The β-ray spectrum of radium E

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Introduction

The problem of the β-ray spectrum of Ra E is too familiar now to require more than brief introduction. Owing to the eminent experimental suitability of this substance, its β-ray spectrum has been investigated widely, and various workers have given summaries of the results up to date, e.g. O'Conor (1937) and Martin and Townsend (1939). Most work has been done on the upper limit or on the form of the intermediate part of the spectrum, with fairly concordant results. Only a scanty amount of work has been done on an accurate investigation of the lower regions of the spectrum, where the experimental difficulties are much greater on account of the necessity of avoiding scattering in the source and along the track of the particles in the spectrograph, and of reducing the absorption in the window of the counter. Richardson (1934) first demonstrated by cloud chamber measurements, using a satisfactorily thin source mounting, that there is a considerable intensity of slow electrons between 15 and 60 ekV, and that the ordinate of the energy distribution curve is about as high in this region as at the previously estimated maximum. However, on account of straggling and other causes, it would be extremely difficult to determine exactly the form of the energy spectrum below 100 ekV by cloud chamber methods, and most other work has been done by semicircular magnetic deflexion with Geiger counters for registration of the particles. The results of chief importance are those of Alichanian and Zavelsky (1937) and of Flammersfeld (1937, 1939). In the discussion below the conclusion is reached that in both these sets of investigations the source mountings were quite satisfactory even down to 30 or 20 ekV, but that in the former the thickness of the counter window ($1\,\mu$ cellulose acetate) can scarcely be regarded as small enough for measurements below 50 ekV, whilst in the latter absorption effects in the $0{\cdot}3\,\mu$ Zaponlak window must begin to enter between 30 and 20 ekV.* Moreover, in both cases the spectrographs are not sensibly free from scattering.

* According to Flammersfeld, no effect above 25 ekV.

The experiments to be described below were made in an attempt at a precise and direct observation of the undistorted spectrum, especially below 100 ekV, and it is believed that the results do represent a practical realization of this ideal, down to the region of 20 ekV at least, without the need for the application of corrections of any kind.

Apparatus

Spectrograph

In magnetic spectrographs for β-ray work employing semicircular focusing, it has hitherto been the custom to have a defining slit close to the source, the separation being usually of the order of 1 cm. It appeared that

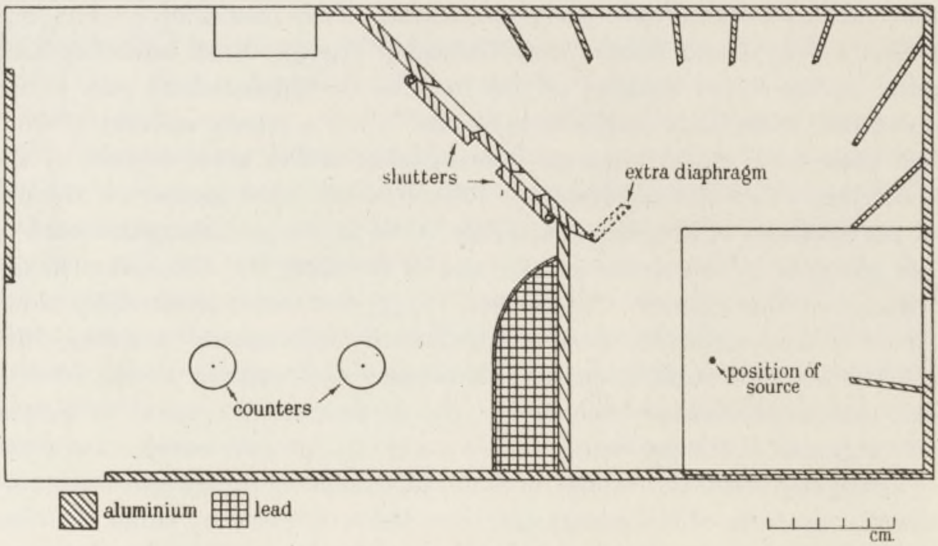


FIGURE 1. β-ray spectrograph.

this was undesirable if the slow disintegration electrons were to be observed, because of the possibility of considerable scattering of all the primary electrons at the slit edges, thereby vitiating the precautions taken to have a thin source mounting, for such an arrangement is qualitatively analogous to a source on a thick mounting. It was therefore decided to have the source in a free space as isolated as possible from other matter (figure 1 and figure 2). The focusing or defining slit was situated half-way round the semicircular path of the particles, where obviously the spatial density of particles traversing the semicircular path is a minimum, and the density of other particles is greatly reduced merely by the increased distance from the source. This slit is situated in the surface which separates the object or source space from the image or counter space. The form of the essential part of this surface was a plane sloping towards the source at an angle of 45° to the line joining source and counters. This form was chosen because, when the slow electrons are deflected through a semicircle, the majority of the other primary particles travel in nearly straight lines

