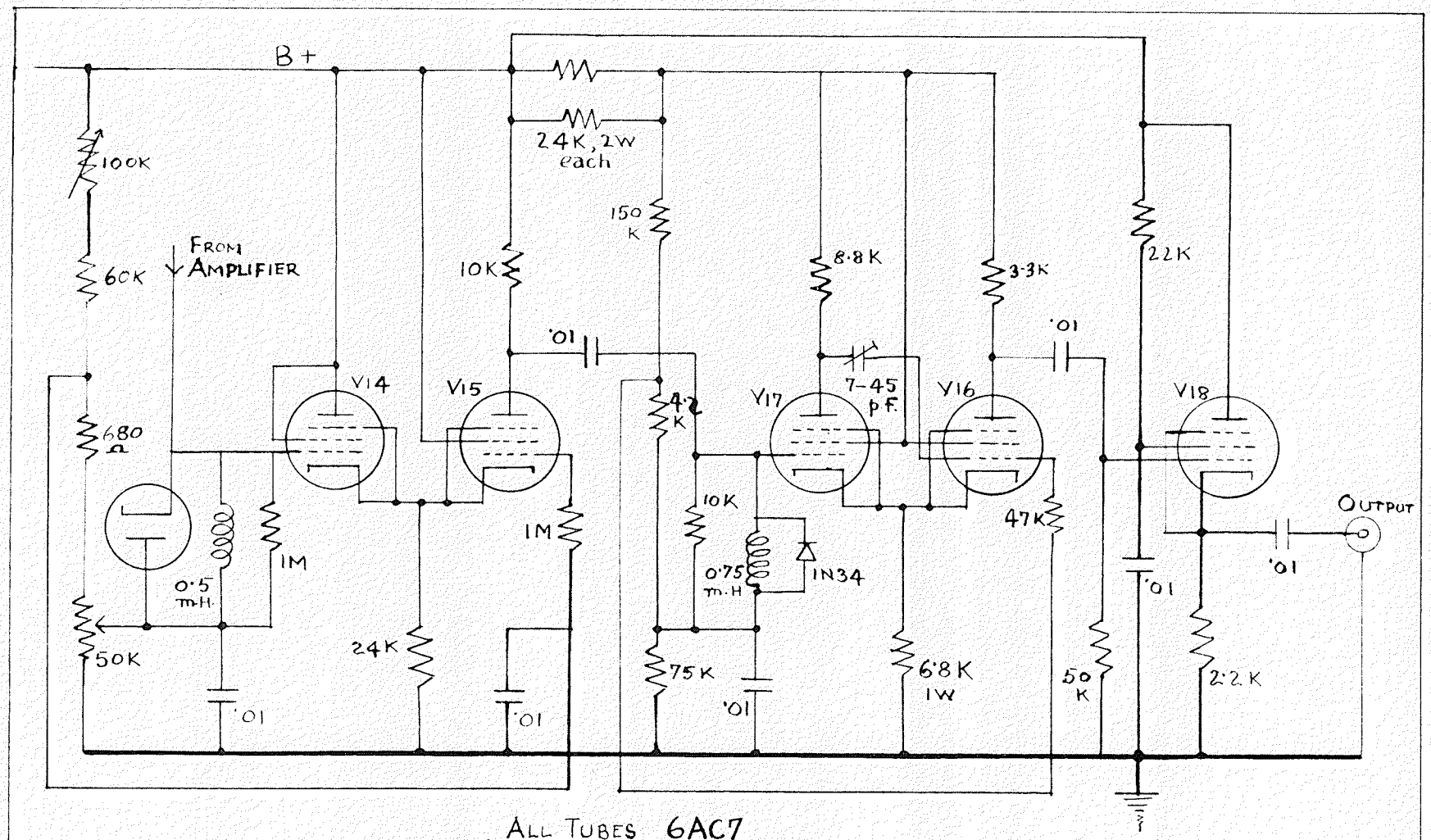
Again, for the present purpose, it was found that some very large pulses were causing triggering in the first section of the amplifier and therefore the above mentioned resistor had to be removed. Loss in gain was compensated by amplification in the preamplifier mixing unit, and by using higher voltages on the photomultiplier tubes. These ''amplified diodes'' as suggested in the above mentioned article, do not prevent the tubes from drawing grid current when over-loaded. They, instead, first let the tube draw the grid current then quickly reduce the undershoot by discharging the coupling condenser through the low forward impedance of the diode. Such a situation specially occurs at the first grid of the latter section of the amplifier where the positive pulse from the first section causes the grid current to flow. Here it was thought preferable to prevent the tube from drawing any grid current at all rather than cure it. For this purpose the output from the first section was so limited by the use of a biased crystal diode that it did not overload the following grid. This biased diode gave a flat topped output which was then shaped by using a small inductor shunted by a diode. The diode needed to shunt the inductor was the same which was employed as an ''amplified diode''. This limitation of the pulse input to the second half of the amplifier reduced the maximum obtainable final output from the amplifier to about 30 volts. The entire modification was, however, considered and by actual test found to be satisfactory for high amplification of small pulses in the presence of large pulses. After all these modifications, the linearity of the

amplifier is bound to be poor; but this does not matter for the purpose in hand. The circuit diagram of the amplifier section (of Model 204C amplifier) as used in this investigation is shown in Fig. 15. Finally, the discriminator (pulse height selector) circuit in the amplifier was modified to deliver a 20 volts positive pulses of duration which could be varied at will over the range of about 0.5 - 2.5 microseconds. The modified circuit diagram of the trigger section of the Model 204C amplifier is given in Fig. 16.



MODUL 204C AMPLIFIER SECTION
(Modified Circuit)

Fig. 15.



MODEL 204C DISCRIMINATOR SECTION
(Modified Circuit)

Fig. 16.

3.5 DOUBLE DISCRIMINATOR:-

For the analysis of pulses from the NaI (Tl) crystal a single channel pulse height analyser was used. It consists of a double discriminator unit followed by a transistor anti-coincidence unit. The latter unit, described in the next section, was provided with continuously variable delay lines which enabled almost complete cancellation of the pulses from the double discriminator unit to be obtained.

The double discriminator unit consists of two conventional trigger discriminators (R50). These can be triggered at slightly different levels of input pulse. The difference in triggering level, which determines the gate width, can be selected by a potentiometer on a bias chain common to both trigger circuits and can be varied from 0 volts to about 15 volts. The bias control, a ten turn ''helipot'', determines the minimum triggering level and can be varied from zero volts to 100 volts. Thus analysis of pulses up to 100 volts in amplitude can be made. The output pulses from both discriminator levels (lower level and upper level) are of positive polarity, are approximately 10 volts and one microsecond long. For more complete description of the circuit, the reader is referred to the literature (R50, R52).

at the base is equal to or greater than the pulse at the emitter in both amplitude and duration. This principle of triggering the transistor by a positive pulse on emitter or a negative pulse on base and prevention of triggering by a positive pulse on the base in proper relationship with the triggering pulse is utilized in the transistorized single-channel differential discriminator designed by Chaykowsky (C56). In the Fig. 17, the pulses from the lower level discriminator are applied to the first emitter through a continuously variable properly terminated delay line and a short time-constant differentiating circuit. The delay line (Advance Electronics Company, Inc., Passaic, New Jersey, Model No. 507) is set to give proper delay without reflection and the differentiating shortens the duration of the pulse to avoid multiple triggering. To the base of the first transistor are applied the pulses from the lower discriminator level through a properly terminated delay line which is similar to one described above. This pulse is not differentiated so that it is greater than the pulse on the emitter in both, amplitude and duration. A crystal diode is used to prevent the negative overshoot, if any, from reaching the base where it could cause triggering. The circuit arrangement of the second transistor, to whose base pulses from the plastic are applied, is similar to that of the first transistor. The collector load for the second transistor is 10,000 ohms so that the output pulse is long enough to register a count in the scaler. An Atomic Instruments Model 200 scaler was used which, required pulses about one microsecond long.

For triggering stability of the transistor one must avoid two independent causes of instability. First, steps should

be taken to avoid instability in the triggering level due to a change in the transistor characteristics. In order to attain the triggering stability it can be shown (S53, P55) that γ_c, the collector impedance of the transistor, should stay as constant as possible. The effect of changes in γ_c can be minimized by using a low value base resistor. On the other hand to insure a pronounced negative resistance characteristic, the base resistor should be large. Generally to obtain both these effects a biased diode is employed in the base of the transistor (S53). In the present circuit, however, it was possible to use a 1000 ohm base resistor which was large enough to give the required negative resistance characteristic; but was small, as compared to γ_c, so that triggering level was quite stable.

The second cause of unstability is the change in emitter bias due to a change in the bias supply. To avoid this, a highly stabilized bias supply is used and a 1000 ohm resistor is connected between the emitter and ground. The potential drop across this resistor fixes the d.c. bias on the emitter. Further, all resistors used in the unit are stabilized carbon.

