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A SCINTILLATION SPECTROMETER FOR HIGH ENERGY BETA DECAYS†

J. G. CRAMER Jr.††, B. J. FARMER††† and C. M. CLASS

Rice University, Houston, Texas

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A scintillation spectrometer has been developed for application to beta decays having end point energies of 3 MeV or more. The spectrometer uses a large plastic scintillator on which the betas are incident from an external source. The beam of betas is restricted to a narrow cone to insure that virtually the total energy is absorbed within the scintillator. Spectra are recorded with a multi-channel pulse height analyzer. The pulse height scale is calibrated in terms of energy by means of the end points of known beta spectra and the edges of Compton recoil electron distributions from gamma rays. The relationship between pulse height and energy is found to be linear up to 13 MeV. End point energies of spectra can be assigned to an accuracy of 1–2% on the basis of the calibration. The response of the spectrometer to monoenergetic electrons for the energies below 3 MeV is found to be essentially Gaussian. Spectra of the beta decays from Ce^{144}–Pr^{144}, Al^{28}, F^{20}, and B^{12} compare favorably with those obtained by magnetic analysis.

1. Introduction

The scintillation spectrometer to be described here has been designed primarily for applications involving shortlived (< 1 sec), high energy (> 3 MeV) beta ray emitting radioactive nuclei. Such nuclei are made usually by bombarding suitable target materials with the beam from a Van de Graaff or other type of accelerator. When such short-lived decays are studied, spectral measurements must be made either during or immediately after activation of the sources which must remain *in situ*.

There are many energetic short-lived beta emitters among the nuclides, especially in the light and medium weight range, but few have been investigated adequately either by magnetic analysis or otherwise, presumably because of the unusual instrumental requirements imposed by the character of the decays. The scintillation spectrometer, however, is well suited for measurements of this type, particularly when one of the low-Z plastic-organic phosphors is used as the scintillating element. Such phosphors are available in large sizes, suitable for measuring even the most energetic betas produced by known radioactive decays. Since an entire spectrum can be recorded at once with a multi-channel pulse-height analyzer, some of the more vexing problems attendant to measuring activities of short half-lives are avoided. The plastic scintillating materials have a linear pulse height response as a function of electron energy which simplifies the task of energy calibration[1]) and they may be shaped to subtend large solid angles at the source, thereby making possible measurements of weak activities which often are encountered in these experiments. Finally, the scintillation spectrometer is an exceedingly convenient instrument to assemble and use. The components are inexpensive and readily available in most laboratories, and the instrument itself is adaptible to many experimental arrangements.

The chief disadvantage of the scintillation spectrometer is that it distorts the shape of a spectrum to some extent during the course of measurement. This distortion is caused primarily by the incomplete absorption of the energy of the incident beta particles within the scintillator and by the finite energy resolution of the instrument in response to monoenergetic particles. Further distortion may occur owing to the detection of scattered betas incident with degraded energy. However, by exercising care in the design and operation of the

† Supported in part by the U.S. Atomic Energy Commission.

†† Now at Indiana University, Bloomington, Indiana.

††† Now with the Ling-Temco-Vought Research Center, Dallas, Texas.

[1]) J. I. Hopkins, Rev. Sci. Instr. **22** (1951) 29;
J. Birks, Scintillation Counters (McGraw Hill Book Co., New York, 1953).

spectrometer, the distortion can be made quite small in most cases and any residual effects often can be removed by using well-known methods of correction[2]).

Earlier applications of the scintillation spectrometer for quantitative purposes have been confined to beta energies in the range from 0.5 to 2.0 MeV[3]). To demonstrate the usefulness of the instrument in the higher energy range, a number of beta spectra having end point energies extending from 3 to 13 MeV have been measured. The results figure which is 7.5 cm in diameter and 9.0 cm long[4]). The scintillator is wrapped in thin aluminum foil and optically coupled to a magnetically shielded Dumont type 6363 photomultiplier tube.

The beam of betas illuminating the scintillator is defined by a conical aperature, 3.0 cm in diameter at its base, which subtends a solid angle of 0.01 steradians when the source is at a standard distance of 60 cm. The aperature is machined in a cylinder of lead to insure that betas having more than grazing incidence at the periphery of the aperature either

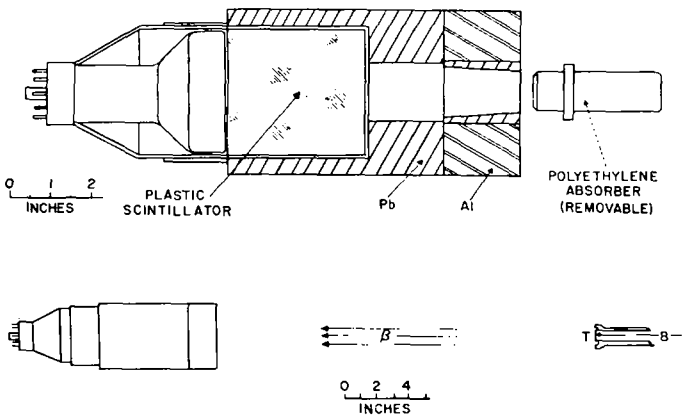

Fig. 1. The beta scintillation spectrometer is shown in the upper part of the figure. The polyethylene absorber is used when making background measurements. Below, the location of the spectrometer with respect to the target T is shown schematically. B indicates the beam from the accelerator.

of these measurements compare favorably with those obtained by other investigators using magnetic analysis.

