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Abstract

The coincidence spectrometer consists of two scintillation spectrometers, each of which can be used as either a beta-ray or a gamma-ray spectrometer, depending on what crystals are used. The pulses from the first spectrometer are analyzed with a single channel analyzer. The pulses corresponding to a certain energy are picked out with the analyzer and are fed into one channel of a coincidence circuit. The pulses from the second spectrometer are fed into the other channel of the circuit. The coincidence output pulses are used to trigger an oscilloscope. The pulses from the second spectrometer are displayed on the screen of the scope. Because the scope is triggered by the coincidence circuit, only those pulses from the second spectrometer which are in coincidence with the selected pulses from the first spectrometer are seen. The pulse distribution of the displayed pulses is recorded by photographic methods. Gamma-ray spectra are recorded by taking still pictures of the screen. Beta-ray spectra are recorded by photographing the screen with a movie camera, so that each individual pulse is recorded separately.

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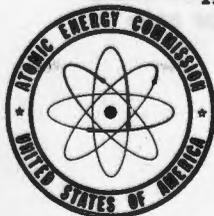
A COINCIDENCE SCINTILLATION SPECTROMETER

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December 9, 1953

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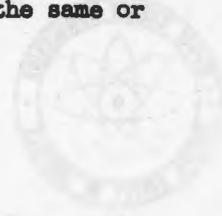
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A COINCIDENCE SCINTILLATION SPECTROMETER

By

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ABSTRACT

The coincidence spectrometer consists of two scintillation spectrometers, each of which can be used as either a beta-ray or a gamma-ray spectrometer, depending on what crystals are used. The pulses from the first spectrometer are analyzed with a single channel analyzer. The pulses corresponding to a certain energy are picked out with the analyzer and are fed into one channel of a coincidence circuit. The pulses from the second spectrometer are fed into the other channel of the circuit. The coincidence output pulses are used to trigger an oscilloscope. The pulses from the second spectrometer are displayed on the screen of the scope. Because the scope is triggered by the coincidence circuit, only those pulses from the second spectrometer which are in coincidence with the selected pulses from the first spectrometer are seen. The pulse distribution of the displayed pulses is recorded by photographic methods. Gamma-ray spectra are recorded by taking still pictures of the screen. Beta-ray spectra are recorded by photographing the screen with a movie camera, so that each individual pulse is recorded separately.

INTRODUCTION

In studying the radioactive decay of a nucleus, one determines in the first place the energy values of the emitted radiation. If these values are determined with high accuracy it is possible to propose a decay scheme by combining the energy values so that a consistent scheme is obtained. However, this method can never give absolute certainty and there are very many cases in which it cannot be used.

The most certain method for composing a decay scheme is to perform coincidence measurements in order to find out how the different transitions are in coincidence with each other. The method of using Geiger-Müller tubes and absorbers is of very limited value. It can be used in very simple decays. In more complicated

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cases one can, it is true, obtain results of some value by employing different absorbers and by using detectors of different sensitivity, but the uncertainty in the interpretation of the results is necessarily great.

The development of scintillation spectrometers with high sensitivity and fairly good resolution has made it possible to perform coincidence measurements even in the case of complicated decays. One can, for example, select a certain gamma-ray with a scintillation spectrometer and use another spectrometer to look for gamma-rays in coincidence with the selected one. It is also possible to select beta-particles within a certain energy interval by means of a scintillation spectrometer and to use another spectrometer to examine the gamma-radiation in coincidence with the selected beta-radiation. One can finally use the reverse method: Select a certain gamma-ray and examine the energy distribution of the beta-radiation in coincidence with the gamma-ray. These three methods of coincidence measurements are hereafter called gamma-gamma, beta-gamma, and gamma-beta measurements, respectively.

In some cases coincidence measurements can make it possible to determine energy values with better accuracy than by direct determination of the energy distribution. If, for example, two gamma-rays are very close in energy, it is difficult to get accurate energy values, especially for the gamma-ray with the smallest intensity. Sometimes one then can isolate one of two adjacent gamma-rays and in this way get a more accurate value for the energy. This method can also be used for beta-rays. It is sometimes rather difficult to resolve a complicated beta-spectrum into components, especially if some of them are of low intensity. A coincidence spectrometer makes it often possible to isolate a certain beta-component from the other ones so that the end point can be determined with better accuracy.

The main problem in coincidence measurements is the counting rate. In order to get good statistics the counting rate must not be too low. A coincidence spectrometer must be designed very carefully in that respect. The most effective scheme is to select a certain radiation component in one of the spectrometers with a single channel analyzer and to analyze the corresponding coincidence pulses in the other spectrometer by means of some kind of multichannel analyzer. The resolving power of the coincidence circuit must, of course, be as high as possible. It is limited by the fact that the pulse width must be great enough to permit pulse height measurements. The number of accidental coincidences must, of course, be kept low. If the source strength is increased in order to obtain a higher counting rate the number of accidental coincidences is also increased. The counting rate is proportional to the source strength, but the number of accidental coincidences is proportional to the square of the source strength. Having a certain resolving power one can therefore increase the source strength only to a certain limit. The only remaining factor to adjust is the solid angles of the crystals at the source. These should then, it appears, be made as large as possible.

