Energy Spectrum of the Beta-Rays of Radium E

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The energy distribution curve for the beta-ray spectrum of radium E has been measured. The spectrum was found to have a maximum at 3.87×10^5 electron volts and an endpoint at $(15.34\pm 0.28)\times 10^5$ electron volts corresponding to an $H\rho$ of 6604 ± 98. The spectrum was obtained by the magnetic focusing method and the particles were counted by a Geiger counter. The absorption of the beta-rays in the counter window was determined and allowed for. The large number of very low energy beta-rays found by H. O. Richardson was not confirmed. The energy distribution found does not agree with that of Fermi's theory. The results obtained are compared with those of previous investigators.

A LARGE amount of work has been done on the distribution of the energy in the β-ray spectrum of radium E with some rather conflicting results. Several investigators find that the spectrum has an upper limit at about 10^6 electron volts corresponding to an $H\rho$ of about 5200. Among those finding this are Schmidt,[1] Gray and O'Leary,[2] Douglas,[3] Sargent,[4] Feather,[5] Madgwick,[6] Gray[7] and Champion.[8] Others have found that the spectrum extends beyond a million electron volts and does not have any definite upper limit but that the intensity falls to zero asymptotically. Danysz,[9] Curie and d'Espine,[10] Yovanovitch and d'Espine,[11] and Terroux[12] have found results of this kind. Very recently H. O. W. Richardson[13] has found that a low energy group of β-rays is emitted which was not observed in the previous work. The present investigation was undertaken to see if these low energy rays could be detected by the magnetic focusing method and to determine the energy distribution more accurately.

The β-ray spectrum of radium E was obtained by the magnetic focusing method and the particles were counted by a Geiger counter connected through a three-stage amplifier and thyratron to a mechanical impulse counter. The magnetic field was produced by a Weiss water-cooled electromagnet. The pole pieces of this magnet were cylindrical in shape and 10 cm in diameter. The current to the magnet was supplied from a 110-volt battery and was measured by means of a Weston standard ammeter which could be read to 0.5 percent. For an air gap of three centimeters it was found that the field increased nearly linearly with the current. Currents ranging from 0.100 to 6.50 amperes were used, the latter value producing a field of about 6000 gauss in the gap.

The strength of the magnetic field was determined by means of a fluxmeter and search coil. The fluxmeter was calibrated by means of a standard line-turn meter. This line-turn meter was first checked for accuracy by connecting it in series with the secondary of a standard mutual inductance. The value of the current through the primary of the mutual inductance was adjusted each time to such a value as to produce about the same flux when it was reversed as did the line-turn meter for a given deflection. The deflections produced by each on the fluxmeter agreed to within 0.5 percent. The fluxmeter was then calibrated using the line-turn meter. This was done by connecting the fluxmeter, line-turn meter, and snatch-coil of the fluxmeter in series and noting the deflections of the fluxmeter for definite values of the flux produced by the line-turn meter. The strength of the magnetic field was now determined for various values of the current. The direction of the current through the magnet was made such as to give the proper field direction for the magnetic focusing apparatus. The current was then increased to 6.50 amperes and reduced to zero so as to give the proper direction to the residual field of the magnet. The field strength was now determined by the snatch

[1] Schmidt, Physik. Zeits. **8**, 361 (1907).
[2] Gray and O'Leary, Nature **123**, 568 (1929).
[3] Douglas, Proc. Roy. Soc. Canada **16**, 113 (1922).
[4] Sargent, Proc. Camb. Phil. Soc. **25**, 514 (1929).
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[6] Madgwick, Proc. Camb. Phil. Soc. **23**, 982 (1927).
[7] Gray, Proc. Roy. Soc. **A87**, 487 (1912).
[8] Champion, Proc. Roy. Soc. **A132**, 672 (1932).
[9] Danysz, Le radium **10**, 4 (1913).
[10] Curie and d'Espine, Comptes rendus **181**, 31 (1925).
[11] Yovanovitch and d'Espine, J. de physique **8**, 276 (1927).
[12] Terroux, Proc. Roy. Soc. **A131**, 90 (1930).
[13] Richardson, Proc. Roy. Soc. **A147**, 442 (1934).

coil. This was done by placing the coil in the field with its faces parallel to the pole pieces, removing it from the field and then reversing it and putting it back. From the area and number of turns on the snatch coil and the calibration of the fluxmeter the value of the field in the gap for each current was determined. The fluxmeter could be read to an accuracy of 0.5 percent with a hand magnifier. All the measuring instruments were kept sufficiently far from the magnet so that their magnetic fields were unaffected by it.