2. Description of the Spectrometer

The spectrometer whose performances will be examined in this work is shown in fig. 1. It consists of a polished cylinder of plastic scintillator[1] which is shielded from all betas except those admitted through an entrance aperture by a housing made of aluminum and lead. The accepted beam of betas is restricted to a narrow cone coaxial with the scintillator to insure that virtually the total energy of the incident particles is absorbed within the counting volume. Betas having energies up to 15 MeV can be measured by the scintillator shown in the will be absorbed or sufficiently degraded in energy by scattering so as not to register in the useful part of the spectrum. The lead cylinder fits into a thick aluminum plate which shields the scintillator from betas incident more obliquely. Bremsstrahlung and background radiation are attenuated in a

[1] Pilot Scintillator B, Pilot Chemicals, Inc., Watertown, Massachusetts.

[2]) G. E. Owen and H. Primakoff, Phys. Rev. **74** (1948) 1406; K. Liden and N. Starfelt, Arkiv für Fysik **7** (1954) 427; L. B. Gardner, I.R.E. Transactions on Nuclear Science, NS-7 (1960) 36.

[3]) P. R. Bell, Beta and Gamma Ray Spectroscopy, ed. K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1955); A. Bisi, E. Germagnoli and L. Zappa, Nuovo Cim. **3** (1956) 1007; D. Gardner and W. Meinke, Int. J. App. Radiation and Isotopes **3** (1958) 232.

[4]) Energy Loss and Range of Electrons and Positrons, Supplement to N.B.S. Circular No. 577, National Bureau of Standards, 1958 (U.S. Government Printing Office, Washington, D.C.).

lead absorber behind the aluminum and the cylindrical surfaces of the scintillator are protected from scattered radiation by a sleeve of lead.

The sources used with the spectrometer in the present work were in all cases but one produced *in situ* by bombardment. The targets were located at the end of a light weight aluminum tube joined to the beam port of the accelerator, and were made by depositing suitable materials on a thin foil which served both as a window for transmitting the betas and as a vacuum seal. When it was necessary to avoid extraneous beta activity from the target backing, foils of gold 25 mg/cm^2 thick were used. Interference from the products of nuclear reactions accompanying the bombardment was avoided by deflecting the beam off the target while the activity was measured. While the beam was on the target, the counter was paralyzed by applying a negative voltage to the focussing electrode of the photomultiplier tube on a signal from a switching circuit[5]). This circuit also controlled the high voltage necessary to deflect the beam from the target when the counter was operating. The period of the switching cycle was variable but usually was adjusted to be less than or equal to the half life of the decay to be measured. The output from the spectrometer after amplification was analyzed by a 256 channel pulse height analyzer.

3. Response to Monoenergetic Electrons

The response to be expected from the spectrometer when measuring continuous beta spectra is best discussed in terms of its response to monoenergetic electrons. If the energy of the incident electrons is completely absorbed within the scintillator and no electrons are incident with degraded energy, then the measured pulse height distribution will be closely approximated by a Gaussian distribution $G(E,E')$ where E' is the kinetic energy of the incident electrons and E is the relative pulse height in the distribution expressed in energy units. The Gaussian distribution results from the statistical nature of the counting process and describes the basic line shape of the instrument.

This basic Gaussian line shape will be altered in practice by other distortion-producing effects which are present to some degree in every measurement. For example, if there is incomplete absorption of the energy of some of the detected betas or if some of the betas are degraded in energy before reaching the phosphor the line shape will be skewed and have a "tail" extending toward lower energies. In the detection of positrons, on the other hand, coincident detection of some of the annihilation quanta will skew the line shape in the opposite direction, giving the distribution a high energy tail. Since these effects are superimposed on the basic Gaussian line shape, the function describing the effective line shape $F(E,E')$, must be written as

$$F(E,E') = \int_0^\infty G(E,E'')\, D(E',E'')\, \mathrm{d}E'' \qquad (1)$$

where E' is the "true" energy of the betas, E'' is the energy delivered to the phosphor, and $D(E',E'')$ is the distortion function which relates the true energy to the energy which the phosphor receives.

Thus, in the absence of additional distortions, D will be a delta function, and F will be identical to G. Energy degradation and incomplete absorption of the energy of the incident electrons will give $D(E',E'')$ a sizable component for the condition $E' > E''$, while coincident detection of positron annihilation quanta will give a component for $E' < E''$. It is of some importance when removing such distortion that the D function arising from annihilation quantum detection is independent of positron energy.