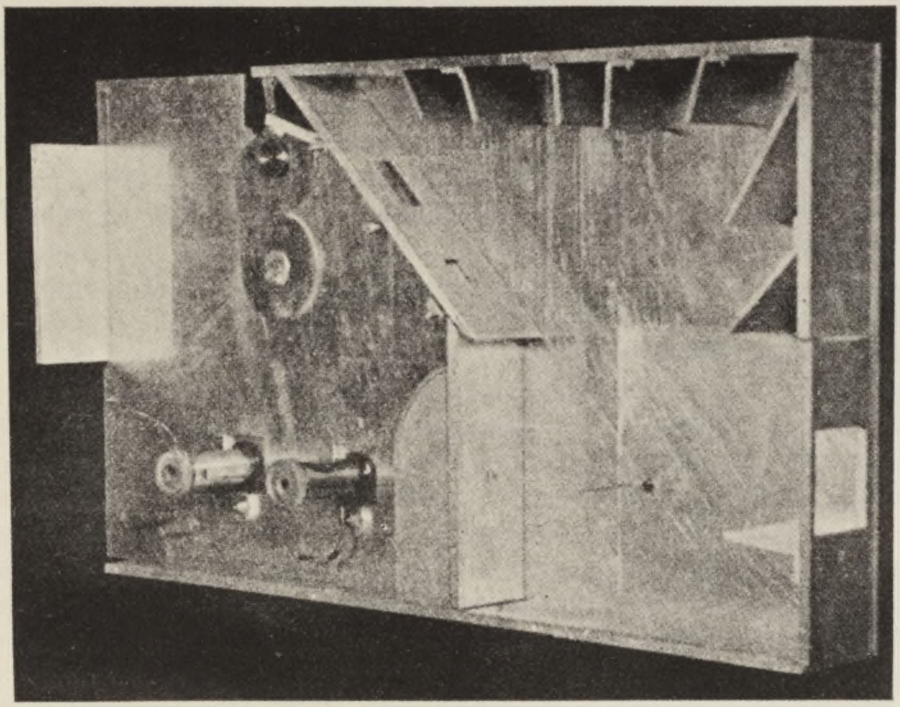


FIGURE 2

radiating from the source, and so merely graze the slit surface. The area of slit edge thus presented for scattering effects is very small; it might have been reduced to zero by tilting the slit surface, so that it pointed slightly above the source. However, little extra advantage was to be gained in this way, and as it was desired for some purposes to have two slits for two different radii of curvature, each being at the top of the relevant semicircular trajectory, it was simplest to have one plane surface pointing to the source with slits in the appropriate positions. The question of whether any appreciable scattering of the main distribution of particles took place at the slit edges was investigated by inserting a diaphragm in the position marked in figure 1 and again observing the spectrum. In these circumstances all particles of momentum slightly greater than those which it is intended to observe are prevented from striking the slit at all. The results confirmed that negligible scattering took place at the slit (see below). The scattering at the slits themselves has been mentioned in detail because particles scattered there have a very large chance of entering the image space, whereas particles scattered at other places in the object space have only a small chance of passing through a slit into the image space. The possibility of scattering at the edge walls in the object space of the spectrograph was circumvented by arranging short, straight diaphragms pointing to the source, in such positions that the edge walls were completely screened off from the counters. This construction is based on the same assumption as before, namely, that when small fields are employed nearly all the particles radiate in straight lines from the source. This screening is, in fact, almost equally efficient if all particles are of the same sign, whatever the magnetic field, i.e. virtually no edge walls are present. The optimum length and number of the diaphragms was obtained by simple calculation. In the case of the side walls, glancing angle scattering would be the principal effect, and so the coating of colloidal graphite which covered the whole of the interior of the spectrograph was considered an adequate precaution. One further feature minimizing the effects of scattering may be mentioned; the counter "slits" consisted of several small holes drilled in a brass plate, the diameter being $\frac{1}{2}$ mm. and the length 1 mm. Particles incident obliquely could therefore enter the counter only by scattering in these holes, while normally incident particles could enter quite freely. Tests showed that this selective effect of the counter slits was, in fact, important.

The spectrograph was constructed so that observations could be made at two radii of curvature, $\rho = 7$ cm. and $\rho = 10$ cm. This necessitated the use of two defining slits and two counters. However, each slit gives a complete "spectrum" along the horizontal axis and so, if both slits are open together, a counter receives particles from two slits. For simultaneous counting to be possible, clearly a diaphragm must be placed so as to run from a point between the focusing slits to a point between the counters. Since this was undesirable for the special purpose of the present investigation, because of the increased scattering effects, only one slit was opened at a time and only the appropriate counter observed. With Ra E, which has a lifetime of 5 days, no disadvantage was incurred. In most of the experiments, in fact, only one counter was used throughout a run, because of the rather elaborate counter circuit employed (see below).

The form of the spectrum produced with a source emitting a continuous distribution of particles from a plane rectangular area was calculated completely for the spectrograph, the details being too long to give here. From the calculation it was possible to choose the various dimensions so that the nominal resolving power $H\rho/\Delta(H\rho)$ was 100, on the assumption that the source would be 1 cm. square, suitably tilted.

It was a very useful feature of the design that owing to the large distance between source and defining slit an extended source could be used while retaining a high resolving power, for it would be very difficult to deposit a strong source of Ra E (~ 1 millicurie) on a very thin film of small area. The length parallel to the magnetic field of all slits was 1 cm.; the other dimensions were:

	Radius of curvature cm.	Effective counter slit width mm.	Defining slit width cm.
I	$7{\cdot}0_0$	1·4	$1{\cdot}1_3$
II	$10{\cdot}0_0$	2·0	$2{\cdot}2_6$

while the tilt of the source was $82\frac{1}{2}°$ to the diameter of focusing. These dimensions were chosen so that a group of electrons of a given $H\rho$ would be counted with equal intensity when recorded in either counter. An excellent check on the performance of the spectrograph was thereby afforded, and it was found that the ratio of intensities of the spectra in the two counters agreed with the calculated value to 1 %.