A diagram of the apparatus used for obtaining the spectrum of the β-rays is shown in Fig. 1. The lead block B fits tightly into the brass box F and is held in place by a peg at A. The source of the β-rays was placed at O and consisted of a nickel wire 0.452 mm in diameter which had been immersed for one hour in a solution of radium D from which the radium F had been completely removed. The wire extended along the axis of the aluminum cylinder L which fitted tightly into the lead block B. A vertical slit 3 mm wide was cut in the aluminum cylinder. A brass plate E_1E_2 extended from the center of the box to the side and had its upper edge in line with the radium E source. The slit S_2 in the brass plate E_1E_2 was 8×0.832 mm and was directly above the window in a Geiger counter C. A slit of the same dimensions as that in the plate was cut in the glass tube of the counter and was covered with cellophane of thickness 0.0254 mm. The cellophane was cemented to the glass with Dupont cement diluted with acetone. There was a similar slit in the copper cylinder of the counter directly under the cellophane window. D is an aluminum partition with a slit at S_1. This partition was removable. The box was lined with aluminum. The outside diameter of the brass box was 10 cm and the distance from O to S_2 was nearly four centimeters. The brass box containing the source was placed between the poles of the magnet and evacuated by means of a Hyvac pump which was kept running during the experiments. The Geiger counter was connected through a three-stage amplifier and thyratron to a mechanical impulse counter capable of counting 125 impulses per second. Counts were made for five-minute intervals for various values of the magnetic field.

The absorption of the cellophane window was measured by observing the counting rates in various fields with additional thicknesses of two and four layers of cellophane placed above the slit S_2. Table I shows the counting rate per minute for various thicknesses of cellophane. Curves were then plotted of the counting rate with a given field against the thickness of the cellophane. These curves were extrapolated to give the counting rates for zero thickness which are given in the last column of Table I. Plotting the percentage absorption for one layer against $H\rho$ gave a straight line over the region investigated and showed that the cellophane window had no appreciable effect when $H\rho$ was greater than about 2400. The results obtained with $H\rho$ less than 2400 were corrected for the absorption of the cellophane window.

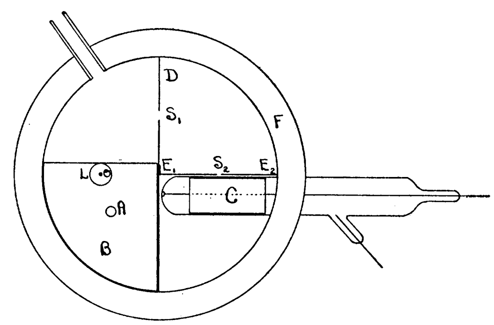

FIG. 1. Magnetic focusing apparatus for obtaining the beta-ray spectrum.

The amplifier, thyratron and mechanical impulse counter system was tested for accuracy in counting. This was done by first noting the residual count; then a small amount of radio thorium sealed in a glass tube was placed successively at three distances d_1, d_2 and d_3 in front of the counter. The radio-thorium increased the counting rate by 36, 61 and 77 counts per minute in the three positions. The radio-thorium

TABLE I. *Variation of counting rate with cellophane thickness.*

$H\rho$ ($\rho=1.975$) cm	One layer	Three layers	Five layers	Zero thickness (calculated)
439	5.1	2.4	—	7.4
573	13.3	7.2	—	19.0
737	25.5	17.0	9.8	35.0
914	44.2	30.0	21.6	58.0
1097	65.0	41.4	33.6	83.0
1274	82.5	60.9	53.0	101.0
1423	123.0	90.2	71.4	148.0
1619	197.3	146.0	113.3	227.0

was then removed and the counting rate obtained for the β-rays from the radium E spectrum for a given value of the magnetic field. The counting rates were also obtained when the radio-thorium was placed in each of the positions d_1, d_2 and d_3. The differences between the counting rates with and without the radio-thorium were found to be equal to the rates due to the radio-thorium alone within the limits of statistical error.