A continuous distribution such as a beta spectrum will be distorted whether the line shape is skewed or is Gaussian. Such a spectrum $P(E')$ is related to the experimentally observed spectrum $Q(E)$ by the equation

$$Q(E) = \int_0^\infty F(E,E')\, P(E')\, \mathrm{d}E' = \int_0^\infty G(E,E'') \int_0^\infty D(E',E'')P(E')\, \mathrm{d}E'\, \mathrm{d}E''. \qquad (2)$$

To illustrate the influence of line shape on a continuous spectrum, this integral has been numerically evaluated for both Gaussian and distortion-skewed

[5]) U. Farinelli and R. Malvano, Rev. Sci. Instr. **29** (1958) 699;
B. J. Farmer and C. M. Class, Nucl. Phys. **15** (1960) 626.

line shapes. $P(E)$ was chosen to be a simple allowed beta spectrum calculated for $Z = 0$ and having an end-point energy of 5.4 MeV. The Kurie plots of the resulting spectra are shown in fig. 2. Plot (a)

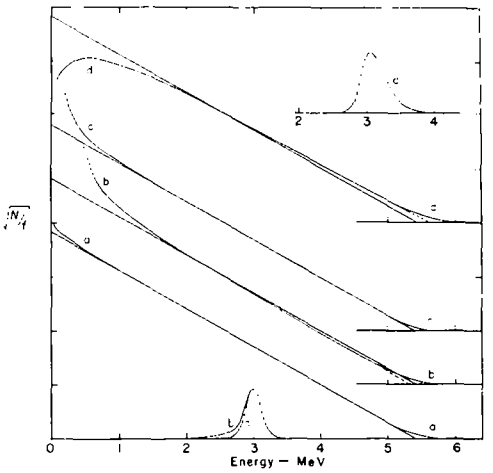

Fig. 2. The effect of line shape on the Kurie plot of a simple Fermi spectrum ($Z = 0$, $E_{max} = 5.4$ MeV). Plots labelled a to d show respectively the effect calculated for a Gaussian line (a), two asymmetric lines characterized by line shape (b) (see text) and a line (d) characteristic of the response to monoenergetic positrons as shown in the upper right hand corner.

shows the effect of a Gaussian distribution having a resolution of 15 % at 1 MeV and varying with energy as $E^{-\frac{1}{2}}$. Plots marked (b) and (c) show the effect of adding a tail on the low energy side of the Gaussian to approximate the first type of asymmetry mentioned above. Rather arbitrarily the tail extends roughly 1 MeV below the line and has an area of about 25 % that of the Gaussian in case (b) and 5 % in case (c). It is seen that the Gaussian line produces no significant distortion except at the extreme high and low energy ends of the spectrum. The asymmetric line corresponding to case (b), however, produces considerable distortion at the energy extremes of the spectrum, as well as a net downward shift in energy. However, the upper third of the spectrum is still fairly linear except in the region of the end point and a fair determination of the end-point energy could be made provided the magnitude of the energy shift was known. This calculation assumes a rather large asymmetry in the line shape in order to emphasize the resulting effect on the Kurie plot. In practice the asymmetry is more closely represented by the line shape used in case (c) which causes no detectable energy shift in the spectrum, although the distortion near the end point is increased in comparison to case (a).

To estimate the distortion effect of the annihilation quanta on a positron spectrum, $Q(E)$ has been calculated as above for a function $F(E,E')$ which roughly describes this asymmetry. The function used in the computation was calculated by assuming all positrons to annihilate at the center of a spherical scintillator 8 cm in diameter which approximates the dimensions of the scintillator used in these measurements. The magnitude of the asymmetry was determined by estimating the probabilities for single and double Compton scattering of a 0.511 MeV annihilation quantum and the probability for this scattering to be in coincidence with a scattering of the other quantum resulting from the annihilation of an incident positron. The Compton recoil electron distributions caused by each type of event were approximated by rectangles and added to the distribution given by those positrons for which no quanta were scattered, after which the Gaussian function was folded in. The appearance of the resulting distribution function $F(E,E')$ is shown in fig. 2 for positrons having a kinetic energy of 3 MeV. The Kurie plot of the spectrum $Q(E)$ which is given by this line shape is also shown (plot d). Not only is there increased curvature near the end point, but there is a net shift in energy of the distorted spectrum by about 200 keV as can be seen by the change in the apparent end point. This shift reflects the shift in the "center of gravity" of the monoenergetic line itself as a result of the asymmetry.

In order to ascertain the actual line shapes $F(E,E')$ to be used in calculating the spectral distortion or for solving eq. (2) for the undistorted spectrum $P(E')$, it would be necessary to measure monoenergetic electrons (or positrons) at various energies E' in the useful range of the instrument under conditions more or less duplicating those for which beta spectra are measured. Unfortunately, practical sources giving monoenergetic electrons above 3 MeV were not available, but for energies

below this value the Rice University Van de Graaff accelerator could be used. Although the accelerator normally is used with positive ions, it was easily converted to accelerate electrons and gave a beam of a few hundred electrons per second having an energy spread of about 3 % after magnetic analysis. Beams of higher energy and greater intensity were not possible without more extensive alterations to the accelerator. The beam emerged from the analyzer through a 5 mg/cm^2 thick mylar window and traversed the standard 60 cm air path to the spectrometer. Preliminary measurements of the response of the counter with the shielding removed revealed that the incident beam was rather strongly divergent, owing partly to initially poor collimation and partly to scattering in the window and air path. The diverging beam, however, enabled a check to be made under realistic conditions for the effect of scattering at the entrance aperture since not only the aperture but also a surrounding annular region was strongly illuminated.