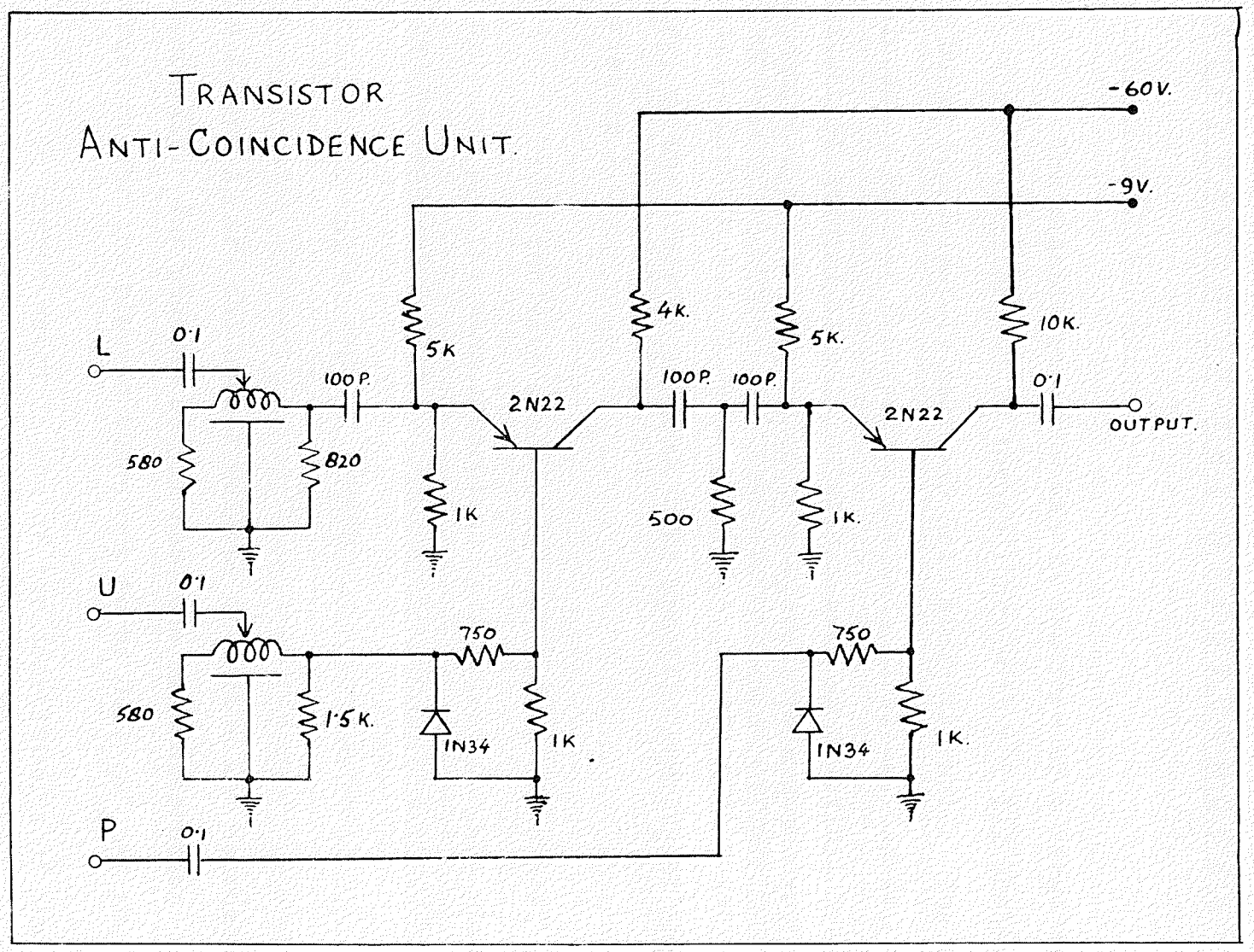

TRANSISTOR
ANTI-COINCIDENCE UNIT.
-60V.
-9V.
L
0·1
100P.
5K
4K.
5K.
10K.
100P.
100P.
0·1
OUTPUT.
2N22
2N22
580
820
1K
500
1K.
U
0·1
750
750
580
1·5K.
1N34
1K
1N34
1K.
P
0·1

FIG. 17.

At 4 Mev the pair production cross-section in carbon is about 5 per cent of the total interaction cross-section and increases quite rapidly with the photon energy. It can, therefore, be concluded for the plastic, as a whole, that its chief mode of interaction with radiation will be by Compton process, at least in the photon energy range of 50 Kev to 4 Mev.

If the Compton cross-section in cm^2 per electron and the number of electrons per c.c. of the plastic is known, the fraction of the total number of gamma photons which undergo a collision in the given length of plastic can be calculated. We proceed to do this calculation:

From the formula $(C_9H_{10})_n$, the gram molecular weight of the plastic = 118.17 n gms.

The number of electrons in a gm. molecule = $6.025 \times 10^{23} \{(6 \times 9) + 10\} n$

$\therefore$ Number of electrons per gm. of the plastic = $\frac{6.025 \times 10^{23} \times 64}{118.17}$

Density of the plastic (given) = 1.05 gms. per c.c.

$\therefore$ Number of electrons per c.c. of the plastic = 3.425×10^{23}

Since the gamma-ray source is placed at the centre of the plastic in the hole, we take 12 cms. as the average length in plastic traversed by a gamma-photon.

$\therefore$ Number of electrons, X, in the average path is given by:

$$X = 4.11 \times 10^{24} \text{ electrons per cm.}^2$$

If σ is the Compton cross-section for a gamma-ray of given energy, the probability of escape through the plastic without a single collision is $e^{-\sigma x}$.

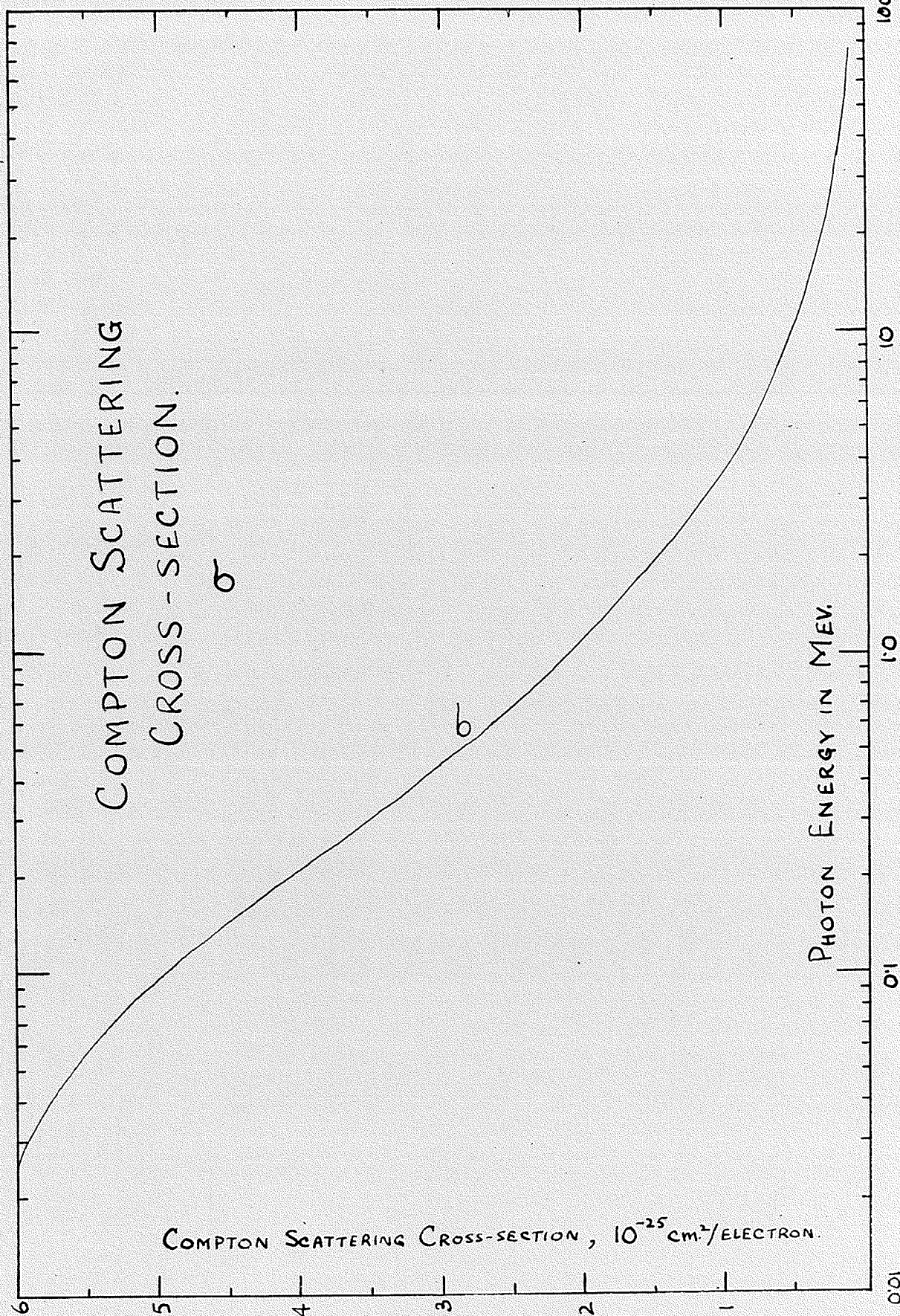

COMPTON SCATTERING
CROSS-SECTION.
σ
σ
PHOTON ENERGY IN MEV.
0·01
0·1
1·0
10
100
COMPTON SCATTERING CROSS-SECTION, 10^{-25} cm.²/ELECTRON.
1
2
3
4
5
6

FIG. 18

The fraction of the total number of photons which suffer one or more collisions in the plastic = $100(1 - e^{-\sigma x})$ per cent.

The Compton cross-section, σ, for various photon energies is shown in Figure 18. This was used to compute the Compton scattering efficiency in the plastic, shown as Curve A in Figure 19A.