The equation for the motion of the β-rays along their paths in the magnetic field is

$$Hev = mv^2/\rho,$$

whence

$$H\rho = mv/e = m_0/e \cdot v/(1-v^2/c^2)^{\frac{1}{2}}.$$

The energy of such rays is obtained from these relations:

$$E = m_0c^2\{1/(1-v^2/c^2)^{\frac{1}{2}} - 1\} \text{ ergs.}$$

$$= 299.8\{[(H\rho)^2 + (cm_0/e)^2]^{\frac{1}{2}} - (cm_0/e)\} \text{ electron volts}$$

$$= 299.8\{[(H\rho)^2 + (1703.41)^2]^{\frac{1}{2}} - 1703.41\}.$$

If we put $H\rho = 1703.41 \tan\theta$, then it can be shown that

$$V = 510{,}682\{\sec\theta - 1\} \text{ electron volts.}$$

In Table II are shown three sets of data obtained for radium E showing the counting rates for various values of the magnetic field. The counting rates for each set of data have had the residual count subtracted. In column five is shown the average of the results for the three sets of data. In column six are the average values of the readings after they have been corrected for the absorption due to the cellophane window. For values of H greater than about 3300 the counting rate was not appreciably greater than the residual count. The curve of Fig. 2 represents the data of column six of Table II plotted against the values of the magnetic field H. The presence of the partition D in the brass box did not appreciably change the end point or tail of the curve. This seems to clearly indicate that the tail is not due to scattering. The curve of Fig. 3 shows a set of data obtained without the partition D in the box. The source used in obtaining these data was stronger than that previously used. The dotted curve was obtained with the partition. This dotted curve represents the data of Fig. 2 multiplied by a factor 1.64 such that the maxima of the two curves coincided. The two curves practically coincide for values of H above the value at the maximum. This shows that the screen had no effect on the end point and number for the higher energies, but reduced the number at the lower energies as was to be expected. The curve of Fig. 2 appears to indicate an upper limit at a value of H of about 3400 gauss. A more

TABLE II. *Counting rates for various values of H.*

H (GAUSS)	SET #1 COUNTS/MIN.	SET #2 COUNTS/MIN.	SET #3 COUNTS/MIN.	AVE. (UNCORR.)	AVE. (CORR.)
222	1.2	1.0	0.9	1.02	1.4
373	7.0	4.3	3.3	4.9	6.7
555	23.0	16.8	15.7	18.5	23.6
720	47.0	40.0	38.3	41.8	50.2
901	100.0	77.7	80.7	86.1	96.5
1080	210.3	180.7	173.0	188.0	197.8
1255	267.0	260.3	249.0	258.8	258.8
1429	292.6	280.0	273.7	282.1	282.1
1610	280.0	270.7	257.7	269.5	269.5
1800	229.0	219.0	210.3	219.4	219.4
1966	187.0	170.7	159.0	172.2	172.2
2150	134.7	123.0	120.7	126.1	126.1
2330	85.3	71.7	70.3	75.8	75.8
2535	54.3	39.0	41.7	45.0	45.0
2685	33.5	20.0	18.0	23.8	23.8
2865	20.0	13.8	14.0	15.9	15.9
3042	11.0	6.3	5.0	7.4	7.4
3220	5.0	3.0	2.0	3.3	3.3
3304	—	—	—	—	0
3600	—	—	—	—	0

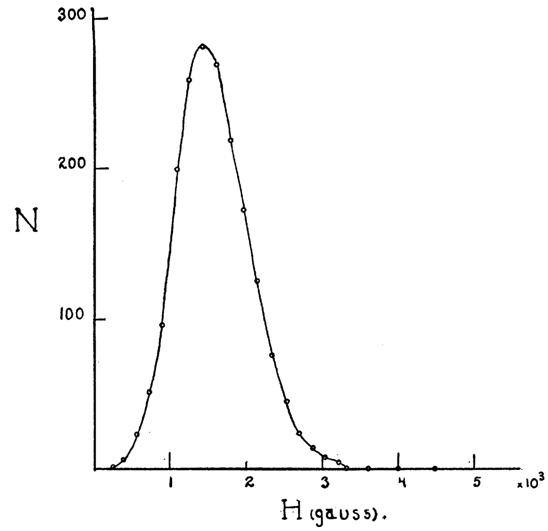

FIG. 2. Counting rates for various values of the magnetic field with the partition D in the brass box.