The line shapes measured with the spectrometer at nominal beam energies of 1.1 and 2.4 MeV are shown in fig. 3. The Gaussian distributions fitted to the data after subtracting a small background arising from X-radiation have "resolutions" of 14 and 8 per cent, respectively, varying approximately

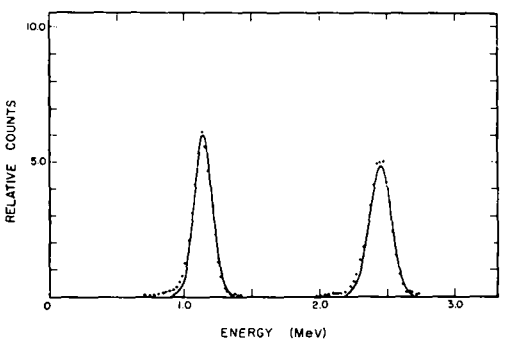

Fig. 3. The response of the spectrometer to monoenergetic electrons having nominal energies of 1.1 and 2.4 MeV is shown. The solid lines are Gaussian distributions fitted to the data.

as $E^{-\frac{1}{2}}$ as expected. The good agreement shown between the Gaussian distributions and the measured line shapes implies that nearly the total energy of the incident electrons indeed is absorbed within the scintillator. To be sure, both lines display a tail to the low energy side, but the area contained in each case is less than 5 % that within the symmetric peak. This small asymmetry can be ascribed to back scattering at the surface of the scintillator and possibly to scattering from the walls of the beam defining aperature. In either case, the relative magnitude of the asymmetric part of the distribution produced by scattering would be expected to decrease with energy[6]) and hence these results at low energy may be taken as a fairly reliable indication of the response over the entire energy range. This statement could be made with even greater certainty were it not for the fact that bremsstrahlung losses become a factor at the higher energies and another possible cause of asymmetry on the low energy side of the line. Further comments on this point will be made below.

In order to simulate scattering conditions at the source such as occur in some cases when spectra are measured, a 25 mg/cm^2 thick gold foil was placed over the mylar window through which the beam was transmitted. Upon repeating the measurements described above, it was found that apart from the expected shift in energy of the lines, there was no effect on the line shape attributable to interposing the foil.

4. Energy Calibration

The calibration of the pulse height scale of the spectrometer in terms of electron energy was made with conversion electrons for energies below 1 MeV and by means of the end points of well-known beta ray spectra and the edges of Compton recoil electron distributions from gamma rays for energies above 1 MeV. The calibration is simplified in principle because the relationship between pulse height and energy for the type of scintillator used here is expected to be linear. Assuming this relationship to hold over the entire energy range, two calibration points suffice to establish the energy scale. However, owing to the relatively imprecise methods used, it was desirable to calibrate at a

[6]) H. Bethe and J. Ashkin, Experimental Nuclear Physics, Vol. I, ed. E. Segrè (John Wiley and Sons, Inc., New York, 1953);
R. D. Birkhoff, Encyclopedia of Physics **34** (Springer Verlag, Berlin, 1958).

number of energies throughout the range of interest and fit the resulting data with the best curve.

Conversion electrons from sources of Cs^{137} and Bi^{207} provided calibration points at 0.662 and 0.973 MeV, respectively[7]). Calibration at energies above 1 MeV were made with sources of the long-lived emitter Ce^{144}–Pr^{144} having an end point energy of 2.99 MeV[8]), and the shortlived nuclei Al^{28}, F^{20}, and B^{12} with and point energies of 2.87, 5.41, and 13.43 MeV, respectively[7,9]). The latter nuclei are all conveniently made at low bombarding energies by means of (d,p) reactions.

Calibration with the continuous beta sources was accomplished as follows: an examination of the Fermi functions $f(Z,E)$[10,†]) showed that the functions had an energy dependence which could be closely approximated by $E^{\text{const.}}$ in the region near the end points. For the cases of interest here, the value of the constant varied between 1.4 and 1.9. Moreover, the pulse height scale expressed in terms of the channel number C of the pulse height analyzer is proportional to the electron energy. As a result the usual function $[N(E)/f(Z,E)]^{\frac{1}{2}}$ needed for the Kurie plot can be replaced by $[N(C)/C^{\text{const.}}]^{\frac{1}{2}}$ where $N(C)$ is the number of counts in a particular channel C. The value of the exponent in the denominator is chosen to suit the decay. In this way, about the last third of the beta spectrum can be linearized and the end point channel number determined. The accuracy of this method of calibration is estimated to be about 2 %.

To obtain additional calibration points somewhat more conveniently that provided by continuous beta sources, use was made of the high energy edge of the Compton recoil electron spectrum given by monochromatic gamma rays. Theoretically this spectrum is peaked sharply at the maximum energy of the recoil electrons, although in practice the peak is much reduced, chiefly by the finite resolution of the spectrometer and by multiple scatterings of the gamma rays. Nevertheless, a vestige of the theoretical edge remains which is suitable for calibration purposes. Spectra measured at various gamma ray energies are shown in fig. 4 along with calculated shapes obtained by folding the theoretical distribution with the experimental resolution in the manner described earlier. The calculation neglects the possibility of multiple

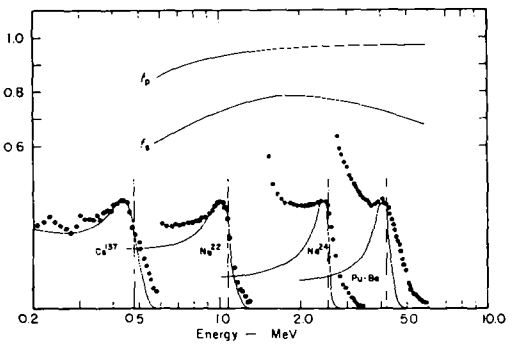

Fig. 4. The measured and computed Compton recoil electron distributions for four gamma rays used in the energy calibration of the spectrometer. The computed distributions are shown by solid lines. The vertical line in each distribution indicates the position of the maximum recoil electron energy. The calibration functions f_s and f_p are also shown.