The spectrograph was constructed of aluminium of thickness 4 mm. (~ range of 2 MeV electron) coated with colloidal graphite. A lead block, $2\frac{1}{2}$ cm. thick, cased in aluminium, was situated between source and counters so that the weak γ-radiation of Ra E was of no influence. The side walls of the spectrograph were 3·6 cm. apart and the least distance from the source to the edge wall was 4·4 cm. (the average distance was ~ 10 cm.). Shutters were arranged behind the defining slits and were controlled from outside by a ground joint. The same zero count was obtained with the shutter closed as with the shutter open and the magnetic field reversed. The spectrograph was contained in a brass box evacuated by a two-stage oil diffusion pump. A very low pressure was thus maintained; it was checked from time to time on a Pirani gauge.

Counters

The counters were Geiger-Müller tube counters arranged with their axes parallel to the magnetic field. In this arrangement particles entering normally approached the central wire and were therefore counted with maximum efficiency. The internal diameter of the counters (and so the path length for the particles) was 1 cm., and the gas pressure was $11\frac{1}{2}$ cm. (air + trace of alcohol). Under these conditions, according to the results of Ornstein and others (1938), particles of all energies should be recorded with uniform efficiency. The length of the counters was 4·0 cm.; the length of the slits 1 cm. The counter walls were of brass thicker than 1 mm. ($\sim$ range of 2 MeV electron). A flat polished brass surface, supported over a slit in the counter wall, carried the window, which faced inwards. In one experiment this window was of mica 1·0 mg./cm.^{2}; in a second of "Zaponlak", showing first order red by reflected light and therefore about $0{\cdot}2\,\mu$ thick and $\sim 0{\cdot}04$ mg./cm.^{2}, and in a third of "Zaponlak" which was black by reflected light and was of the order of $0{\cdot}05\,\mu$ thick and $\sim 0{\cdot}01$ mg./cm.^{2}. (A second order blue film by direct weighing was $\sim 0{\cdot}05$ mg./cm.^{2}.) When using these exceedingly thin windows of "Zaponlak" it was not possible to admit sufficient alcohol to the counters to make them self-extinguishing. They were therefore controlled by the Wynn-Williams circuit using a thyratron. Since the counters had a small volume, only a small impulse was obtained from them—in many cases too small an impulse to operate a thyratron directly. For this reason the pulses were first amplified in two high-frequency pentode stages and then passed to a thyratron. The *entire* circuit was direct current coupled, so as to avoid the various disadvantages of condenser coupling. Owing to these precautions a very satisfactory characteristic was obtained with the counters; voltage changes and small pressure changes were without detectable influence on the counting rate. It was found that if the thyratron recovery was rapid, multiple kicks would appear. This was probably due to the fact that de-ionization of the counter was then incomplete. The effect was avoided, without increasing the resolving time too much, by employing quite small quantities of alcohol with the air in the counters. Small quantities of alcohol leaked only slowly through the 0·01 mg./cm.^{2} window of "Zaponlak", and a large reservoir was attached. Observations with a source of Ra (D + E) in equilibrium showed that the efficiency of the counters remained constant from day to day. A direct test with two sources showed that there was no appreciable loss of counts at a counting rate of 1000 per min., which was about twice the maximum rate effective during the main observations.

Magnetic field

The magnet used was the permanent magnet described by Cockcroft, Ellis and Kershaw (1932). The uniformity and constancy of a given field have been checked by Ellis (1932) and by other workers. The method of measuring the field was that described by Ellis, in which the throw from a search coil rotated in the field is balanced against the throw from a Duddell standard inductometer. Since the field strength was altered many times during a run and it was obviously very inconvenient to have to open the vacuum box during counting, for admission of a search coil to measure each field, a coil was rotated outside the box in the stray field. This coil was held rigidly in a fixed position with respect to the pole pieces and the throws were calibrated against the throws at the same field from a standard search coil in the gap. The calibration so obtained was constant to 1 part in a 1000 and the accuracy in the measurement of the field was more than adequate for the purpose required.

Source

The source of Ra (D + E) or of Ra E was deposited by rapid evaporation *in vacuo* of a drop of solution on a $\frac{1}{2}\mu$ aluminium foil. The area of the drop was considerably less than 1 cm.^{2}, while the area of the foil was about 15 cm.^{2}. The foil was attached at its four corners to a thin, three-sided mica frame ($\sim$ 6 cm. stopping power) which rested lightly in the appropriate position in the spectrograph. Thus the radioactive material was well isolated from heavy matter. It is shown below that, in conformity with theoretical expectation, such a thin foil of aluminium introduces negligible reflexion effects even down to the lowest energies ($\sim$ 13 ekV). The Ra (D + E) source was in equilibrium but contained impurities giving some absorption in the source at lower energies, equivalent to about 0·17 mg./cm.^{2} normal thickness. The Ra E was perfectly pure and free from Ra D, being separated by a cathodic deposition on platinum at a current density even below that at which Ra D appeared on the anode. In this way much stronger sources were obtainable than by deposition on platinum cathodically polarized with hydrogen. The source strength was $\sim$ 2 millicuries, enabling rapid counting at small magnetic fields. The statistical error of a point was $1 \sim 2\%$.