A photon will give, in a single collision, an amount of energy to the recoil electron, dependent on the inclination, θ, of the scattered photon direction to the initial direction. It is this energy given to the electrons in the plastic which could be expected to be re-emitted as light photons which could be detected by the photomultiplier tubes. There will, however, be a minimum of detectable energy corresponding to the bias level in the electronic circuitry following the photomultipliers. This bias level can be translated into a critical angle, θ_c, such that any photon which is scattered at an angle less than θ_c will not have given to the recoiling electron an energy which is sufficient for detection. Thus, the detection efficiency in the plastic will be given by the fraction of the total number of photons which are scattered between the angles θ_c and 180 degrees.

For different gamma-ray energies curves can be plotted showing the energy transferred to the electron versus the angle of scattering of the photon. These are shown in Figure 19B (computed from curves in National Bureau of Standards Circular 542). From these curves the critical angle, θ_c, for the various photon energies can be read off. This has been done for a number of different bias levels.

The fraction of the scattered photons which fall outside this angle θ_c can be determined from a family of curves shown in Figure 19C for different gamma-ray energies. (The curves in Figure 19C have been computed from curves in an article by C.M. Davisson and R.D. Evans (D52).)

The Compton scattering efficiency curve (Curve A Figure 19A) is then multiplied by these fractions to give a new set of ''detection efficiency'' curves (Curves B Figure 19A). The experimental curve (Curve C, Figure 19A) indicates that the bias level was probably very close to 25 Kev. The theoretical curve at low energy levels differs considerably from the experimental. This is due to multiple Compton processes in the plastic which make possible the detection of certain photons which would not be detected if there were only one collision.

A study was also made of the pulse height distribution in the plastic. Curves for Cs^{137} and Zn^{65} sources are shown in Figure 20. The peaks on these curves are considerably more pronounced than on normal Compton curves. This indicates a fairly complete absorption of a considerable proportion of the gamma-ray energy.

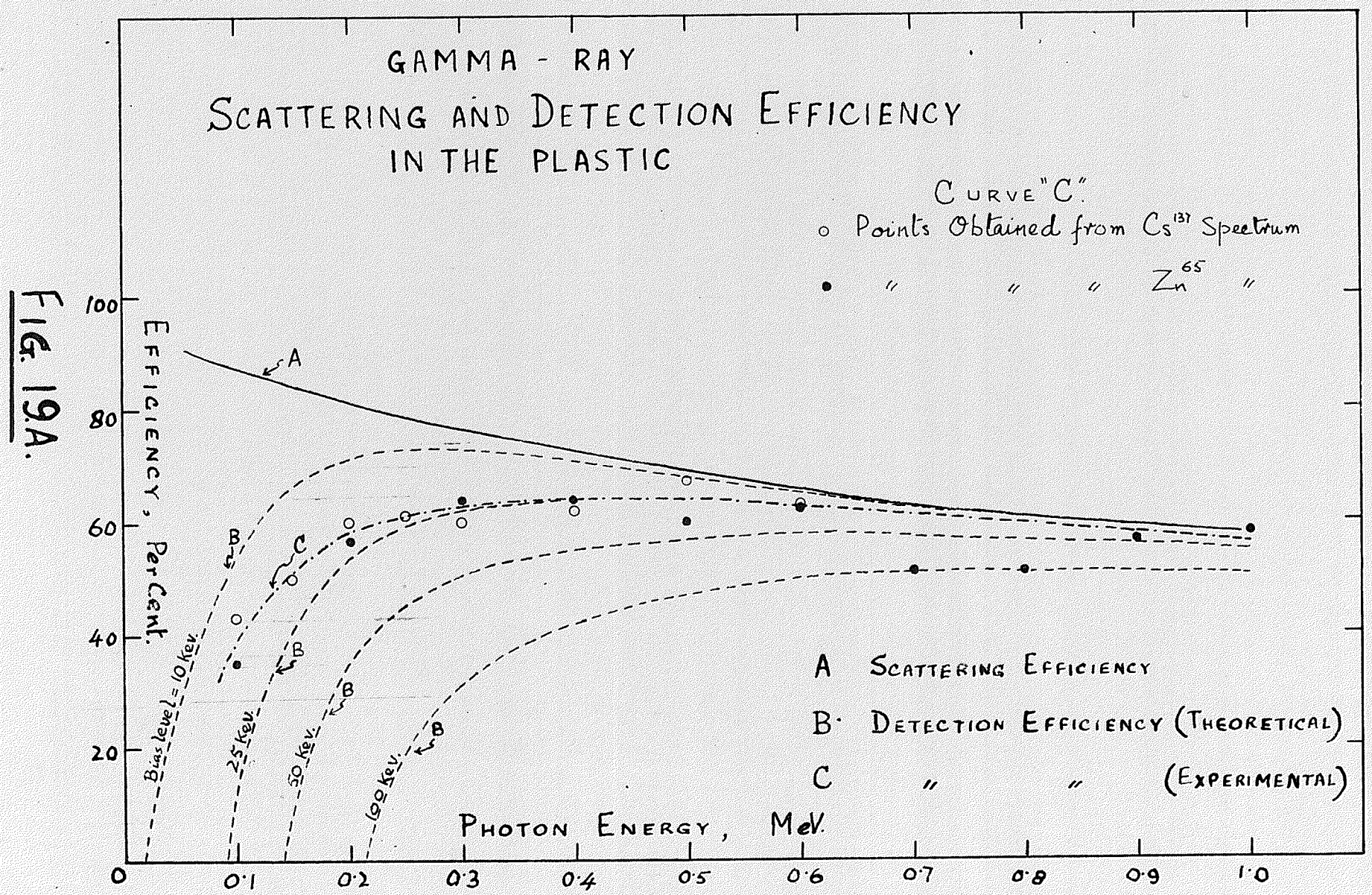

GAMMA - RAY
SCATTERING AND DETECTION EFFICIENCY
IN THE PLASTIC
CURVE "C".
o Points Obtained from Cs137 Spectrum
• " " " Zn65 "
EFFICIENCY, Per Cent.
100
80
60
40
20
0
A
B
C
Bias level = 10 Kev.
25 Kev.
50 Kev.
100 Kev.
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
PHOTON ENERGY, MeV.
A SCATTERING EFFICIENCY
B DETECTION EFFICIENCY (THEORETICAL)
C " " (EXPERIMENTAL)

FIG. 19A.

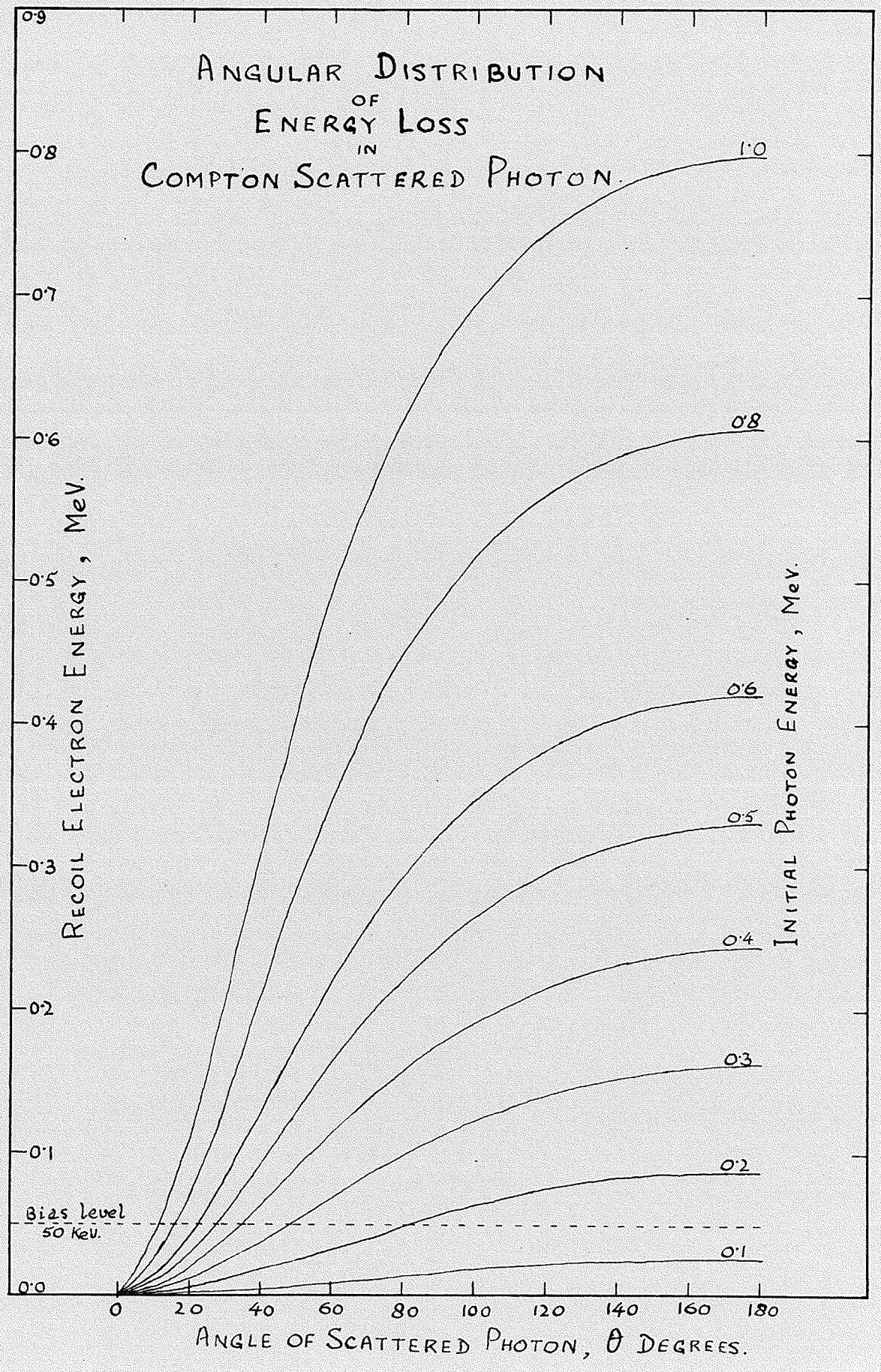

ANGULAR DISTRIBUTION OF ENERGY LOSS IN COMPTON SCATTERED PHOTON.
RECOIL ELECTRON ENERGY, MeV.
INITIAL PHOTON ENERGY, MeV.
1·0
0·8
0·6
0·5
0·4
0·3
0·2
0·1
Bias level 50 KeV.
0·0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
0
20
40
60
80
100
120
140
160
180
ANGLE OF SCATTERED PHOTON, θ DEGREES.