Using large solid angles brings with it a new problem, however. Consider a certain gamma-spectrum containing two gamma-rays in cascade and a third one whose energy is roughly equal to the sum of the energies of the first two. There is a certain chance that the two rays which are emitted in cascade will be absorbed in the same crystal. The two quanta then add together and give a pulse-height distribution whose maximum is about the same as the maximum of the distribution produced by the third gamma-ray. This effect is especially important when the solid angles are large and the intensity of the third gamma-ray is low. It may even be impossible to separate the third ray from the other two with a pulse analyzer although the energies lie far apart. Similar difficulties may arise if a beta-ray and the gamma-ray which succeeds it are absorbed in the same crystal. For these reasons too large solid angles are inadvisable.

A further difficulty in scintillation spectrometer coincidence work lies in the scattered radiation. This radiation influences the measurements in several ways. A background of scattered radiation is obtained, which blurs fine details in the pulse height distribution. The radiation scattered directly backwards from one crystal to the other is especially troublesome because of the unwanted coincidences it causes. Suppose, for example, that a quantum ejects an electron by Compton collision in the first crystal and that the quantum is scattered directly backwards. Its energy is then about 200 Kev.* and it has a high probability of being absorbed in the second crystal. It is therefore evident that if the pulse-analyzer channel is set on the upper part of a Compton distribution, a peak at 200 Kev. is obtained in the corresponding coincidence spectrum. False peaks are also obtained, for the same reason, if the channel is set at 200 Kev. This effect can be diminished by placing a lead plate between the crystals.

APPARATUS

The apparatus described here is an improved model of a previous design.¹ A sodium iodide crystal, $1\frac{1}{2}$ inches diameter and $\frac{1}{2}$ inch thick, in connection with a DuMont photomultiplier model K1177, is used as a gamma-ray spectrometer. The crystal is held in place on the top of the tube by a thin lucite ring. Thick silicone oil (10^6 cps) gives optical contact between crystal and tube. The crystal is enclosed by a thin walled aluminum container, which is coated with a thin layer of magnesium oxide on the inside by holding it in the smoke from burning Mg metal. The container is cemented to the top of the tube in order to get the crystal hermetically sealed. The spectrometer was put together in a dry box in a helium atmosphere. The phototube is painted with black Glyptal in order to make it lighttight. An anthracene crystal, $1\frac{1}{2}$ inch in diameter, in connection with a DuMont photomultiplier model K1177, is used as a beta-ray spectrometer. The crystal is mounted in the same way as the sodium iodide crystal. It is, however, coated with a thin aluminum foil with a thickness of 3 mg/cm^2 . The anthracene crystal

* see Appendix I.

¹Sven A. E. Johansson, S. Almgvist, Arkiv för Fysik, 5, 427 (1952).

absorbs gamma-rays to some extent. In order to obtain pure beta-spectra it is necessary to determine this effect and to correct for it. Separate runs with an absorber to stop the beta-rays give the magnitude of this gamma-ray contamination in the beta-ray spectra. In order to reduce this effect, the thickness of the anthracene crystal is made as small as possible. Therefore different crystals are used for different beta-energies. One must of course be sure that all beta-particles are completely stopped in the crystal.

The photomultipliers are attached to boxes which contain a voltage dividing network for the high voltage and a cathode follower. Figure 1 shows a picture of the spectrometer arrangement. The spectrometers are attached to a ring stand. They can be adjusted in different positions. The apparatus can therefore be used for measurements on angular correlations.

A schematic diagram of the apparatus is shown in Figure 2. The pulses from the two cathode-followers are amplified in two linear amplifiers with 12 Mc bandwidth and a gain of about 100. The amplifiers are followed by two pulse-shapers which give output pulses with a flat top. A circuit diagram of the cathode-follower, amplifier and pulse-shaper is given in Figures 3a and 3b. The pulses from the first spectrometer are analyzed by a one-channel pulse-height analyzer. The analyzer is of a design given by Francis and Bell.² The output pulses from the analyzer are counted by a scaler of conventional design. The pulses from the second spectrometer are led to an integral discriminator. It consists essentially of a schmitt trigger circuit and a pulse-shaping circuit. It gives output pulses of the same height and shape as the pulses from the single-channel analyzer, i.e. 15 volts height and a time-constant of 0.5 μ sec. A circuit diagram of the discriminator is shown in Figure 4. The counting rate in the discriminator is determined by a conventional scaler. The output pulses from the single-channel analyzer and the integral discriminator are coupled to a coincidence circuit. This circuit is of a type described by Wiegand.³ The pulses from the first spectrometer, however, are delayed in the single channel analyzer. The size of this delay depends on the width of the pulses going into the analyzer. In this case it is about 0.75 μ sec. In order to compensate for the delay, the pulses from the integral discriminator are delayed for the same length of time by a delay line of the proper length. The resolution of the coincidence circuit is determined by the width of the incoming pulses. It is about 1 μ sec. The coincidence circuit is coupled to a pulse generator. The input of the generator consists of schmitt trigger circuit which discriminates between coincidence pulses and single pulses from the coincidence circuit. The output part of the generator consists of a blocking oscillator which gives fast pulses of constant height. They are used in the pulse recording system to indicate the presence of a coincidence. They are also

² J. E. Francis and P. R. Bell, ORNL-1470.

³ C. Wiegand, Rev. sci. Instr., 21, 975 (1950).