Experiments and results

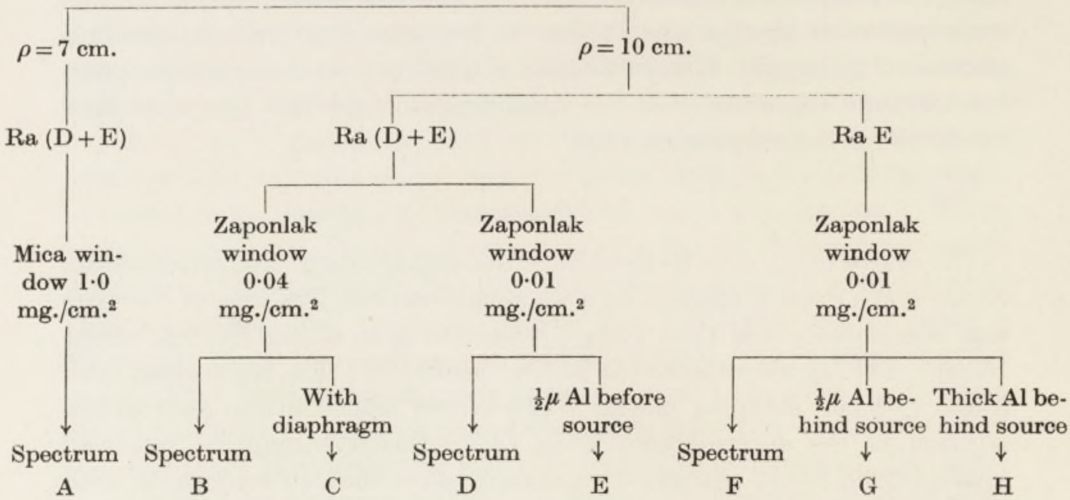
Of the sets of results the most important are A, B and D, and F; these together give directly the undistorted spectrum throughout its whole range. The other results are secondary in character and are included as providing a check, in various ways, on the primary results:

Set A is valid from the region of the upper limit to 300 ekV without appreciable absorption.

Sets B and D extend from 300 to 50 ekV; absorption in the source is appreciable only below 100 ekV.

Set F extends from 200 to 13 ekV and is valid throughout the range without appreciable absorption (or reflexion).

Plan of experiments



The same source was used in A, B and D, and the relative intensities at the two radii of curvature agreed with calculation to 1 %, showing that scattering was negligible. A different source was used in F and the curve was normalized to fit those in A, B and D. Hence the complete distribution curves in figures 3 and 4 on energy and on momentum bases were obtained. These curves are discussed in detail below.

Secondary results

Some of the results A to H are exhibited in figure 5.

Set A, absorption in 1 *mg./cm.*² *mica at counter.* It has sometimes been the practice to make allowance for counter window absorption on the basis of Schonland's (1925) results for transmission of cathode rays through aluminium foil. Such a comparison would, however, seem to be erroneous, and evidence is not lacking that this is the case. The transmission ratio of Schonland's data relates to all particles transmitted into the forward hemisphere, and this gives rise to the well-known initial flat portion on the transmission curve. With a Geiger counter as recording instrument, however, only a comparatively narrow cone of particles is detected with full

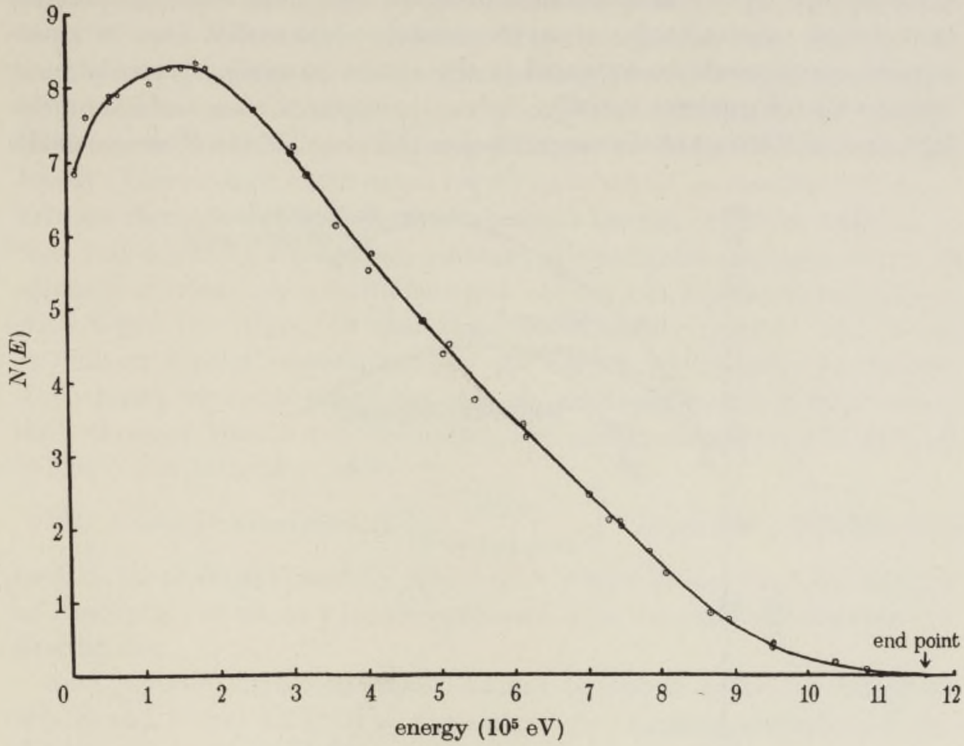


FIGURE 3. Energy distribution curve for Ra E.