FIG. 19.B.

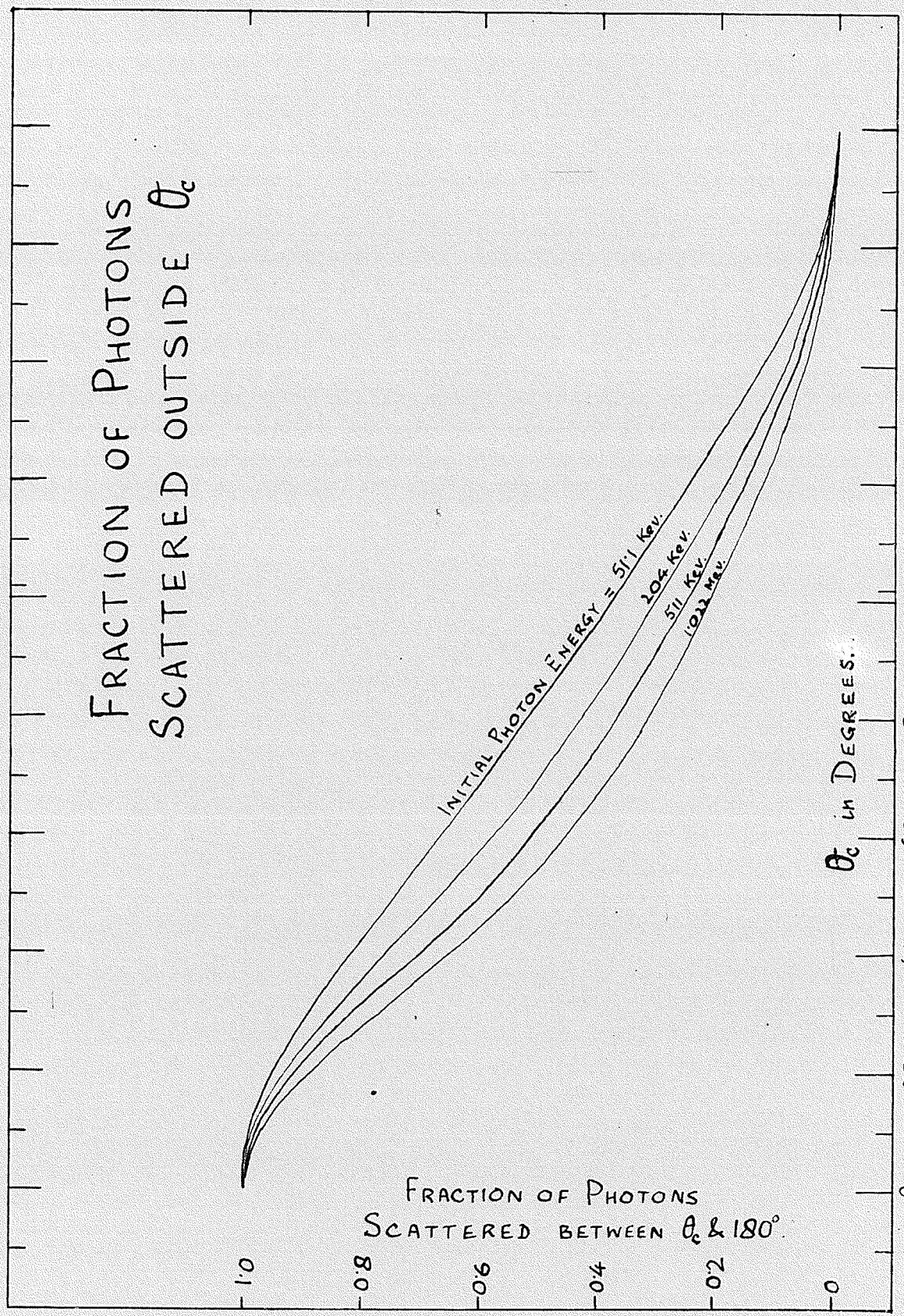

FRACTION OF PHOTONS SCATTERED OUTSIDE θ_c
INITIAL PHOTON ENERGY = 51·1 Kev.
204 Kev.
511 Kev.
1·022 Mev.
θ_c in DEGREES.
FRACTION OF PHOTONS SCATTERED BETWEEN θ_c & 180°
1·0
0·8
0·6
0·4
0·2
0
0
20
40
60
80
100
120
140
160
180

FIG. 19C.

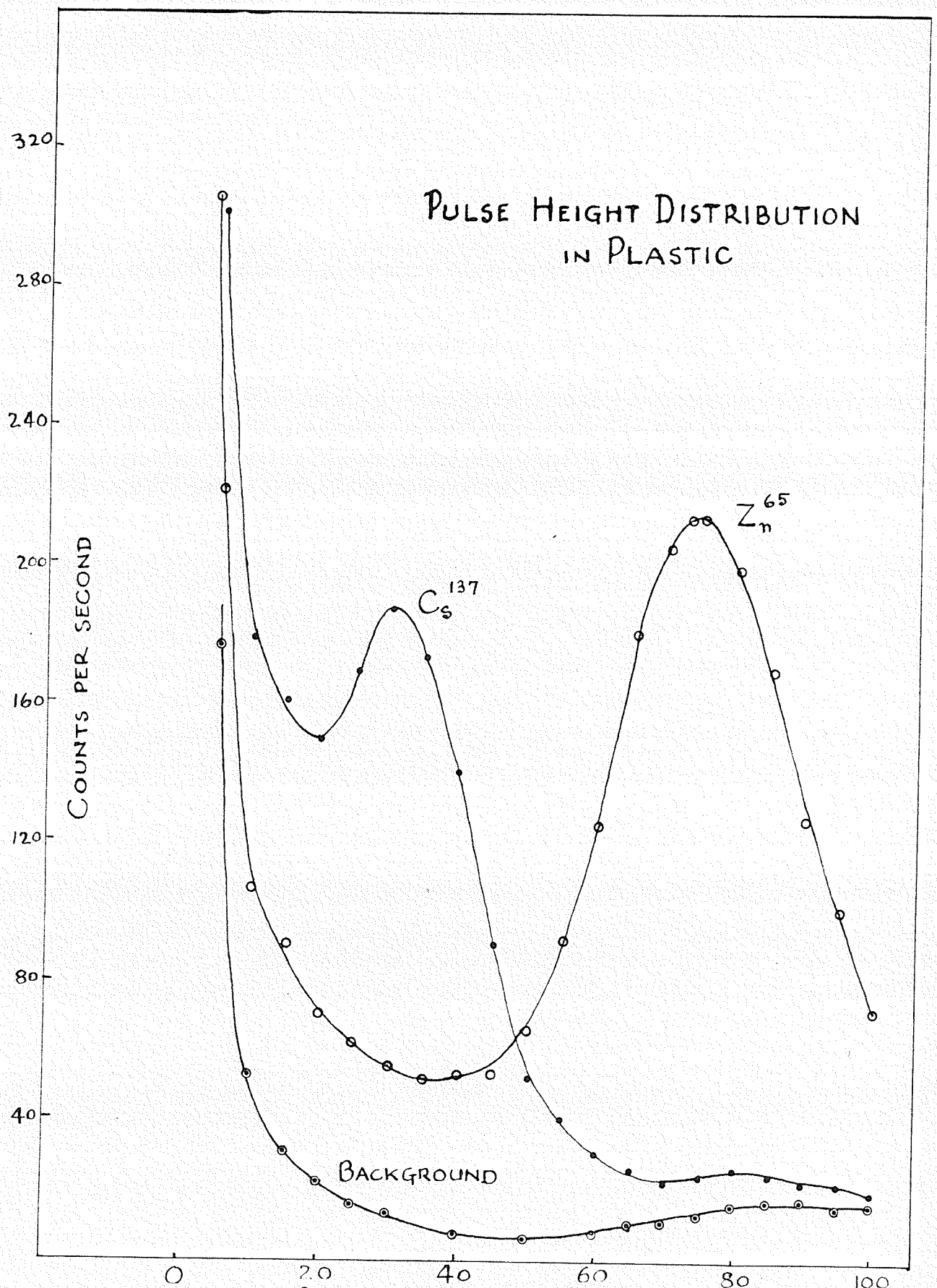
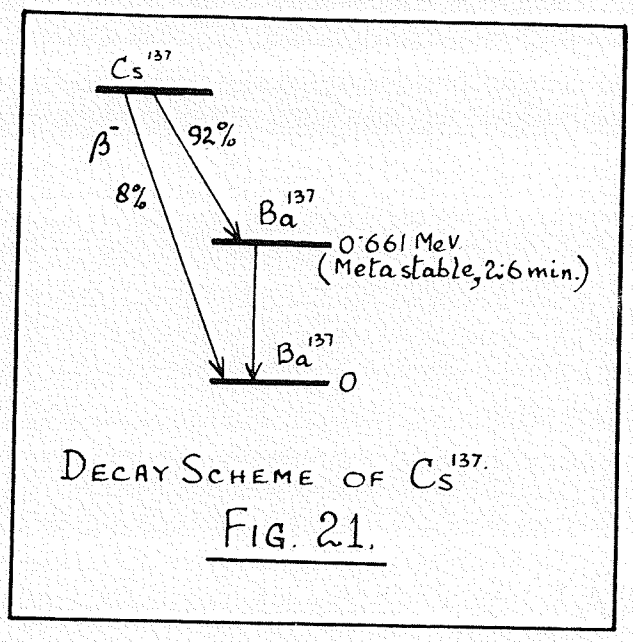

PULSE HEIGHT DISTRIBUTION
IN PLASTIC
320
280
240
200
160
120
80
40
COUNTS PER SECOND
Cs^{137}
Zn^{65}
BACKGROUND
0
20
40
60
80
100
PULSE HEIGHT IN VOLTS

FIG. 20.