Compton processes. While the agreement between the calculated and experimental shapes is certainly not exact because of the neglected factors it is adequate for a relationship between pulse height and energy to be established which is reliable to an accuracy of about 3 %. This is done with the aid of the calculated functions f_p and f_s also shown in fig. 4, the former giving the fraction of the maximum recoil energy at which the peak of the experimental distribution will occur, and the latter giving the maximum energy of recoil in terms of a fraction of the peak height. The sources used for calibration were Cs^{137}, Na^{22}, Na^{24}, and Pu-Be which give gamma rays with energies of 0.663, 1.28, 2.75, and 4.43 MeV, respectively[7,9]).

A calibration curve presenting a composite of results from all sources is shown in fig. 5. Ten data points covering the range of energies from 0.5 to

† This function is defined as on page 21 of the NBS tables[10]) but is multiplied here by ε/η to make it appropriate for energy rather than momentum distributions.

[7]) D. Strominger, J. M. Hollander and G. T. Seaborg, Rev. Mod. Phys. **30** (1958) 585.

[8]) N. J. Freeman, Proc. Phys. Soc. (London) **73** (1959) 600.

[9]) F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11** (1959) 1.

[10]) Table for the Analysis of Beta Spectra, National Bureau of Standard Applied Mathematics Series **13** (1952) (U.S. Government Printing Office, Washington, D.C.).

13.4 MeV are included. The data taken with continuous sources have been corrected for energy losses sustained by the electrons in traversing roughly 100 mg/cm^2 of material between the source and the scintillator. For 3 MeV electrons, this correction varied from 100 to 125 keV because of the different backings used with various sources[4]). The correction is not independent of electron energy, but in the region between 1 and 15 MeV, it increases on the order of only 10 %. The losses incurred with the conversion electrons were less than 15 keV since the sources in these cases were located just a few centimeters from the scintillator and the intervening material amounted to about 10 mg/cm^2.

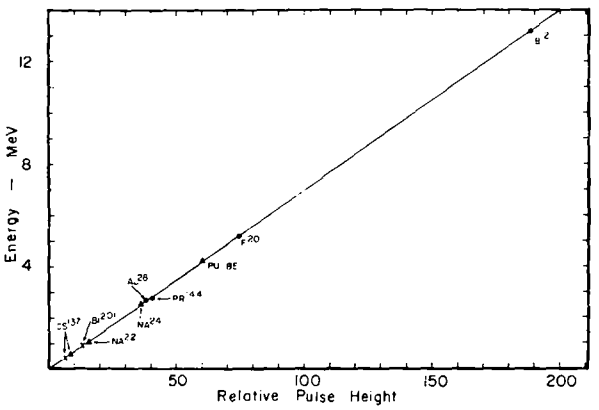

Fig. 5. The energy calibration of the pulse height scale of the spectrometer. The calibration points shown are obtained from the edges of Compton recoil electron distributions (triangles), internal conversion electrons (× 's), and beta spectra (circles).

The relationship between pulse-height and energy, shown in fig. 5, is indeed linear to within the accuracy of the measurements implying that virtually all the energy of the incident electrons is absorbed within the scintillator. This is not unexpected for beta energies up to 5 MeV inasmuch as the bremsstrahlung losses are still minor, and transverse scattering of electrons through the walls of the scintillator can not occur. However, linearity beyond this energy rests on a single calibration point due to B^{12}. That this point falls on the extension of the straight line through the lower energy data is a comforting although somewhat surprising result because at these higher energies scattering through the walls can occur and bremsstrahlung losses are no longer negligible. In regard to the first point, however, a rough calculation shows that an insignificant number of electrons scatter out of the scintillator, the probability for this to occur being about half a per cent for a 10 MeV electron[6]). On the other hand, the bremsstrahlung loss for a 13 MeV electron is about 5 %, diminishing to about 2 % at 5 MeV[6]). Such losses should be detectable if the emitted radiation escapes from the scintillator. The fact that the calibration point for B^{12} does lie on the line suggests that much of this radiation is re-absorbed, which is reasonable in view of the dimensions of the scintillator. The inference made from these and the foregoing measurements using monoenergetic electrons is that the line shape remains essentially symmetric at all energies of interest.

In earlier calibration measurements the pulse height corresponding to the B^{12} end point energy was smaller than expected when a linear extrapolation was made from the low energy region. The cause for this was found to be a non-linearity in the output voltage from the phototube for large input signals when it was operated at the gain corresponding to the normal dynode voltage of about 1000 V. By reducing this voltage to 750 V, linearity over the entire pulse height range was restored.

It is also interesting to note that the calibration points taken with the continuous beta sources and

the gamma ray sources all lie on the same straight line within the error of the measurements. This suggests that the different regions of the scintillator have the same efficiency of optical coupling to photo-cathode, inasmuch as the betas were confined to small axial regions of the scintillator, while the gamma radiation illuminated the entire volume. The uniformity of response was checked in another way by directing a collimated beam of Co^{60} gamma rays onto the wall of the scintillator in a direction transverse to the axis. Successive pulse height distributions taken with the beam at 1 cm intervals along the length of the cylinder, showed no detectable differences until the region 1–2 cm from the photo-cathode was reached where the gain fell off. However, this region was not penetrated by betas in any of the present measurements.