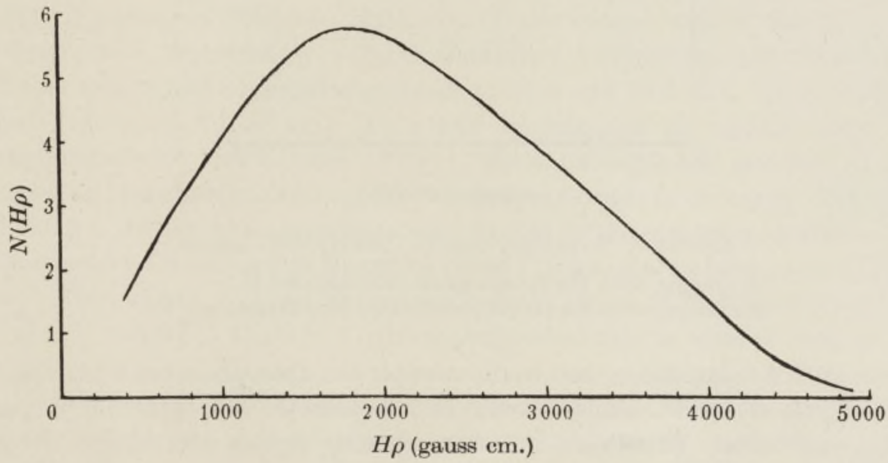


FIGURE 4. Momentum distribution curve for Ra E.

efficiency and all the particles in the forward hemisphere could not possibly be detected. Accordingly, an approximately exponential form of transmission curve would be expected in this case—certainly a curve already falling with full gradient initially. An example from the work of Flammersfeld, and of Martin and Townsend makes this clear. From Flammersfeld's

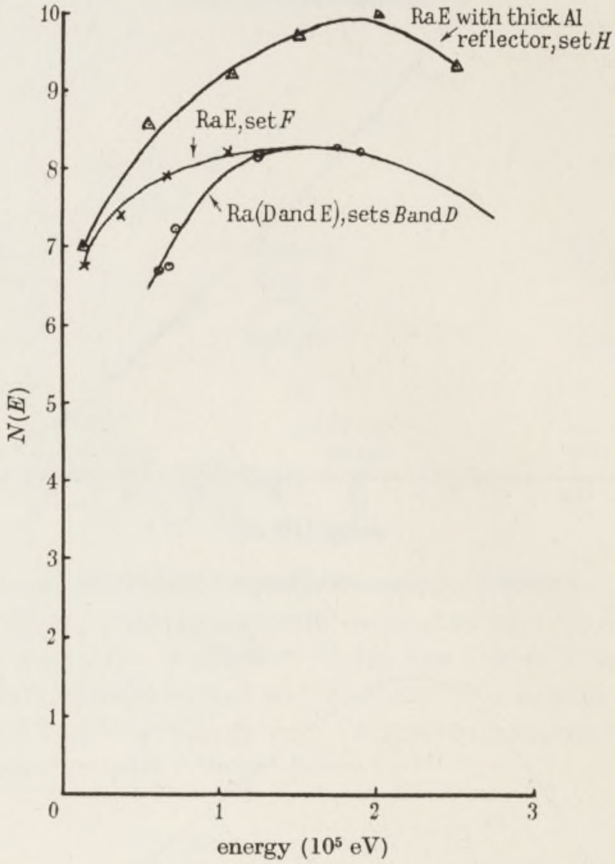


FIGURE 5. Secondary results. Distribution curves.
×, points with Ra E and $\frac{1}{2}\mu$ Al reflector, set G.
⊙, points with Ra (D + E) and extra diaphragm, set C.

curve with 5μ aluminium before the counter the absorption per 1 mg./cm.^{2} is 10 % at ·173 ekV, while Martin and Townsend find about 7 % per 1 mg./cm.^{2} mica. At 81 ekV the corresponding figures are 24 and 20 %. If the absorption were linear from the start to the end of range, the absorption of 81 ekV electrons in 1 mg./cm.^{2} would be 10 %, while an actual observation of Schonland (1925) gave 3 % absorption of 81 ekV electrons in 1·5 mg./cm.² aluminium. Thus Schonland's data are quite inapplicable to most cases of counter absorption. The effect is even more marked with coincidence counters. In this case Langer and Whittaker (1937) found about 59 % transmission through 6·85 mg./cm.² of aluminium for 335 ekV electrons, where Martin and Townsend's figure would be 80 % transmission. Lastly, Ference and Stephenson (1938) have made observations of transmission through thin collodion films using a Faraday cylinder collector, so that only a cone of transmitted particles of small solid angle entered, in an attempt to reproduce conditions which obtained in a previous experiment with a counter. Here the absorption is enormously greater than in the Schonland type of experiment and the curves are roughly exponential. The writer's results for absorption in 1 mg./cm.² mica were in fair agreement with those of Martin and Townsend, and of Flammersfeld, viz. $9\frac{1}{2}$ % at 173 ekV and 24 % at 81 ekV.