4.2 Cs^{137} SPECTRUM:-

The decay scheme of Cs^{137} is well established (W50, W51, L51). It decays to Ba^{137} by negatron emission. A single gamma-ray of energy 0.661 Kev (isomeric state) (Mu52) is emitted in the process. Half-life of the activity is 37 years. The decay scheme (H53) is given below in Fig. 21.



DECAY SCHEME OF Cs^{137}.

FIG. 21.

The Cs^{137} source of about 0.5 microcurie strength was sealed in a thin lucite disk of diameter equal to that of the NaI (Tl) crystal. To check the reduction of the back-scattered peak, the source was placed first outside the crystal (source position A, Fig. 5) and then between the crystal and photomultiplier tube (source position B, Fig. 5). The pulse height distribution curves were drawn with each source position. The curves of Fig. 22 show that with the source between the NaI (Tl) crystal and photomultiplier tube there is no reduction in the back-scattered

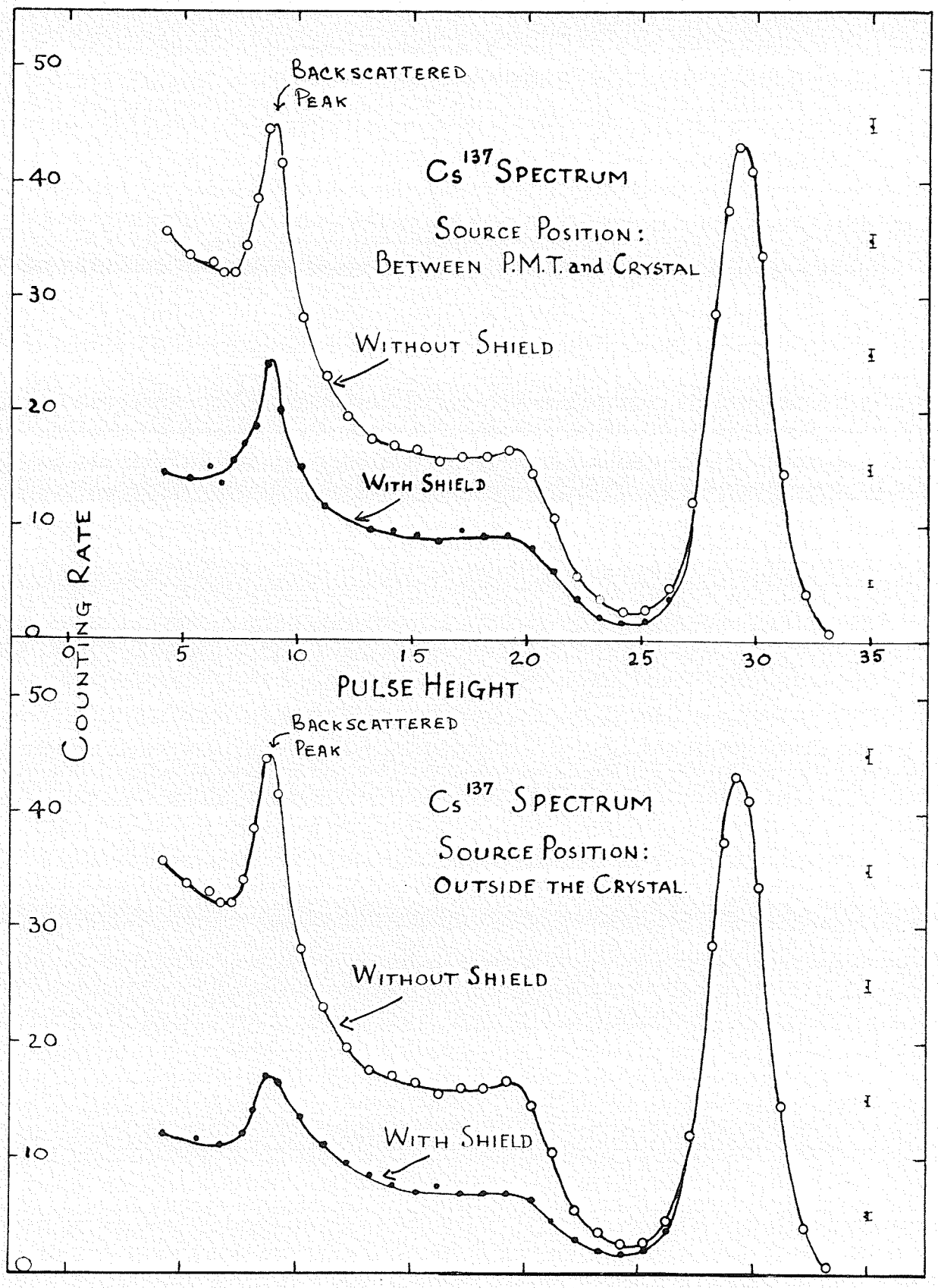

BACKSCATTERED PEAK
Cs 137 SPECTRUM
SOURCE POSITION:
BETWEEN P.M.T. and CRYSTAL
WITHOUT SHIELD
WITH SHIELD
COUNTING RATE
PULSE HEIGHT
BACKSCATTERED PEAK
Cs 137 SPECTRUM
SOURCE POSITION:
OUTSIDE THE CRYSTAL.
WITHOUT SHIELD
WITH SHIELD

FIG. 22.

peak. With source in position A the back-scattered peak is considerably reduced. In fact, if all the back-scattering were caused by the plastic, the peak should be eliminated completely.*

It was pointed out that the physical presence of a plastic shield around the NaI (Tl) crystal might cause considerable increase in the Compton portion of the spectrum. Pulse height distribution curves were drawn with the plastic shield physically present and physically removed to investigate the effect. In Fig. 23 are shown three pulse height distribution curves for the Cs^{137} source. Curve A is obtained without the Compton reducing arrangement but with the shield physically present. Curve B is obtained with the shield removed both electronically and physically. Curve B is that which will be obtained by any ordinary scintillation spectrometer. As can be seen from the curves A and B, the physical presence of plastic increases the back-scattered peak and the low energy part of the curve, up to the back-scattered peak. It has no detectable influence on the higher energy portion of the curve, that is, the portion after the back-scattered peak. Curve C is obtained by using the anti-Compton shield to reduce the Compton part of the spectrum. The difference between curve C and curve A gives a measure of the detection efficiency of the plastic shield. Comparison of the curve C with the curve B shows the net improvement achieved by the total absorption spectrometer over an ordinary scintillation spectrometer. The reduction achieved in

---

*In all subsequent measurements source position A was used.

the Compton portion is about 35 per cent and is very close to the theoretically obtained value (Fig. 19). Also shown on a reduced scale in Fig. 23 is the Ba X-ray caused by internal conversion. Since there is no other event associated with the internal conversion, which can be detected in the plastic shield, there is no reduction in the X-ray peak; but the part below it due to Compton effect is reduced.