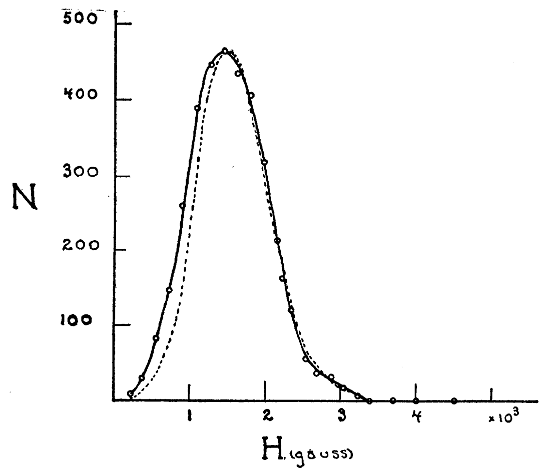

FIG. 3. Comparison of the counting rates for various values of the magnetic field without (solid curve) and with (dotted curve) the partition D in the box.

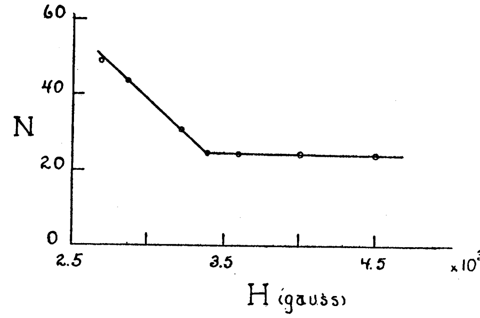

FIG. 4. Counting rates for various values of the magnetic field at the high energy end of the spectrum.

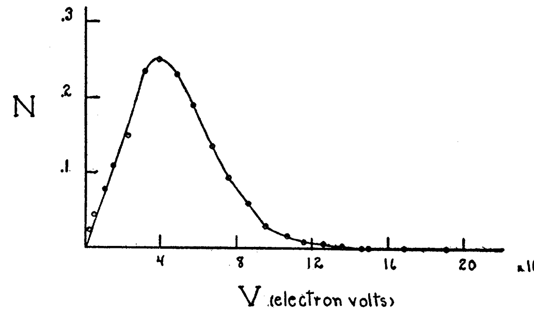

FIG. 5. Energy distribution curve of the beta-rays.

detailed study of this endpoint is shown in Fig. 4. This indicates an upper limit at $H=3380\pm50$ gauss. Readings were taken for values of the magnetic field as great as 4500 gauss and no increase in the counting rate above the residual value was found for any field strength above 3400 gauss. This upper limit represents an $H\rho=6604$ ±98 corresponding to an energy of (15.34 ± 0.28) $\times10^5$ electron volts. The value of ρ used in computing the upper limit was one-half the distance from the side of the wire nearest S_2 to the edge of S_2 nearest the wire, which was 1.954 cm. In computing the energy distribution curve, however, the value used was one-half the distance from the side of the wire nearest S_2 to the center of S_2, a distance of 1.975 cm.

This value of the upper limit is higher than that obtained by such investigators as Madgwick, Sargent, Feather and Champion who obtained values for the endpoint from $H\rho=5000$ to $H\rho=5500$. On the other hand Terroux found there was no definite upper limit, while Curie and d'Espine and Yovanovitch found a band extending from $H\rho=6000$ to $H\rho=12{,}000$.

The ordinates of the curve of Fig. 2 were divided by H to give the distribution with respect to $H\rho$ and then divided by $\sin\theta$ to give the distribution with respect to the energy which is shown in Fig. 5. This curve has a maximum at 3.87×10^5 electron volts. The average value of the energy obtained from this curve by graphical means is 4.71×10^5 electron volts. Fig. 6 shows the experimental curve and the curve obtained from the Fermi theory. Both curves have been reduced to unit area and the abscissae are proportional to the energy instead of being actual energies. Since all the energy distribution curves of the simple type of the different radioactive substances are of the same general form, Fermi's theory should apply to all. He, however, points out that the present theory which he has thus far developed does not apply to radium E. The curve of Fig. 6 shows this to be the case.