Sets B and D, absorption in $\begin{pmatrix} 0{\cdot}2\mu \\ 0{\cdot}04\ \mathrm{mg./cm.}^2 \end{pmatrix}$ "*Zaponlak*". This film was used down to 50 ekV, and by comparison with 0·01 mg./cm.² film showed no absorption at all, as would be expected from the results of Ference and Stephenson.

Set C, effect of extra diaphragm. As may be seen in figure 5, points from sets B and D and set C lie on the same curve, showing scattering at the defining slit to be negligible.

Sets B, C, D and E, absorptions in source and in $\frac{1}{2}\mu$ aluminium before source. By viewing the source of Ra (D + E) and other foils by transmitted light, it appeared that the thickness of the source was of the order of 0·1 mg./cm.². Accordingly, a foil of aluminium $\frac{1}{2}\mu$ thick was placed in front of this source and observations taken at 50·5 and 83·0 ekV. It is evident that absorption in or near the source corresponds as regards order of magnitude with the Schonland type, since particles are incident at all angles on the absorber and a narrow emergent beam is observed. The tilt of the foil (which was approximately parallel to the source) was about 7°; the effective thickness was therefore cosec $7° \times \frac{1}{2}\mu$ of aluminium = 1·1 mg./cm.². This would give, on Schonland's data, about 87 % transmission at 50·5 ekV and 97 % at 83 ekV; the experimental figures were 87 and 95 % respectively.

Passing next to absorption in the source of Ra (D + E), the experimental absorption at 50·5 ekV relative to a pure Ra E source was 16 %, which would require ~ 1·36 mg./cm.², or 0·16 mg./cm.² normal thickness (the Ra D contributed a considerable part of this mass). Such a thickness would give about 4 % absorption at 83 ekV, while the experimental value was 3·7 %.

Set G, reflexion from extra ½μ aluminium behind source of Ra E. As may be seen from figure 5, there is no distinguishable difference between points with and without the extra ½μ aluminium behind the source, even down to 13 ekV. There are no reflexion data covering precisely the case of isotropic incident radiatian and grazing emergence, but existing data would suggest that with such a foil the reflexion would be at most a few per cent even at very low energies (20 to 13 ekV); the experimental result is taken to indicate that no appreciable reflexion was present with the pure Ra E source on ½μ aluminium down to 20 ekV at least.

Set H, reflexion from thick aluminium foil. The aluminium foil was several millimetres thick; reflexion was at grazing emergence and there appear to be no data for comparison. No interpretation of the curve is offered and it is shown chiefly by way of contrast to the result with an isolated thin source. It has a definite maximum at about 188 ekV, whereas the curve of Flammersfeld for Ra E on diamond had no maximum, while Martin and Townsend found for normal emergence from platinum that the ordinates were increased in a constant ratio. It seems probable that in some at least of the many curves for Ra E with thick sources, the maximum was partly due to a reflexion effect and not solely to absorption of particles of the lower energies in the window of the counter or ionization chamber.

The photoelectric lines of Ra D were not investigated in the present experiment because with a permanent magnet and fixed counters this would have been a very lengthy operation.

Discussion

As shown in the previous section, the curves of figures 2 and 3 represent directly the undistorted β-ray spectrum of Ra E in respect of energy and momentum. It may be stated at the outset that there is very close agreement in nearly every detail between these distributions and those published recently by Flammersfeld. The most conspicuous feature of the energy curve is the well-defined maximum at about 150 ekV. The end-point, which was not investigated for a precision determination in view of already existing concordant results, is 1·17 MeV, in complete agreement with these. Perhaps the most interesting single feature of the curve is that the mean energy is 340 ekV, which is in remarkable agreement with the calorimetric determinations, viz. 344 ± 34 ekV, by Ellis and Wooster (1927) and 337 ± 20 ekV by Meitner and Orthmann (1930). This again provides strong evidence that distortion of the spectrum has been completely eliminated. The number of electrons of energies between 15 and 60 ekV, given as about 8 %

by Richardson, is 7·3 %. The momentum ($H\rho$) distribution curve has a maximum at $H\rho = 1800$ G-cm. compared with Flammersfeld's 1750 G-cm.

A strict comparison with theory is hardly possible since the case of a forbidden transition in a heavy nucleus has not been treated satisfactorily and the results are uncertain especially at the low energy end of the spectrum. However, the usual method of exhibiting Fermi and K.U. plots affords at least a useful comparison of experimental results.