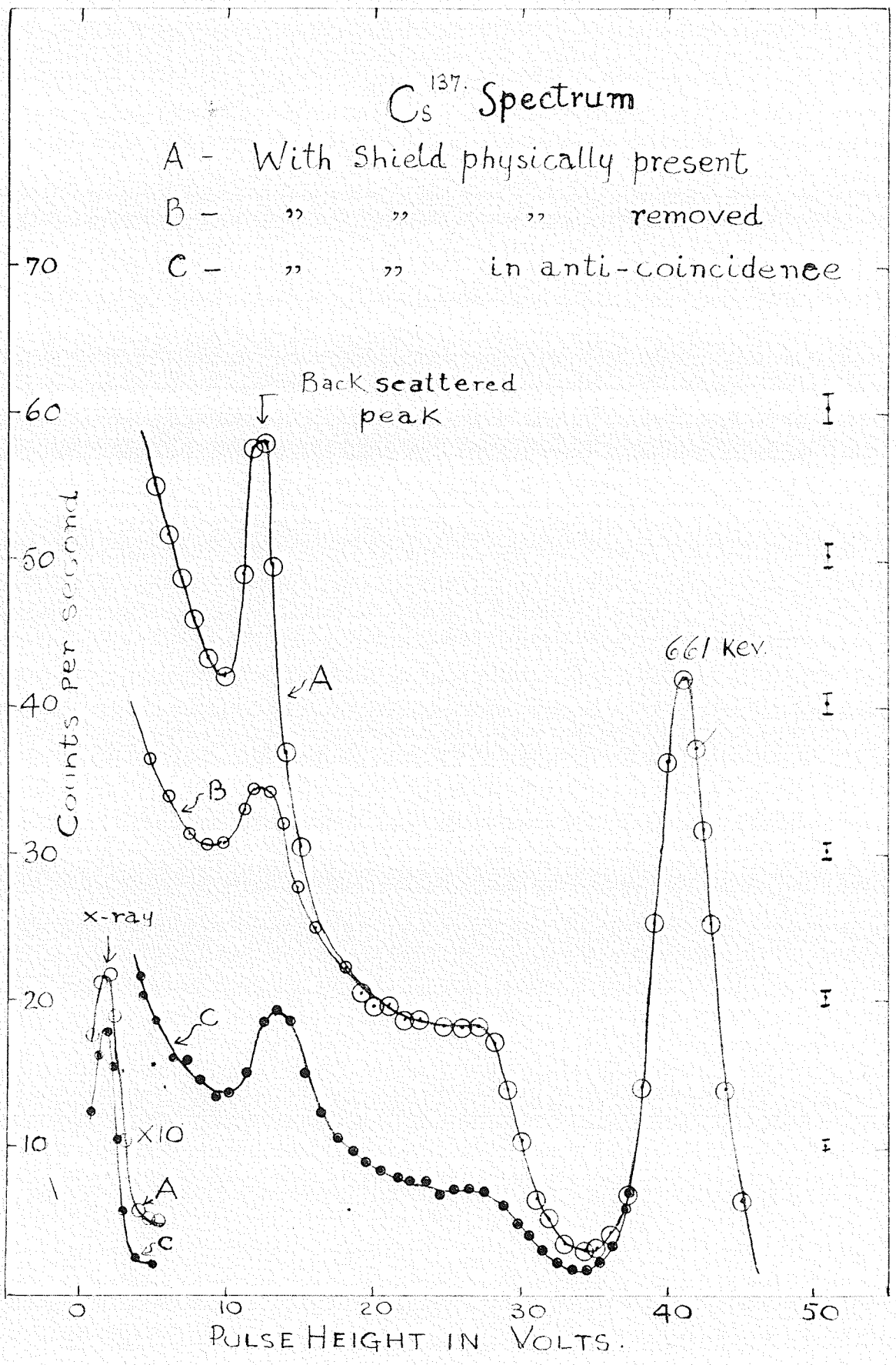
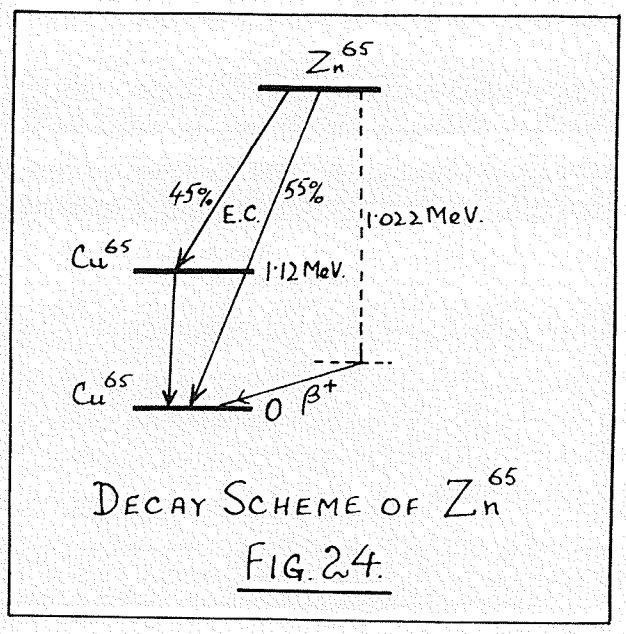

Cs^{137} Spectrum
A - With Shield physically present
B - " " " removed
C - " " in anti-coincidence
Back scattered peak
661 Kev.
A
B
C
x-ray
X10
Counts per second
70
60
50
40
30
20
10
0
10
20
30
40
50
Pulse Height in Volts.

FIG. 23.

4.3 Zn^{65} SPECTRUM:-

Zn^{65} decays to Cu^{65} mainly by K capture (97.5%) and partly by positron emission (2.5%) (G46, F51, Ma52). A gamma-ray of energy 1.12 Mev is emitted (M49). The half-life of the activity is 250 days. The decay scheme (H53) is given in Fig. 24 below. Because



DECAY SCHEME OF Zn^{65}

FIG. 24.

the photoelectric cross-section is roughly proportionate to about $(E)^{-3.5}$ and the Compton cross-section to $(E)^{-1}$ where E is the gamma-ray energy, this gamma-ray of 1.12 Mev causes more Compton scattering in proportion to photoelectric process than the 661 Kev Cs^{137} gamma-ray. This 1.12 Mev gamma-ray is, therefore, a good source for testing the performance of the spectrometer. The pulse height distribution curves for Zn^{65} gamma-ray are shown in Fig. 25. As before, the curve A is obtained without the Compton reducing arrangement but with the shield physically present, curve B is obtained with the shield removed physically and

curve C is obtained by using the anti-Compton shield to get a reduction in the Compton portion of the spectrum. Here also it is confirmed that the physical presence of the plastic does not alter the shape and the size of the Compton portion of the curve except the low energy part up to the back-scattered peak. The annihilation peak is obtained by the capture in the NaI (Tl) crystal of one of the positron annihilation quanta. The other quantum goes to the plastic and has a good chance of being detected there. Thus the annihilation peak is greatly reduced, as can be seen from the curve C of Fig. 25. The Copper X-ray peak could not be resolved because of its very low (7.8 Kev) energy.

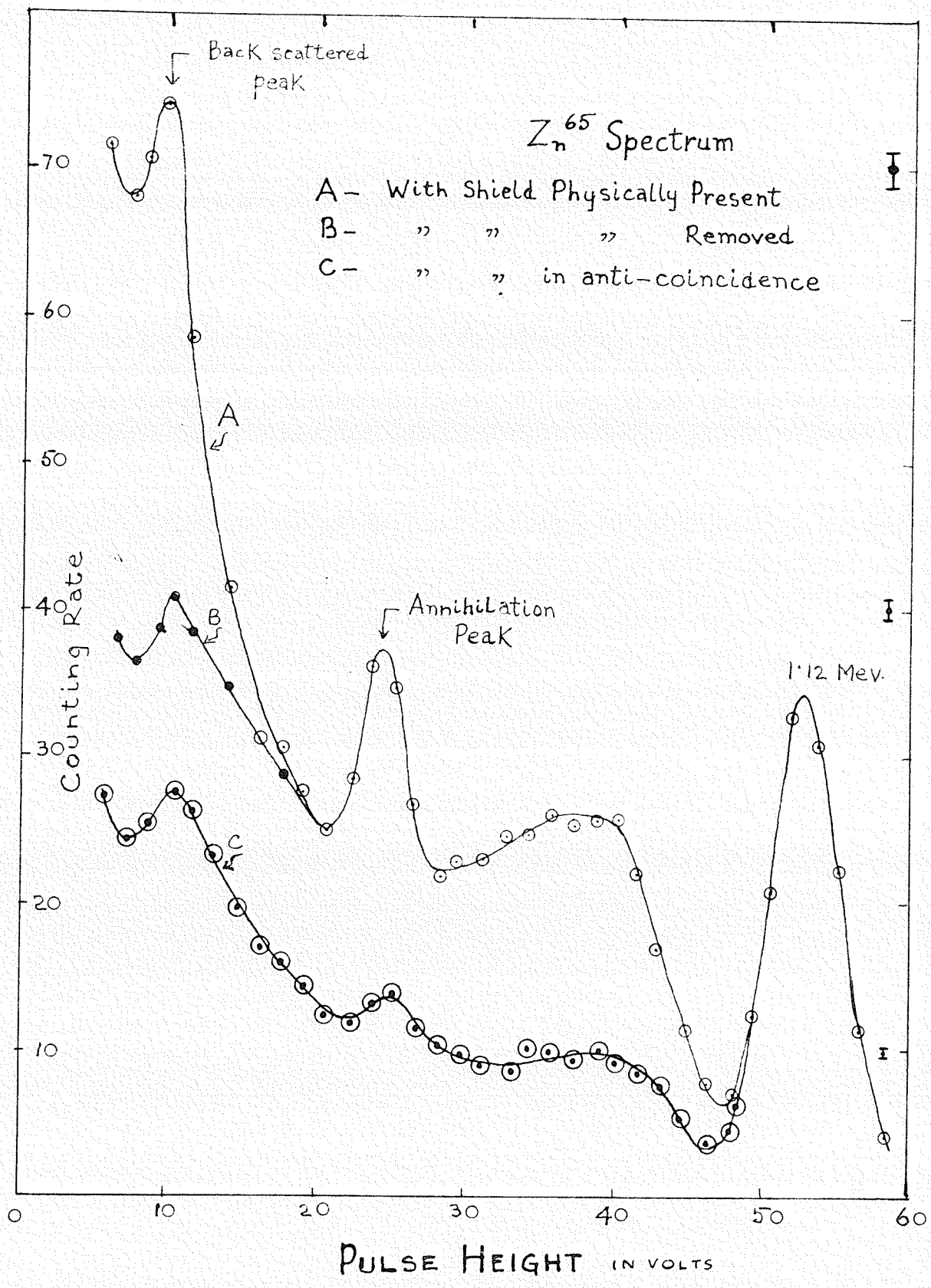
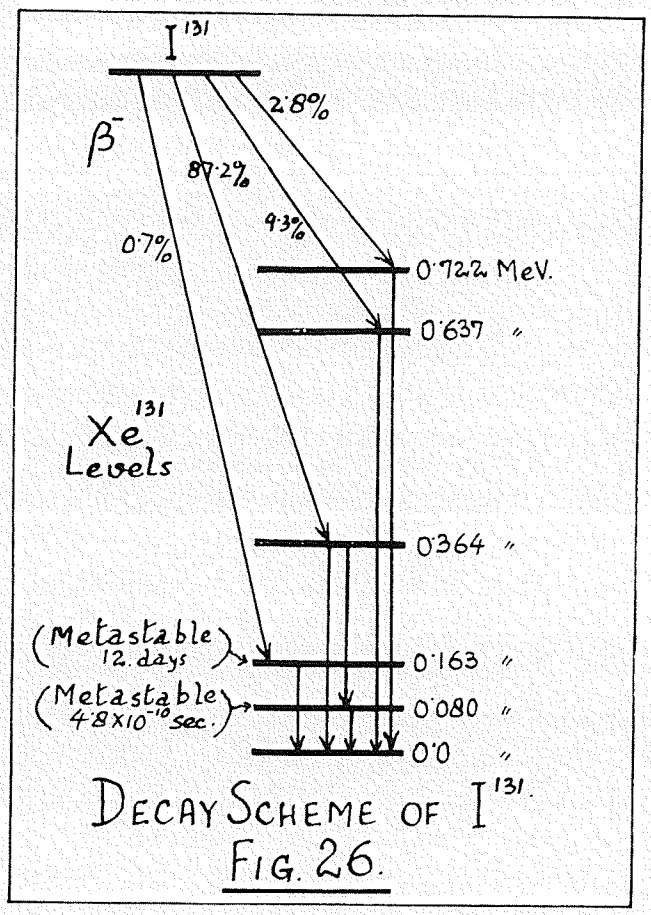