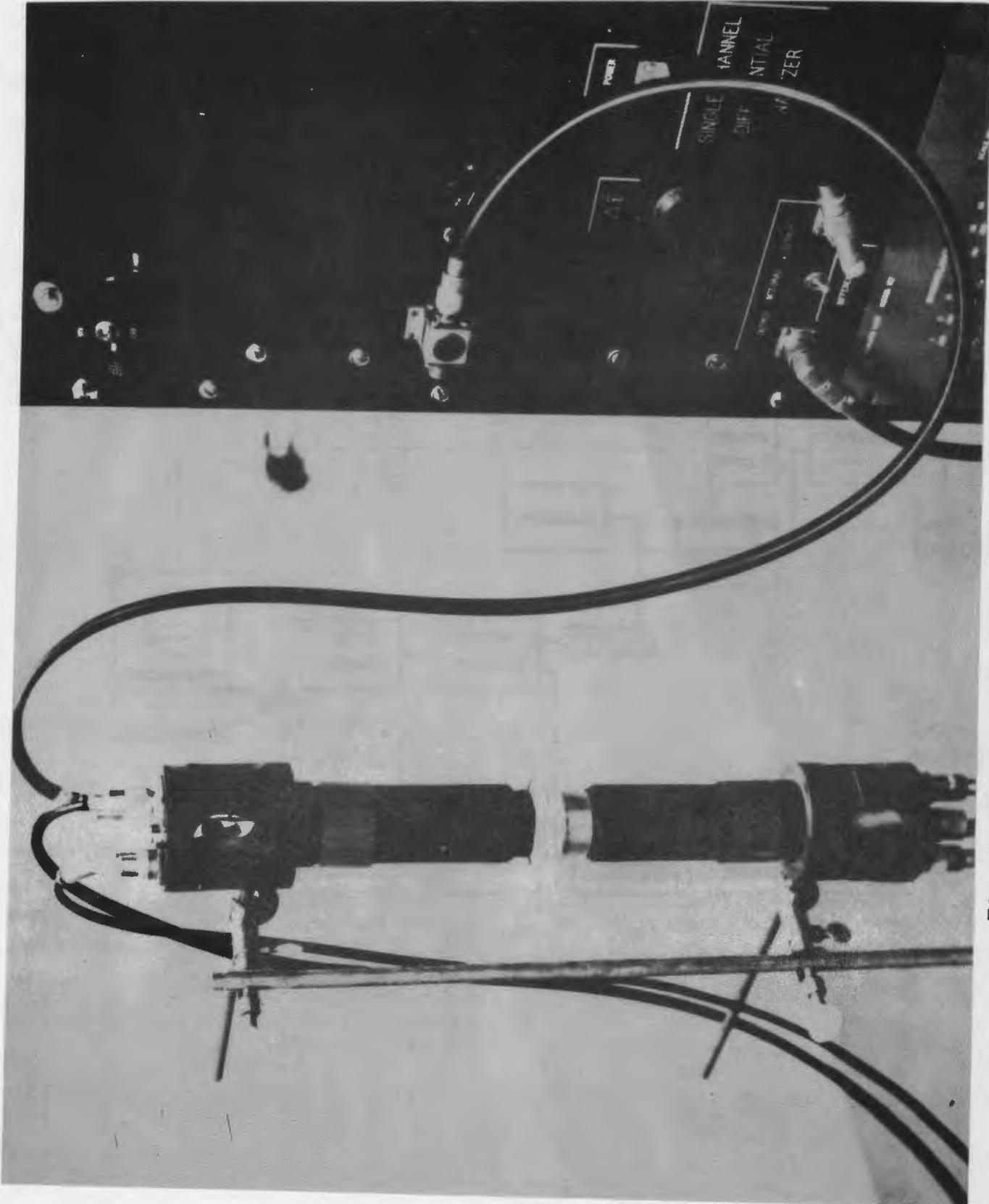


Fig. 1 Spectrometer Arrangement.

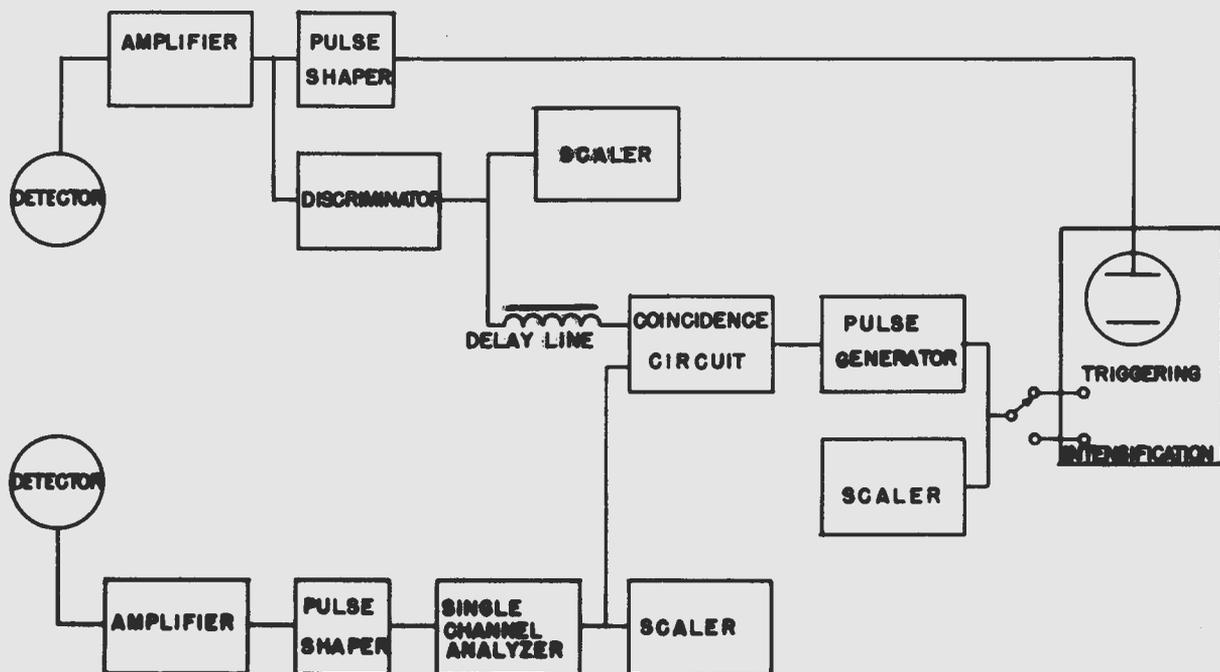


Fig. 2 Schematic Diagram of the Apparatus.