For $Z = 83$ and neutrino mass $= 0$

$$\left[\frac{N(\eta)}{\eta + 0{\cdot}355\eta^2}\right]^{\frac{1}{2}} \propto [\sqrt{(1+\eta_0^2)} - \sqrt{(1+\eta^2)}], \quad \text{(Fermi)}$$

$$\left[\frac{N(\eta)}{\eta + 0{\cdot}355\eta^2}\right]^{\frac{1}{4}} \propto [\sqrt{(1+\eta_0^2)} - \sqrt{(1+\eta^2)}], \quad \text{(K.U.)}$$

where η = momentum of β particle in m_0C units, $\eta_0 = \eta$ at upper limit.

The two plots are given in figure 6 and show the usual features, the K.U. plot being straight for a considerable portion of the energy range and then falling rapidly as the upper limit is approached, while the Fermi plot is concave upwards through most of the energy range but has a smoother approach to the observed upper limit. This limit occurs at 3·30 in m_0C^2 units, while the extrapolated K.U. end-point is 3·85 m_0C^2. The difference, 0·55 m_0C^2, is the so-called neutrino mass. Corresponding figures, according to other workers, are:

	Extrapolated end-point	Extrapolated end-point – experimental end-point
Flammersfeld (1939)	3·79	0·50
Martin and Townsend (1939)	3·80	0·47
Alichanian and others (1938)	3·69	0·37
O'Conor (1937)	3·52	0·22
Langer and Whittaker (1937)	3·82	0·52
Lyman (1937)	3·68	0·45

The explanation of the difference between observed and extrapolated end-points in terms of a finite neutrino mass seems of doubtful validity. Although Alichanian and others, and O'Conor, find that the introduction of this quantity brings about agreement between experiment and the predictions of the K.U. theory, Lyman, Flammersfeld and the writer find that agreement is quite impossible by this means, nor apparently can the results of Martin and Townsend be reconciled. Alichanian and others found that the required neutrino mass for the Th C spectrum was 0·8, while Zavelsky states that agreement is not possible for the Th C″ and Th B spectra unless an intermediate energy is taken as the limiting energy, lying between the observed and extrapolated K.U. limits. Thus it seems that the simple hypothesis of attributing the discrepancy between observed and

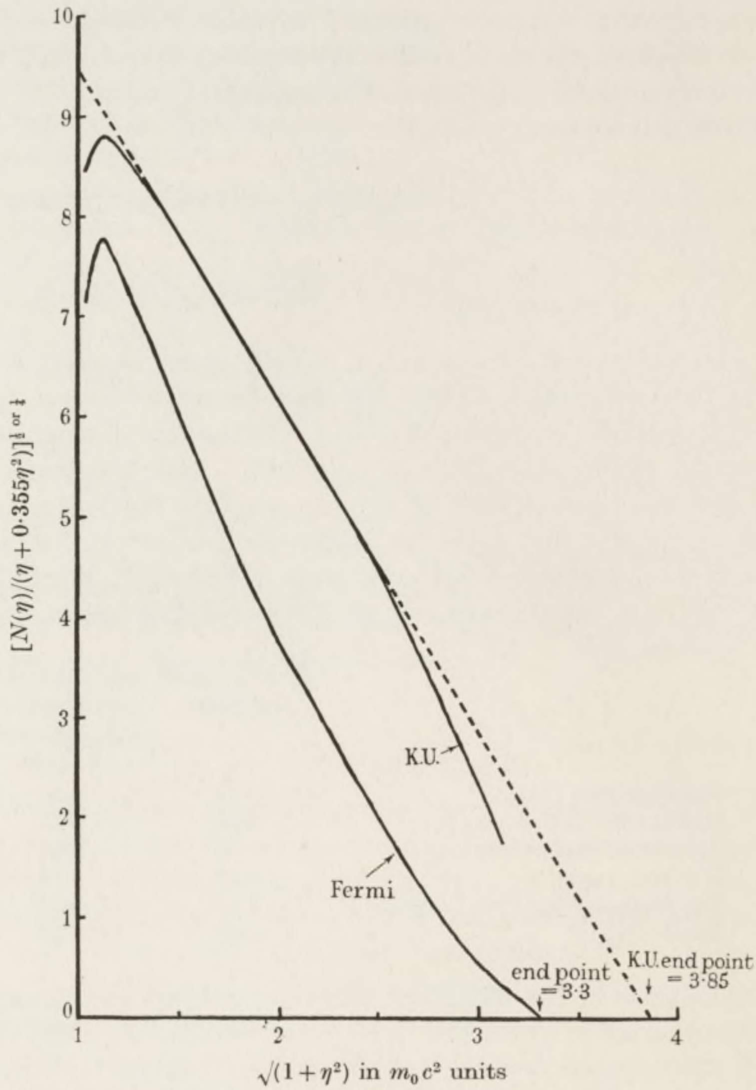


FIGURE 6. Fermi and K.U. plots for Ra E.

extrapolated K.U. limits to the effect of a finite neutrino mass is not generally tenable. As was pointed out by Richardson, an improved agreement with the Ra E experimental curve may be obtained by taking a linear combination of Fermi and K.U. terms, but even then the agreement is not wholly satisfactory. Likewise, the modifications to the distribution introduced by the β-decay theory of Yukawa (1938) do not result in appreciable improvement in this matter.