Back scattered peak
Zn^{65} Spectrum
A – With Shield Physically Present
B – " " " Removed
C – " " in anti-coincidence
A
B
C
Annihilation Peak
1·12 Mev.
Counting Rate
Pulse Height in volts
0
10
20
30
40
50
60
70

FIG. 25.

4.4 I^{131} SPECTRUM:-

After establishing the effectiveness of the anti-Compton shield in reducing the Compton spectrum by studying gamma-rays from Cs^{137} and Zn^{65} sources, it was decided to analyse a more complicated source. I^{131}, which decays by negatron emission to Xe^{131}, has a well established decay scheme (B52). It is shown in Fig. 26 given below (H53). Since the high energy (above 364 Kev)



DECAY SCHEME OF I^{131}.

FIG. 26.

portion of the I^{131} spectrum is of low intensity, its Compton contribution in the lower energy (364 Kev and below) region is very small. There not being any point of real interest to be investigated in the region above 364 Kev, it was considered adequate to investigate the I^{131} spectrum from zero up to the 364 Kev

intense gamma-ray only. This made it possible to get the curves with both the reduced and unreduced Compton parts (i.e. with and without the use of anti-Compton shield) within a few hours. This interval (about 3 hours) being much smaller than the I^{131} half-life (8.14 days), the reduction in source intensity during the experiment could be neglected. Having determined the curve only up to 364 Kev gamma-ray, the effect of the physical presence of the plastic shield on the spectrum was determined in a separate test. This was done by drawing the spectrum with the shield physically present and then physically removed. The two sets of curves so obtained were normalized and are shown in Fig. 27.

As can be seen from the decay scheme given above, the 80 Kev gamma-ray and the 284 Kev gamma-ray are self-coincident and because there is some angular correlation between them which is different from 0^{o}, if one of them goes into the NaI (Tl) crystal, the other will go into the plastic where it may be detected. These two gamma-rays (80 Kev and 284 Kev) should therefore be reduced in the curve C of Fig. 27. The fact that the 284 Kev line is not reduced substantially, indicates that the 80 Kev gamma-ray is **not** being detected very well in the anti-Compton arrangement. As mentioned in an earlier section, there is a two fold nature of the efficiency in Compton reduction. Firstly there is the probability of capture in the plastic of the gamma-photons Compton scattered from the NaI crystal. Secondly there is the probability that the light photons originating in the plastic will reach the photo-cathode of the multiplier tube and be

detected there, that is, converted into photo-electrons, which will give rise to a pulse higher than the level of discrimination. It appears that for the 80 Kev photons, both the above mentioned factors combine to give a lower detection efficiency in the anti-Compton arrangement with the result that the 284 Kev gamma is not reduced appreciably.

A close comparison of the curves A and C of Fig. 27 shows that unlike the Cs^{137} spectrum (Fig. 23) the X-ray peak in I^{131} spectrum is partly reduced by the anti-Compton shield. This is because the Xe X-rays do not arise from the conversion of one single ''unassociated'' gamma-ray, but from several gamma-rays some of which are ''in cascade''. The Xe X-rays arising from the conversion of 163 Kev, 364 Kev, 637 Kev and 722 Kev gamma-rays cannot be affected by the plastic shield. On the other hand when a 80 or 284 Kev gamma-ray is converted, its associated gamma-ray goes into the plastic where it may be detected and hence this X-ray may be eliminated. We can now perform an analysis in the following way.

The X-ray peak in the curves A and B (Fig. 27) is composed of three parts, namely,

X, the part due to conversion of unassociated gamma-rays

Y, the part due to conversion of associated gamma-rays

and Z, Compton tails (natural background is neglected).

If e is the efficiency of detection of gamma-rays in the plastic shield, H_b and H_c, the heights of the X-ray peaks in the curves B and C (Fig. 27) respectively will be given by:

$$H_b = X + Y + Z$$

and $$H_c = X + (1-e)\ (Y+Z)$$

Eliminating (Y+Z) from the above two equations, we get:

$$X = H_b - \frac{H_b - H_c}{e}$$

Hence, $$\frac{X}{X+Y} = \frac{H_b - (H_b - H_c)\ 1/e}{X+Y} = \frac{H_b - (H_b - H_c)\ 1/e}{H_b - Z}$$

Assuming e to be equal to 2/3, the curve for X was calculated and is shown as the curve D in Fig. 27. Various estimates were made of the shape of Compton tail lying under the X-ray peak. This enabled an evaluation of $(H_b - Z)$ to be made. As estimated from the Fig. 27, the intensity of the X-ray due to the conversion of unassociated gamma-rays is about 28% of the total X-ray intensity. This is quite close to the 30% calculated from the data given by Bell and Graham (B52).

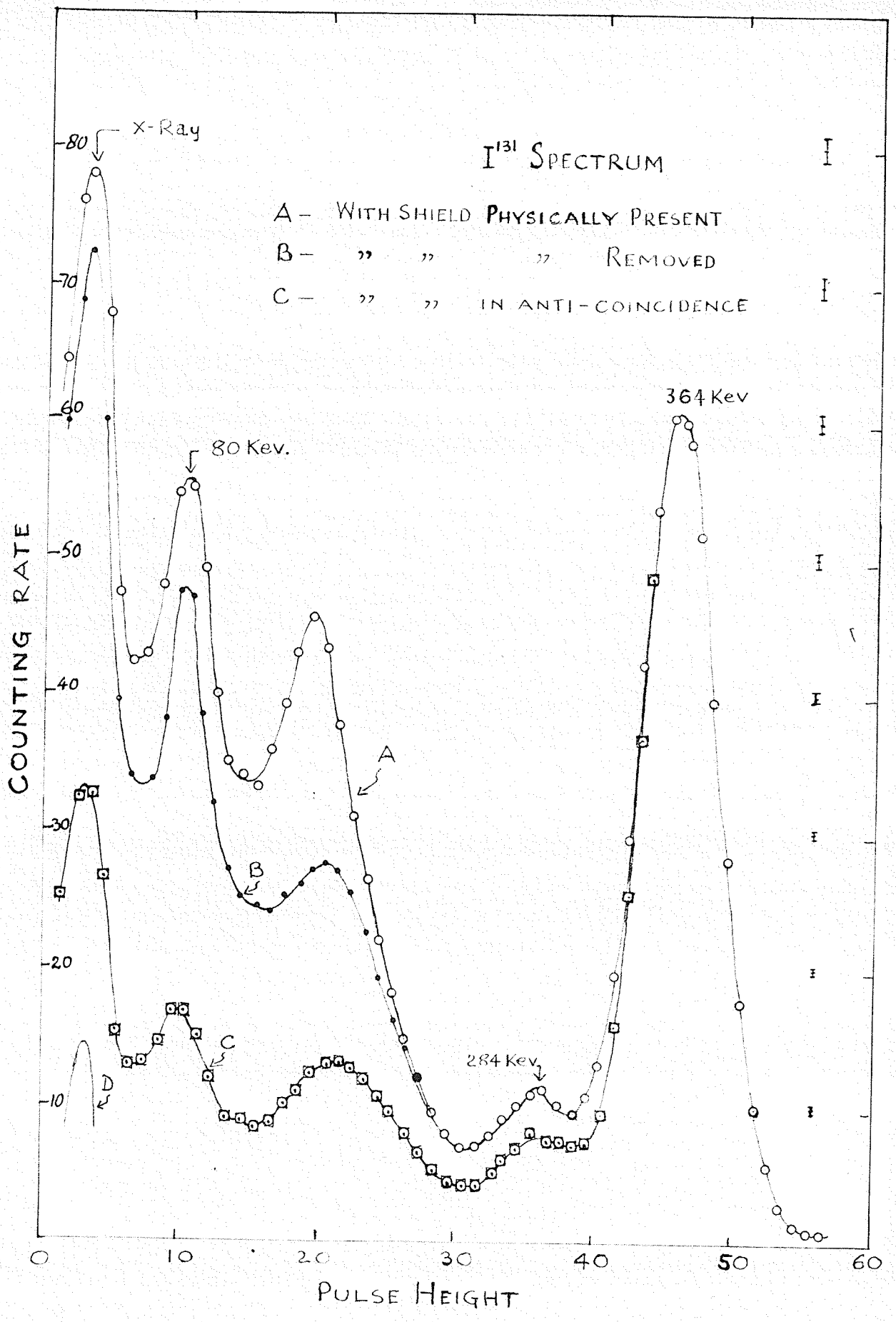

I^131 SPECTRUM
A – WITH SHIELD PHYSICALLY PRESENT
B – " " " REMOVED
C – " " IN ANTI-COINCIDENCE
X-Ray
80 Kev.
364 Kev
284 Kev
A
B
C
D
COUNTING RATE
PULSE HEIGHT
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60

FIG. 27.