The endpoint of the β-ray spectrum of radium E has been estimated from the effective range of the particles in various substances such as paper and aluminum and has been found to be between an $H\rho$ of 5000 and 5500 corresponding to an energy of 10.3 to 12.1×10^5 electron volts. This method was used by Schmidt, Gray, Douglas, Feather and Sargent. A kink always appears in the absorption curve which is taken to be the effective range of the fastest particles in the substance. From this it is possible to estimate the endpoint of the spectrum. It is quite often rather

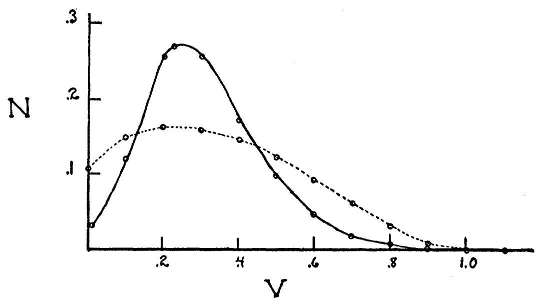

FIG. 6. Comparison of the experimentally determined energy distribution (solid curve) with that given by the Fermi theory (dotted curve).

difficult to detect this kink accurately in the presence of gamma-rays. Terroux points out that since the energy distribution spectrum has a sudden inflection at $H\rho = 5000$, one would also expect a kink in the absorption curve at this point. The kink does not then indicate complete absorption but only a sudden change in the absorption. If the right-hand side of the steep portion of the curve in Fig. 5 is extended to the axis it is found to cut the axis at about a million electron volts. This, however, neglects the tail which is definitely present.

Madgwick investigated the spectrum using the magnetic deflection method and an ionization chamber to detect the particles. He found an upper limit at about $H\rho = 5000$ which is considerably lower than the value found above. Champion measured the length of the β-ray tracks of radium E in a cloud chamber. From the tracks examined he concludes that the spectrum has an upper limit at $H\rho = 5500$ or about one million electron volts. Also Gray and O'Leary have estimated that less than one atom in 25,000 emits a β-ray with an $H\rho$ greater than 8000. Danysz, Curie and d'Espine, and Yovanovitch and d'Espine using photographic plates and magnetic focusing methods find a band extending from about 6000–12,000. Likewise Terroux, using the same method as Champion, obtains results which show that the spectrum does not end at $H\rho = 4900$–5500 but has a tail which extends beyond $H\rho = 12{,}000$. He also estimates that only about four percent of the total number of particles emitted have an $H\rho$ greater than 5000, which is in good agreement with the results of the present investigation.

The curves obtained by Henderson[14] in determining the endpoints of thorium C and thorium C″ spectra have a tail and definite endpoint similar to those observed for radium E in the present investigation. The curves obtained by Gurney[15] for radium C and radium C′ also have similar tails and endpoints.

In the previous work on radium E the various investigators who have placed the endpoint at values of $H\rho$ from 5000–5500 seem to have assumed that the tail, if present, was due to scattering and have neglected it. Since curves obtained both with and without the partition D in the brass box of the focusing apparatus in the present investigation indicate the same endpoint for the spectrum, the tail cannot be due to scattering. In the previous work the middle slit D was placed near the source and was wide. Such a slit does not define a beam with as small a range of ρ as a slit placed half-way along the path of the beta-particles. The few high speed particles observed by Terroux and others at values of $H\rho$ greater than 6700 may possibly have been due to contamination of the source.

Using a cloud chamber, H. O. Richardson has found a group of low energy β-rays for radium E extending from 0.10–0.65×10^5 electron volts. The numbers of β-rays for values of the energy in this region were greater than the number obtained at the maximum value of the energy distribution curve. The present experiments do not indicate the presence of such a large number of low energy β-rays. The curve in Fig. 5 only shows a number of β-rays of energy 0.40×10^5 electron volts equal to about 18 percent of the maximum number. This cannot be explained by the absorption of the cellophane as this has been allowed for. It is possible therefore that most of H. O. Richardson's low energy rays were secondary rays due to collisions of higher energy rays with atoms. This possibility was considered by Richardson but he thought that the number of low energy rays which he observed was probably too great to be explained in this way.

The writer wishes to express his indebtedness to Professor H. A. Wilson for suggesting the problem and for his interest and guidance during the progress of the work.

[14] Henderson, Proc. Roy. Soc. **A147**, 572 (1934).
[15] Gurney, Proc. Roy. Soc. **A109**, 540 (1925).