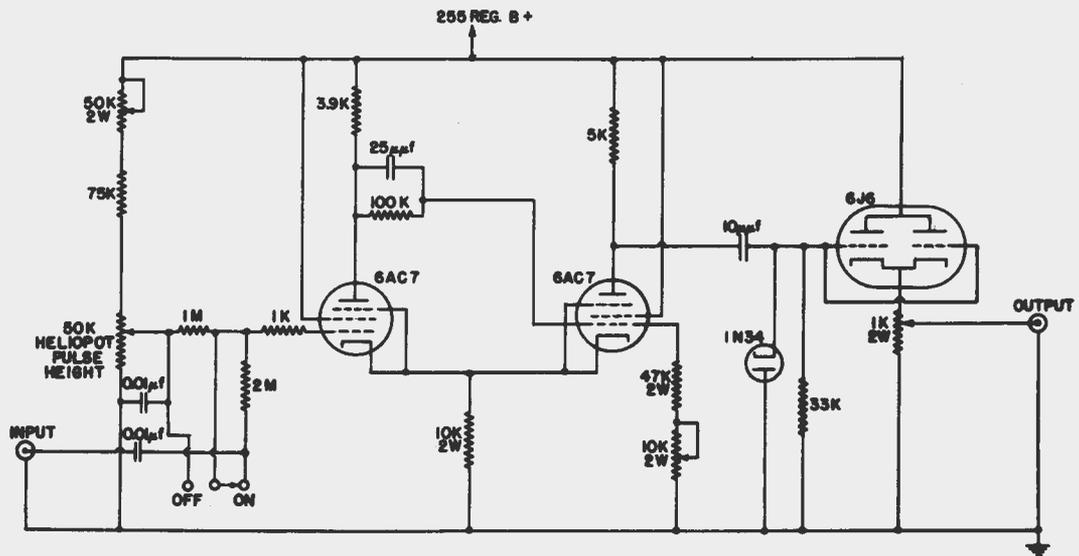


Fig.4 Circuit diagram of the pulse-height discriminator.

counted by a scaler in order to get the number of coincidences. A circuit diagram of the pulse generator is shown in Figure 5.

The determination of the pulse-height distributions is performed by using an oscilloscope, DuMont 404A. The following method was used for beta-radiation: The pulses from the pulse-shaper of the second spectrometer are coupled to the horizontal deflection plates of the scope. No sweep is applied to the other pair of plates. The pulses appear on the screen as dots on account of their flat top. The distance of a dot from the base-line gives the height of pulse. The brightness is then decreased so that the dots no longer are visible on the screen. When the pulses from the pulse generator are coupled to the intensification circuit of the scope the coincidence pulses appear as dots on the screen. Due to the fact that the intensifying pulses are very fast only a part of the flat top of the pulses is intensified. The dots on the screen are recorded by a movie camera with continuous film transport. The pulse-height distribution is obtained by running the film in a "dot counter" according to Zaffarano et al.⁴ It is also possible to use the apparatus as a single beta-spectrometer. The triggering level of the pulse generator is, in that case, adjusted so that also single pulses from the coincidence circuit are able to trigger the generator. A convenient calibration with simple and well-known spectra can be obtained in this way.

Gamma-ray are also recorded by using the scope. The pulse generator is connected to the triggering circuit of the scope. The coincidence pulses appear then on the screen. They are recorded by means of a DuMont oscilloscope camera, which takes still pictures of the screen. The exposure time depends on the frequency of the pulses. A base line is obtained by triggering the scope with a separate pulse generator for a short period of time during each exposure. Figure 6 shows a typical picture of a pulse distribution. One can directly see a number of peaks in the pulse distribution. The pictures are run through a microphotometer in order to get quantitative results. The microphotometer traces give both pulse-height and intensity. Figure 7 shows the trace corresponding to the picture in Figure 6.

It is very easy to measure the relative pulse-height accuracy from such a trace. Before each run the spectrometer is calibrated by taking pictures of some well-known gamma-ray spectra. The calibration gives the energy-scale of the spectrometer and makes it possible to get the energy-values of the radiation to be examined. From the densities of the photometer curve one can calculate the relative intensities of the corresponding pulse-height spectrum. It requires that the characteristic curve of the film be known. This curve is obtained in the following way: The pulses from a pulse generator are displayed on the screen of the scope. A series of pictures is taken with different values on the pulse frequency. The characteristic curve of the film is obtained by running the pictures in the photometer and plotting the density versus the frequency. The sweep speed, frequency, aperture of the camera and exposure time were kept about the same as in the

⁴W. A. Hunt, W. Rhinehart, J. Weber and D. J. Zaffarano, ISC-359.