4.5 ANALYSIS BY SUBTRACTION:-

For a given gamma-ray source, pulse height distribution curves with and without the Compton reduction can be obtained by the spectrometer. As already shown by the spectra of Cs^{137}, Zn^{65} and I^{131} sources, the reduction in the Compton part is only partial because the detection efficiency in the anti-Compton shield is not 100 per cent. By taking the difference between the two curves (with and without Compton reduction) the Compton shape for a gamma-ray spectrum can be computed and then subtracted from the unreduced Compton curve. This will leave only the photo-peaks and thus features which originally were small and dubious will now be quite prominent.

Suppose that the main visible features of a gamma-ray spectrum taken by an ordinary scintillation spectrometer are a Compton part C and a photo-peak where the counting rate is P. Suppose that the source contains another weak gamma-ray whose photo-peak, p, falls in the Compton region, C, of the strong peak, P. In ordinary gamma-ray spectrum the counting rate in the Compton region will thus be $(C + p)$ and p being much less than C, the small photo-peak may not be recognizable. If now a spectrum is taken with the total absorption spectrometer described in this thesis, the Compton portion will be reduced to, say, 1/n of its original value but the photo-peak will remain as before. The counting rate in the Compton region will now be $(\frac{C}{n} + p)$. If this part be multiplied by n and then the unreduced Compton curve be subtracted from it, the resulting curve will have a

counting rate (n - 1)p, that is, only the photo-peak will be shown.

The standard deviation in the counting rate N at any point of a spectrum is, due to statistical fluctuations, given by $\sqrt{N}$. In the spectrum, of the source of features outlined in the preceding paragraph, obtained by an ordinary scintillation spectrometer, the small photo-peak ''p'' could only be suspected if $p > \sqrt{C}$. On the other hand, in the spectrum obtained by the total absorption spectrometer, C is reduced to $\frac{C}{n}$ and hence the small photo-peak can be suspected if $p > \sqrt{\frac{C}{n}}$. This shows that the efficiency of the total absorption spectrometer for the recognition of weak gamma rays in presence of strong ones is improved by a factor of $\sqrt{n}$ over the ordinary scintillation spectrometer where n is the Compton reduction factor. Also, it should be noted, that the subtraction analysis could only be carried out when $p > \sqrt{\frac{C}{n}}$, that is, there is a definite suspicion of the presence of ''something'' apart from the Compton portion.

This method of analysis by subtraction was applied to the I^{131} curve. In Fig. 27 the curve C was multiplied by 4 and then from this was subtracted the curve A. Resultant curve is shown in Fig. 28. Here the features are quite clear. The 80 Kev line is almost completely absent. The 284 Kev line is now obviously reduced indicating that it is coincident with some other line (80 Kev in this case). The weak 163 Kev line is now very distinct. Previously it was hidden in the Compton from the strong 364 Kev gamma line. It should be noted that the back-scattered peak of 364 Kev falls at 150 Kev whish is very close to 163 Kev and is undistinguishable from it in Fig. 27.

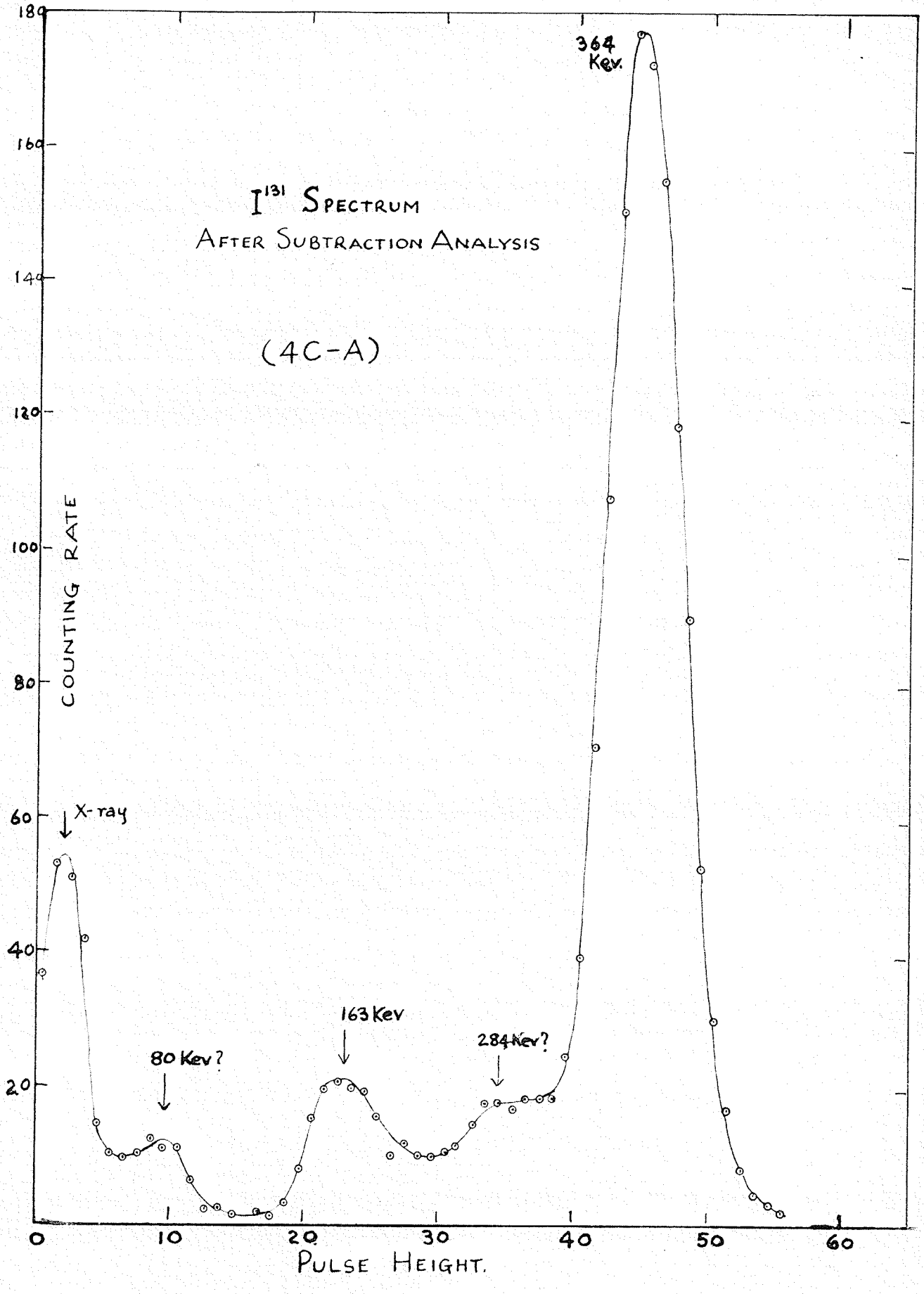

I^131 SPECTRUM
AFTER SUBTRACTION ANALYSIS
(4C-A)
364 Kev.
X-ray
80 Kev?
163 Kev
284 Kev?
COUNTING RATE
PULSE HEIGHT.
180
160
140
120
100
80
60
40
20
0
10
20
30
40
50
60

FIG. 28.

CHAPTER 5.

CONCLUSION

A definite improvement and simplification in the gamma-ray spectrum is achieved by the use of this spectrometer as compared with spectrum obtained from an ordinary scintillation spectrometer. The improvement is in the ease of recognition of the weak gamma-rays which happen to fall in the Compton portion of an intense gamma-ray. Simplification is in the total number of gamma-rays observed in the spectrum. They are fewer because all the self-coincident lines tend to cancel each other.

This spectrometer could be used to draw the gamma-ray spectra with reduced Compton portion. If the internal conversion X-ray peak is also resolved, such a curve with reduced Compton portion, can be utilized to calculate the internal conversion coefficients for certain isotopes with fairly simple decay schemes.

The use of an anti-Compton shield, as outlined in this thesis, is of great potential value. In scintillation gamma-ray spectroscopy, measurements may be made with the source outside the anti-Compton shield and the radiation collimated through a hole in the shield or with the source inside the shield but outside the crystal. In both, weak gamma-rays may be investigated and cascades may be identified.

In coincidence studies and particularly in angular correlation studies, an anti-Compton shield could be utilized to reduce substantially the number of spurious counts.

A large well type crystal with the source placed at the centre is very useful for certain purposes because it adds all the coincident gamma-rays. The effectiveness of such a large crystal spectrometer may further be increased by using a Compton reduction shield as described in this thesis. It will give a more complete reduction in the Compton portion, especially if a very large crystal is not acceptable because of its inferior resolution. Probably a liquid scintillator tank as the anti-Compton shield will be more economic than the plastic shield described in this thesis.

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