5. Measurements of Sample Spectra

To illustrate the performance of the spectrometer the spectra and Kurie plots of the same beta activities as used for calibration purposes will be presented. These activities have decay schemes of varying degrees of complexity. All previously have been studied by magnetic analysis and these results will be presented for comparison. The energy scales in the figures to follow have been corrected for energy losses in the intervening material between the source and scintillator. Background in the spectra originating primarily from gamma radiation associated with the beta decays has been subtracted with the aid of the complement mode of the pulse height analyzer by repeating the measurements with the polyethylene plug, shown in fig. 1, inserted into the entrance aperture to absorb the electrons. As discussed above, the evidence available on the response of the spectrometer suggests that the asymmetries in the line shape for monoenergetic electrons remain small in the energy interval of interest. Consequently, the only correction which was applied to the spectra was one for the effect of resolution broadening. As shown, this correction is small at these energies, being significant only in the region of the end points, and was made by an iterative procedure which has been described elsewhere[2]). Its effect will be shown explicitly for the spectrum of F^{20} to be presented below.

1. Ce^{144}–Pr^{144}

The source for this measurement was prepared by depositing 50 microcuries of Ce^{144}–Pr^{144} in acid solution on a carbon foil 50 micrograms/cm² thick and evaporating to dryness. As a safety precaution the carbon foil was sandwiched between two aluminum foils each 2 mg/cm² thick. The source in this and all succeeding measurements was at the standard distance of 60 cm from the scintillator. The beta spectrum of the decay is shown in fig. 6,

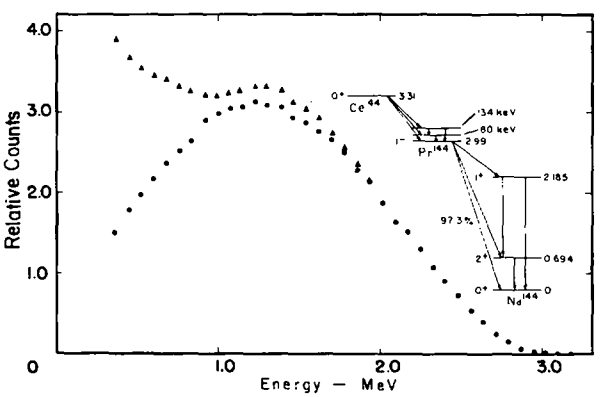

Fig. 6. The beta spectrum of Ce^{144}–Pr^{144} measured with the scintillation spectrometer before (triangles) and after (circles) background subtraction.

both before and after the background was subtracted. From the decay scheme, presented to the right in fig. 6, it is seen that 97 % of the decays from Ce^{144}–Pr^{144} contribute to the highest energy

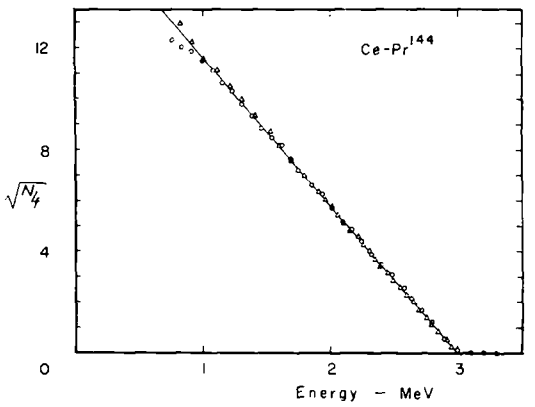

Fig. 7. The Kurie plot of the Ce^{144}–Pr^{144} beta spectrum. The scintillation spectrometer data (circles) are shown in comparison with the magnetic spectrometer data of Freeman[8]).

component of the spectrum having an end point energy of 2.99 ± 0.03 MeV[8]). The weak population of the excited states gives rise to the gamma ray background which distorts the uncorrected spectrum below 2 MeV. The Kurie plot of the spectrum with background removed is shown in fig. 7, and for comparison a plot of the same spectrum measured with a magnetic spectrometer is shown[8]). The ordinates have been normalized at 2.0 MeV. Below 1 MeV, the scintillation spectrometer data fall below the straight line through the higher energy points, indicating that the background was possibly over-subtracted in this region. However, the two sets of data are otherwise in good agreement. A small correction for resolution has been applied in the region of the end point to the scintillation spectrometer data.

2. Al^{28}

The source of Al^{28} was made by bombarding an aluminum foil 2.4 mg/cm² thick with 2 MeV deuterons. Advantage was taken of the 2.3 minute half-life of this activity to measure the beta spectrum after the accelerator voltage was turned down, following activation of the source foil. Al^{28} decays primarily by an allowed transition having an end point energy of 2.87 MeV to the first excited state of Si^{28} which then decays by a 1.78 MeV gamma ray to the ground state[7]). Two investigations of the direct transitions to the ground state have set the intensity of this component at less than 2 % and less than 0.8 % [11,12]).