Turning next to the low energy part of the distribution, the writer's curve lies below the K.U. curve after 150 ekV, the reduction being 6 % at 100 ekV, 13 % at 50 ekV, and 32 % at 13 ekV, as deduced from the non-linearity of the K.U. plot. This cannot be due to any kind of absorption in the counter window or in the source. Flammersfeld (1939), on the other hand, finds practical agreement with the K.U. distribution down to the lowest energies, while Alichanian and Zavelsky (1937) find the experimental curve above the K.U. curve to the extent of 10 % at 50 ekV. It appears to the writer that Flammersfeld's explanation of the latter result as due to scattering, etc. in an aged source is definitely untenable. The writer encountered no such effect with a source similar to that of Alichanian and Zavelsky ($\frac{1}{2}\mu$ aluminium) and in any case the effect of an impure source is always to reduce the apparent number of slow particles, "absorption" being more important than back scattering, cf. preceding section, sets B, C, D, E.* The writer therefore considers that extraneous scattering must have played some part in the spectrograph of Alichanian and Zavelsky and to a lesser extent in that of Flammersfeld also, and the following considerations appear to favour this conclusion. Although it is not possible to say precisely what effect absorption by scattering had in the counter window of 1μ cellulose acetate used by Alichanian and Zavelsky, yet it seems very likely that this absorption was greater than the authors considered. On the basis of the type of absorption which obtained in the counters of Martin and Townsend, of Flammersfeld and of the writer, the "absorption" in 1μ cellulose acetate would be about 18 % at 30 ekV and 22 % at 20 ekV. Hence the properly "corrected" curve would be expected to be even higher than that given by Alichanian and Zavelsky since they assumed an absorption of only 4 % at 40 ekV. However, such a curve could hardly be regarded as correct and the excess at low energies must be attributed to scattered particles. The spectrograph had a defining slit close to the source and several limiting slits round the semicircular trajectory, and edge effects may well have been present. If this were in fact the case, the complete agreement with the K.U. distribution found by these authors using the same apparatus for Th C″ and Th B requires further consideration.† In the experiments of Flammersfeld the mean energy of the distribution is

* Apart from the effect of back scattering, "absorption" in the source (for small thicknesses) removes completely more particles from the lowest energy range than it reintroduces into this range by the retardation of particles of higher energy.

† The excess of particles at low energies (300 ekV downwards), found by Martin and Townsend, may almost certainly be attributed to the inadequate gas pressure of 5 cm. air in the counter, giving a higher efficiency of detection for particles of lower energy.

330 ekV, which is slightly but appreciably lower than the calorimetric values. This fact alone suggests that the low energy part of his curve may be slightly too high. The radius of curvature employed in Flammersfeld's spectrograph was 4 cm., while the writer used 10 cm. for the low-energy region. The definining slit was not immediately in front of the source but it was not, on the other hand, as far away as possible and, most important of all, the slit presented practically the same solid angle or aperture for admission into the "image" or counter space of particles of all energies. In the spectrograph used by the writer, the effective aperture at small fields was smaller the higher the energy of the particle, so that practically only the relevant low energy particles entered the image space at small magnetic fields, and a stray electronic "atmosphere" was avoided, cf. preceding section, set C. Although certain low energy photoelectron lines appeared perfectly sharply in Flammersfeld's experiments, this is no proof that a contribution of scattered particles from the whole of the distribution was not present as well. The absorptions of a line and of the neighbouring continuous background in 2μ "Zaponlak" were found to be the same, but this hardly rules out the possibility that the background should contain $5 \sim 10\%$ of scattered radiation, and indeed the latter might appear nearly homogeneous if most scattered particles were produced at the slit edges, because of the mode of observing the zero count.* Thus the final conclusion would seem to be that the slight disagreement between the curves of Flammersfeld and the writer below 150 ekV may probably be attributed to the effects of scattering in the former case. The writer's curve showing fewer slow electrons than corresponds to the K.U. distribution for an allowed transition might conceivably exhibit just that reduction in the number of these electrons which appears to be generally expected in a forbidden transition, but at present this interpretation is entirely speculative in character. On the other hand, the K.U. plot obtained here, with the marked fall at each end, is similar to some of the possibilities described by Hoyle (1937, 1938).

It is a pleasure to thank Dr N. Feather for his continued interest in the work and to acknowledge the valuable assistance of Mr E. Wild of Trinity College with the observations in the latter stages of the experiment.

Summary

The β-ray spectrum of Ra E has been investigated with a magnetic spectrograph of special design with a source on $\frac{1}{2}\mu$ aluminium and a counter window of 10^{-5} g./cm.^{2} Zaponlak.

* This zero count in fact varied somewhat with the magnetic field.

It is considered that the experimental results represent directly the distribution of particles from about 20 ekV upwards without distortion from any cause. The energy curve has a maximum at 150 ekV and an end-point at 1·17 MeV, with a mean energy of 340 ekV in complete agreement with calorimetric determinations. The momentum curve has a maximum at $H\rho = 1800$ G-cm. in satisfactory agreement with Flammersfeld, $H\rho = 1750$ G-cm. The intermediate part of the K.U. plot is straight, the energy difference between experimental and extrapolated end-points being 0·55 $m_0 C^2$; on the other hand, the introduction of a finite neutrino mass does not bring about agreement with theory. The K.U. plot also falls below the straight line below 150 ekV, and resembles some of the possible distributions for "forbidden" transitions, as given by Hoyle.

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