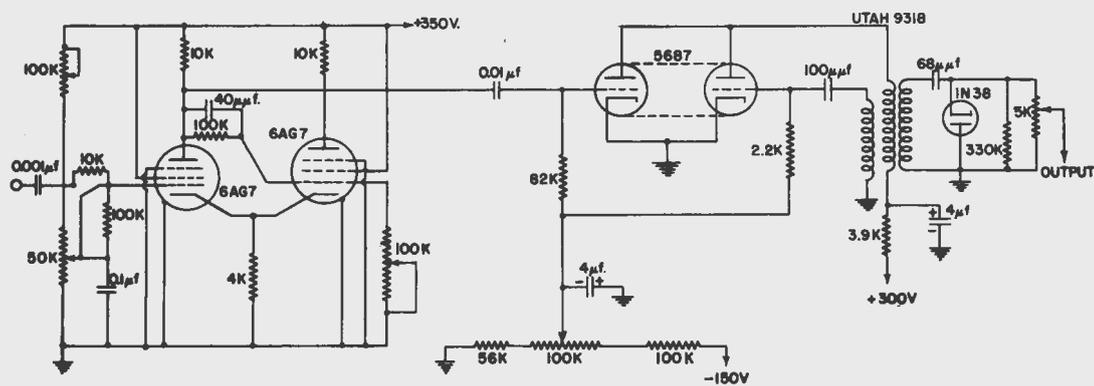


Fig. 5 Circuit diagram of the pulse generator.

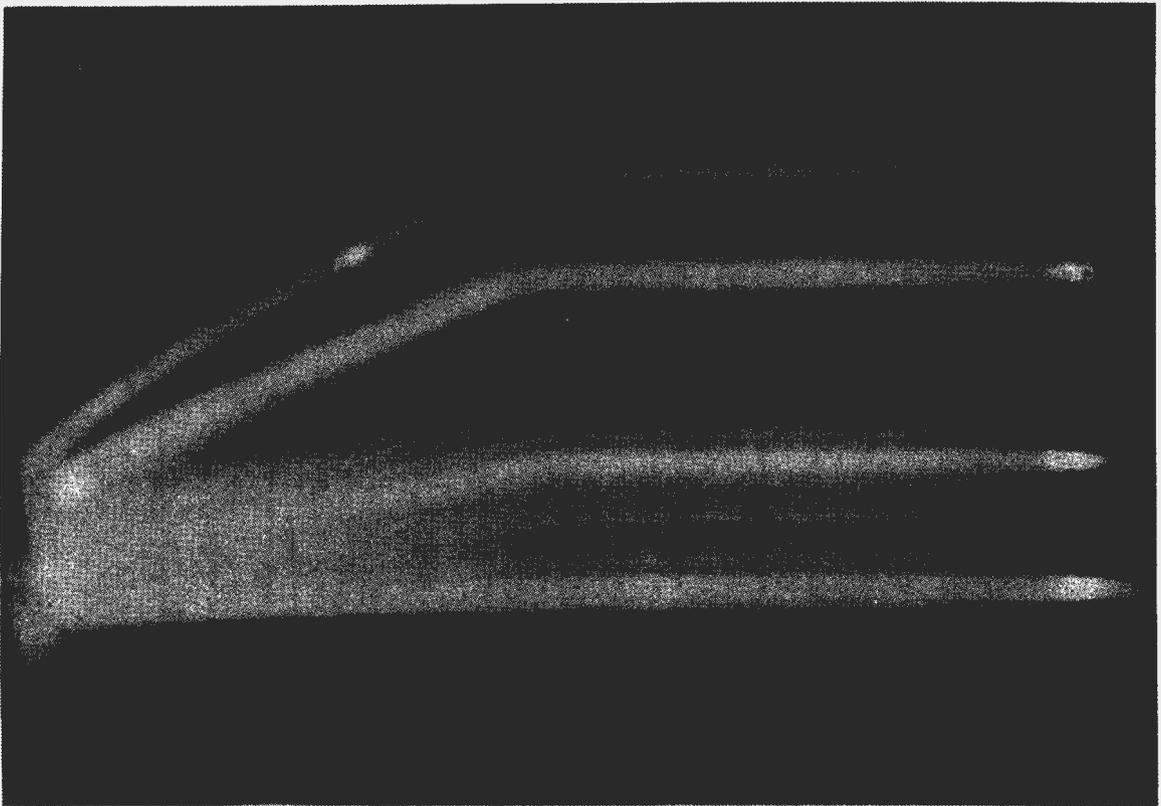


Fig. 6 A pulse-height distribution picture.