The presence of the strong gamma ray gave rise to a large background in the spectrum below 1.5 MeV amounting to about 50 % of the total number of counts. This background was subtracted in the usual way except for a small modification intended to provide greater precision. A NaI scintillation spectrometer shielded from the betas by paraffin monitored the gamma ray yield as the beta spectrum was recorded. For the background subtraction an additional absorber was placed before the NaI crystal identical to that shielding the beta spectrometer, and the subtraction was continued until the number of gamma ray counts accumulated equalled the number measured in the initial exposure. To provide sharper discrimination against extraneous background, the window of the pulse height selector used with the NaI counter spanned the photo peak of the 1.78 MeV gamma ray line.

The Kurie plot of the scintillation spectrometer data is shown in fig. 8 along with comparison plot of data taken with magnetic analysis[11]). The agreement between the two sets of data is adequate,

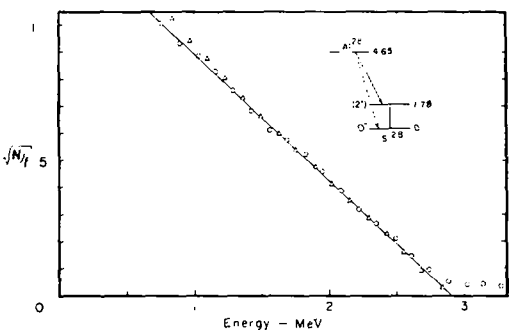

Fig. 8. The Kurie plot of Al^{28} beta spectrum. The scintillation spectrometer data (circles) are shown in comparison with the magnetic spectrometer data of Motz and Alburger[11]).

[11]) H. T. Motz and D. E. Alburger, Phys. Rev. **86** (1952) 165.
[12]) J. L. Oslen and G. D. O'Kelley, Phys. Rev. **93** (1954) 1125.

even in the region below 1.5 MeV where the large background has been subtracted. Good statistics in the scintillation spectrometer measurements helped to reduce the scatter in this region. In the high

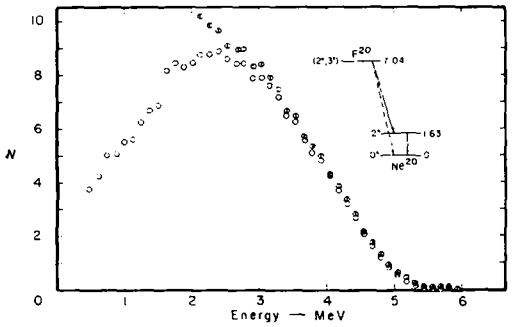

Fig. 9. The beta spectrum of F^{20} measured with the scintillation spectrometer before (split circles) and after (open circles) background subtraction.

backing with 2 MeV deuterons. The half life of the activity is 11.4 sec. The decay scheme of F^{20}, shown on the right in fig. 9, is similar to that of Al^{28} except for the differences in transition energies. The strong allowed transition has an end point energy of 5.41 MeV and is followed by the emission of a 1.63 MeV gamma ray which produces the same background problem discussed above. The upper limit on the intensity of the ground state transition has been placed at 0.04 %[13]).

Fig. 9 shows the spectrum of F^{20} before and after the background subtraction which was made as described in the discussion of Al^{28}. At 1.0 MeV the background represents about 80 % of the total number of counts. Because these data are not as good statistically as in the foregoing example, there is a greater scatter in the points.

Fig. 10 shows the Kurie plot of this spectrum after background subtraction along with the mag-

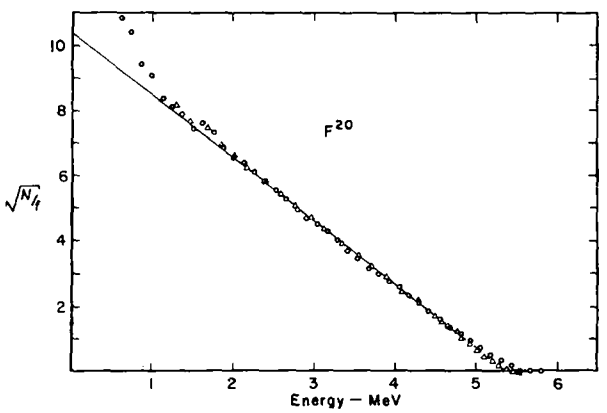

Fig. 10. The Kurie plot of the F^{20} spectrum. The scintillation spectrometer data (circles) after background subtraction are shown in comparison with the magnetic spectrometer data of Wong[13]). The effect of the resolution correction is shown in the region of the end point by the dotted line.

energy region, the evidence for a high energy tail is definite and suggests the presence of a weak ground state transition. No resolution correction has been applied to the scintillation spectrometer data in this case.

3. F^{20}

F^{20} was produced by bombarding a target of PbF_2 evaporated onto a 25 mg/cm^2 thick gold

netic spectrometer data of Wong[13]) for comparison. The dotted line near the end point is a fit to the resolution-corrected data in this region. It joins smoothly to the straight line through the lower energy data points. The corrected scintillation spectrometer data agree well with those obtained by magnetic analysis down to 1 MeV and confirms the absence of a higher energy component in the decay.

[13]) C. Wong, Phys. Rev. **95** (1954) 761.