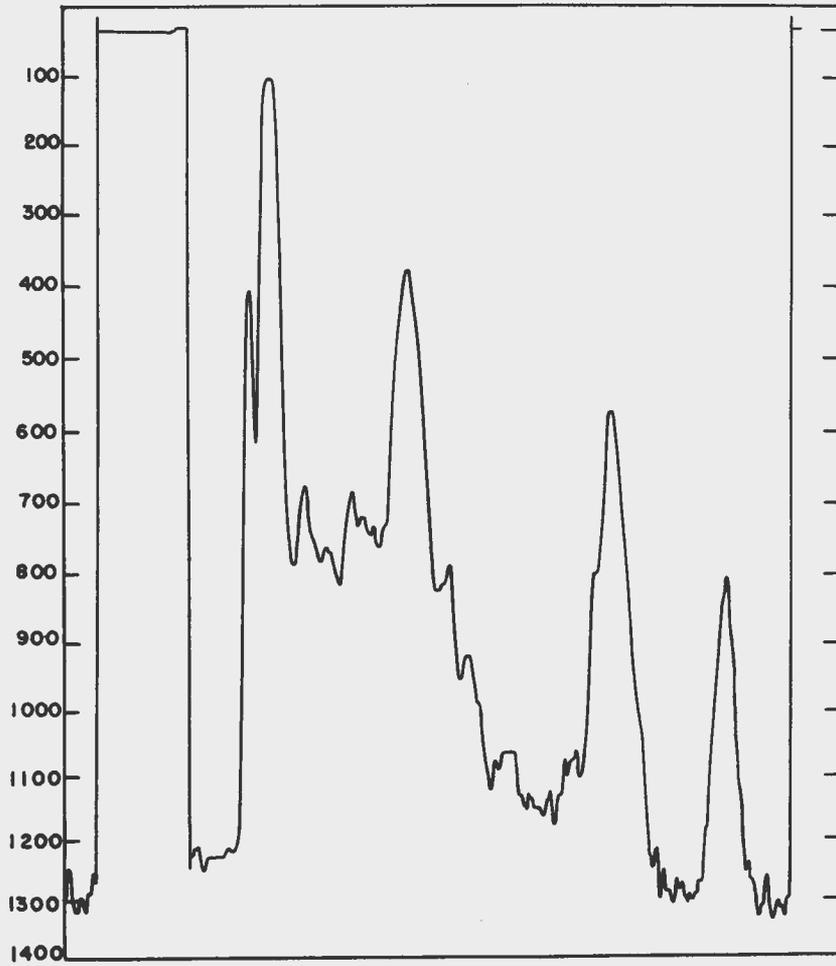


Fig. 7 A microphotometer trace of the pulse-height distribution shown in Fig. 6.

measurements. The characteristic curve should therefore be directly applicable for determining the intensity from the density. In doing so, the photometer curves are divided in a certain number of pulse-height intervals and the mean value of the density in each interval is determined from the curves. The characteristic curve gives the corresponding intensities. In this way one can convert the pulse-height versus density curves from the photometer to energy versus intensity curves.

It is important in this connection to discuss the statistical errors. The photometer curves are not completely even due to the statistical fluctuations in pulse-height. This irregularity depends on the thickness of the trace on the oscilloscope screen. A thick trace gives even curves but the resolving power is lower. The statistical errors which have to be attributed to the points of the pulse distribution curves depend on the size of the intervals used in calculating the curves from the photometer traces. The errors also depend on the thickness of the trace on the oscilloscope screen, especially if the intervals are made small. It is fairly easy to calculate approximate values for the statistical errors.

This method of obtaining gamma-ray spectra is fast and convenient. It gives energy-values of high accuracy. The intensities are less certain but pulse-height distributions obtained in this way show good agreement with those recorded with a single channel analyzer.

THE PERFORMANCE OF THE SPECTROMETER

The resolution of the anthracene beta-spectrometer was determined with a thin Cs^{137} source. Figure 8 shows the pulse-height distribution. The internal conversion peak at 625 Kev. has a full width at half-maximum of 11 per cent. This resolution allows one to make fairly accurate measurements on continuous beta-ray spectra.

It is necessary, in analyzing beta-spectra, to make some corrections. The resolution is still so low that it must be taken into account. Corrections can be made according to Palmer and Laslett.⁵ It is also necessary to correct for the non-linear response of the anthracene crystal to electrons, especially at the low energy range. This correction was made using the measurements of Hopkins.⁶

The resolution of the sodium iodide gamma-ray spectrometer is 5-7% for the Cs^{137} 661 Kev. line. It varies, depending on the particular combination of crystal and phototube. The bigger crystals have somewhat lower resolution. It is desirable in coincidence work, however, to have big crystals. The resolution is therefore in many measurements somewhat lower than the optimum one.

⁵AECU-1220, "Beta-Ray Spectrometry with an Anthracene Scintillation Spectrometer", by J. P. Palmer and L. J. Laslett.

⁶J. L. Hopkins, Phys. Rev., 77, 406 (1950).

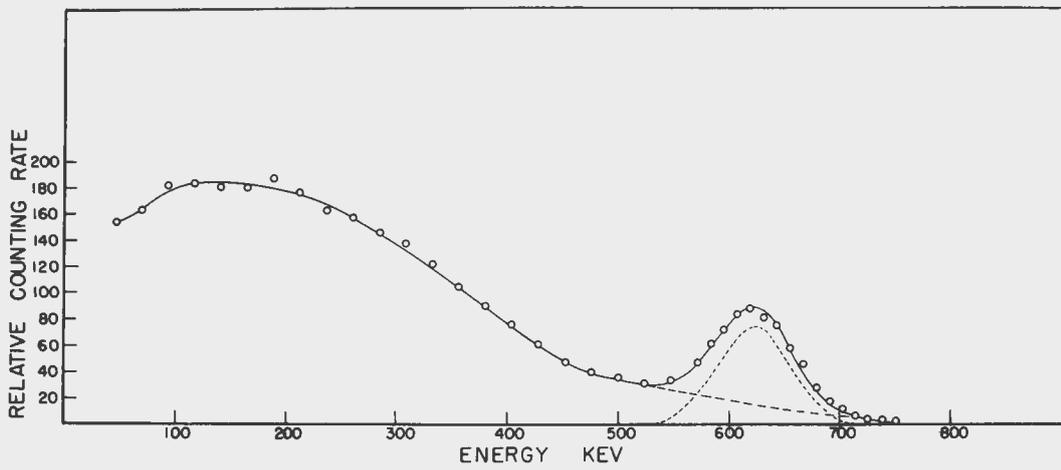


Fig. 8 The beta-ray spectrum of Cs^{137} .

This apparatus can be used for three different types of coincidence measurements: beta-gamma, gamma-beta and gamma-gamma measurements.

In beta-gamma measurements, one selects by the single channel analyzer a certain energy range in the beta-spectrometer and determines the pulse-height distribution for the gamma-radiation which is in coincidence with the selected beta-radiation. It is possible to select completely only the highest beta-component in a complicated beta-spectrum. For lower energies one selects a mixture of two or several beta-components. The proportions between the different components depend on the setting of the channel. A change of channel setting will therefore affect the shape of the gamma-ray coincidence spectrum. One can in this way get valuable information about the decay scheme. Figure 9a shows a typical gamma-ray spectrum without coincidences and Figure 9b a beta-gamma coincidence spectrum of the same source.

In gamma-beta coincidence measurements one selects a certain gamma-ray and records the corresponding beta-spectrum. Here one faces the same problem as in the case of beta-gamma measurements. It is in general impossible to isolate a certain gamma-ray from the other ones. In this case it is easier, however, on account of the peaks in the gamma-ray spectrum due to the photoelectric effect. This is especially true for energies below 500 Kev. The analyzer channel is therefore set on a photo-peak and the corresponding beta-spectrum is recorded. Measurements of this kind give very certain information about the decay scheme. Sometimes they also give more accurate energy values than the conventional method of successive subtractions in the Fermi plot. Figure 10a shows a Fermi plot of a beta-spectrum with three components. The breaks in the curve stand out very clearly. Figure 10b and 10c show Fermi plots of two coincidence spectra of the same source. The two lower components are very well separated.

The third type is gamma-gamma measurements. A certain gamma-ray is selected in the first spectrometer by the single-channel analyzer in the same way as in the preceding case. The second spectrometer is used as a gamma-ray spectrometer and the coincidence spectra are recorded as previously described.

It is generally not necessary to perform all three kinds of coincidence experiments in order to set up a decay scheme. The fact that all three can be performed offers a valuable possibility to check the measurements.

This apparatus can also be used as a two-crystal "Compton spectrometer". The gamma-radiation impinges upon one of the crystals and the back-scattered radiation is detected by the other one. The scattered radiation has an energy of about 200 Kev. and the single channel analyzer is set on that value. The coincidence pulses from the second spectrometer are recorded in the usual way. Figure 11 shows a two-crystal spectrum of the 661 Kev. line from Cs^{137} . This

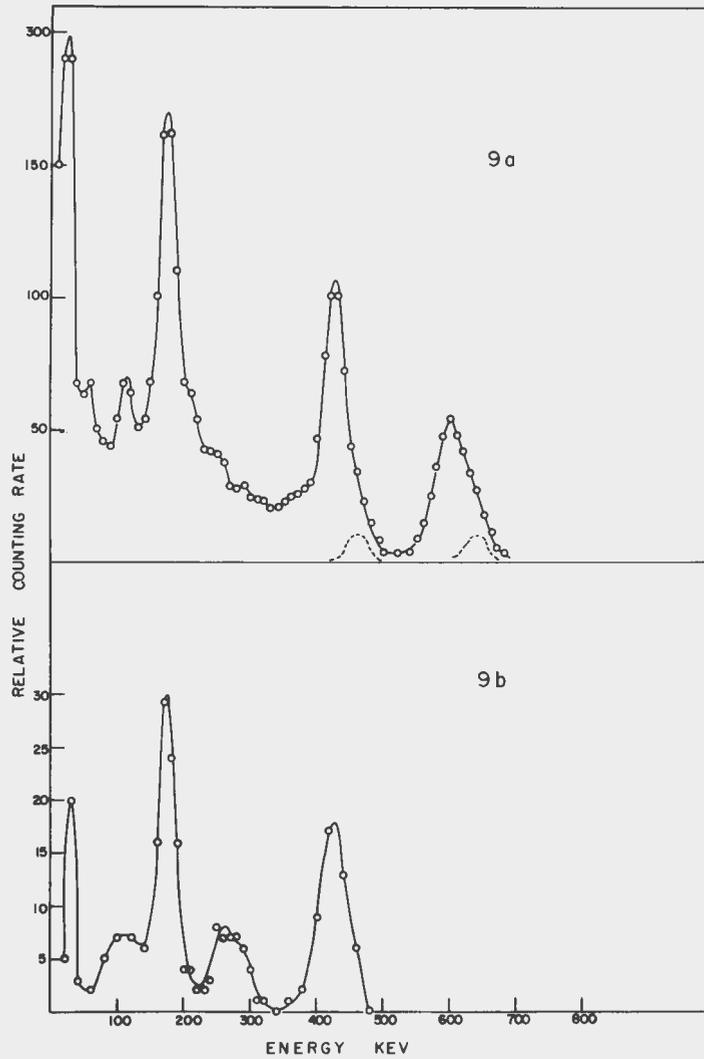


Fig. 9 a: Gamma-ray spectrum of Sb^{125}
b: Beta-gamma coincidence spectrum of Sb^{125} .