4. B^{12}

The source of B^{12} was produced by bombarding a target of natural boron with 3 MeV deuterons. The target was about 20 mg/cm^2 thick and stopped the incident beam. It was made by pressing finely divided boron powder into a self supporting disc which was then cemented to a 4 mg/cm^2 thick aluminum foil. The half life of B^{12} is 20.3 msec and the decay scheme is complex; however, approximately 97 % of the transitions occur to the ground state of C^{12}. A Kurie plot of the spectrum obtained with the scintillation spectrometer is shown if fig. 11 along with the plot of data obtained from the earliest of the two magnetic spectrometer measurements[14]). This measurement imposes the severest test of the spectrometer, since the possibilities for distortion of the line shape due to radiative losses, transverse scattering through the walls, and non-uniform response in the scintillator are here the greatest encountered. The reasonable agreement of this data with that taken by magnetic analysis down to fairly low energies, confirms the earlier conclusion that such distortions are indeed small.

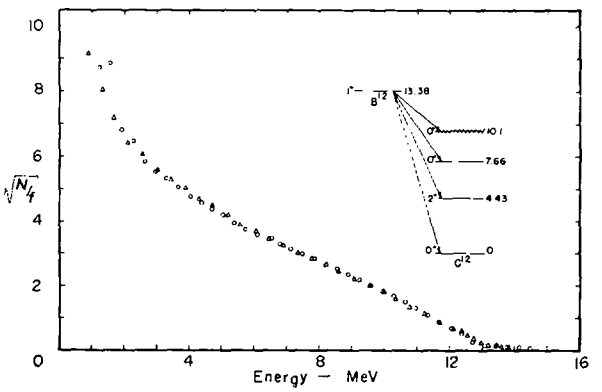

Fig. 11. The Kurie plot of the B^{12} spectrum. The scintillation spectrometer data (circles) are shown in comparison with the magnetic spectrometer data of Hornyak and Lauritsen[14]).

5. Sc^{41}

To illustrate the response of the spectrometer when measuring positons, the Kurie plot of the spectrum of Sc^{41} is shown in fig. 12 [15]). The source was made by evaporating Ca metal onto a 25 mg/cm^2 thick gold foil which was then bombarded with 4 MeV deuterons. The resulting positon spectrum is actually a composite of components contributed by Sc^{41}, K^{38}, and K^{38m} although the latter is believed to be of minor importance. The end point energies of these components are 5.61, 2.68, and 5.1 MeV, respectively. The half lives of Sc^{41} and K^{38m} are about 0.6 and 0.95 sec, respectively. The energy scale for the Kurie plot has been cor-

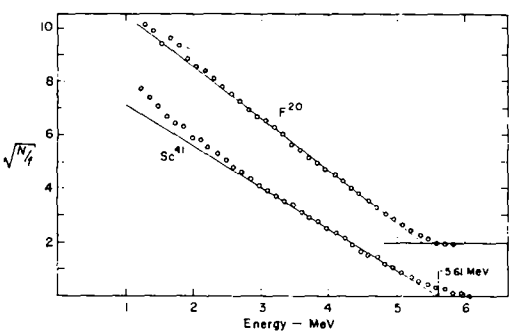

Fig. 12. The Kurie plot of the positon spectrum from Sc^{41} with correction for the positon energy shift, and for comparison, the plot of the electron spectrum from F^{20}. The former spectrum is actually a composite of components from Sc^{41}, K^{38m}, and K^{38}. The open circles are the data after the background has been subtracted. The dotted line near the end-point shows the effect of a resolution correction based on calculated positon line shapes.

[14]) W. Hornyak and T. Lauritsen, Phys. Rev. **88** (1950) 160.
[15]) J. G. Cramer, Jr. and C. M. Class, Nucl. Phys. **34** (1962) 580.

rected for the shift resulting from the asymmetric line shape as discussed earlier. When the plot is compared with that for F^{20}, it is seen that there is increased curvature near the end point as expected, but that otherwise, the spectra are similar.

6. Conclusion

It has been shown that the spectra and Kurie plots obtained from measurements carried out with a scintillation spectrometer compare favorably with similar results obtained from measurements with magnetic spectrometers.

Furthermore, measurements and calculations made in an effort to determine the amount of distortion present in the observed spectra, reveal that for electron measurements the amount of distortion is small and can be neglected except in the region of the end point where a correction for the effect of finite resolution is necessary. In measurements of positon spectra, distortion is a more serious problem, owing to the coincident detection of annihilation quanta; but quantitative measurements still can be carried out provided a correction for this distortion is made, based on either calculated or experimental positon line shape functions. The energy scale of the spectrometer can be established to an accuracy of better than two per cent with calibration measurements of internal conversion electrons, gamma rays, and beta spectra, thereby enabling fairly precise energy measurements to be made. These factors, along with the ease of construction and operation of the instrument and the speed with which data may be obtained should make scintillation spectrometers of this type extremely useful in measurements where convenience, compactness and simplicity of operation outweigh extreme precision as experimental considerations.

Acknowledgement

We should like to thank Mr. J. P. Aldridge for the numerical calculations connected with the discussion of the spectral distortions, and the Rice University Computing Center for the use of their facilities.

Note added in proof: Tests on several versions of the scintillation spectrometer described above have recently been made with monoenergetic electrons and positons at several energies in the range 5 to 18 MeV, using the electron linear accelerator of the Lawrence Radiation Laboratory at Livermore, California. A full exposition of the results of those tests will appear subsequently, but it can be stated here that they substantially confirm the conclusions of this paper and will make possible more quantitative distortion corrections.