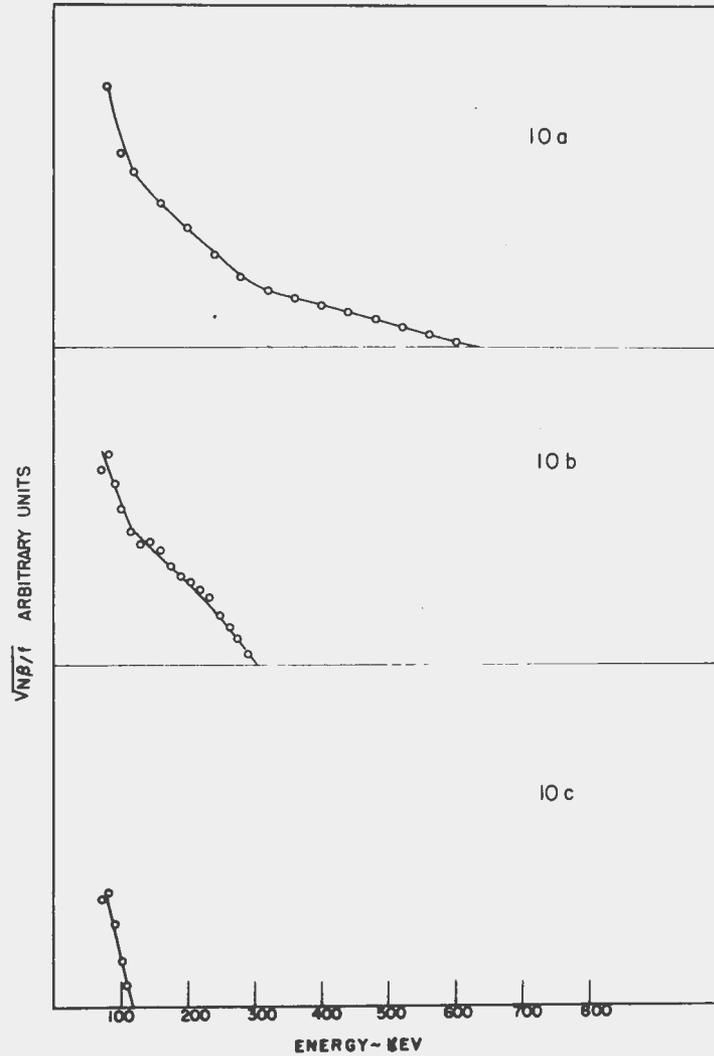


Fig. 10 Fermi plots of a: beta-spectrum of Sb^{125}
b and c: gamma-beta coincidence spectra of Sb^{125} .

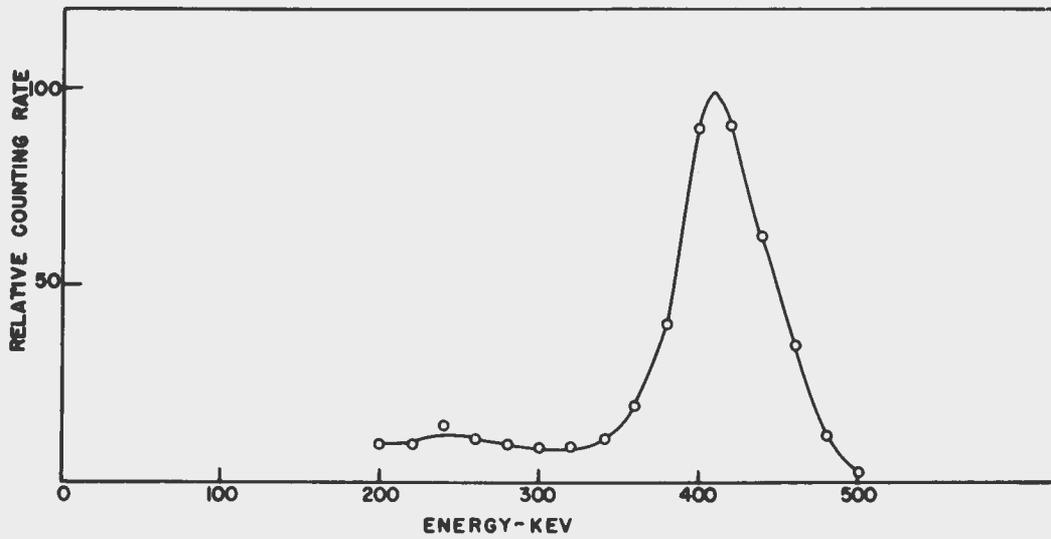


Fig. 11 Two-crystal spectrum of the gamma-ray from Cs^{137} .

arrangement is valuable for resolving complicated gamma-ray spectra. It may happen, for example, that a weak photo-peak is superimposed upon the edge of a Compton distribution. It is then very hard to detect and its energy difficult to determine. A two-crystal spectrometer avoids troubles of this kind due to the fact that every gamma-ray gives only one peak in the pulse-height distribution.

The author is greatly indebted to Dr. D. J. Zaffarano for his interest and assistance in this work.

APPENDIX I

The change in wave length of a quantum undergoing a head-on collision with an electron is given by the Compton relation:

$$\lambda_{180^\circ} - \lambda_{0^\circ} = 2 \frac{h}{m_0 c}$$

Converting from wave length to energy, we find

$$h\nu_{180^\circ} = \frac{h\nu_{0^\circ}}{1 + \frac{2h\nu_{0^\circ}}{m_0 c^2}}$$

The "back scattered" gamma-rays from material surrounding the source and scintillation crystal will therefore give rise to another spectral "line" at an energy given by

$$E_{\gamma'} = \frac{E_\gamma}{1 + 3.91 E_\gamma}$$

where E_γ is the energy of a gamma-ray emitted by the source.

The energies are measured in Mev.