The Distribution of Energy in the β-Ray Spectrum of Radium E.

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[Plate 12.]

1. *Introduction.*

There exists some conflicting experimental data concerning the distribution of energy in the β-ray spectrum of radium E. The earliest work, carried out by Schmidt* in 1907, using both the absorption and magnetic deflection methods, showed that the spectrum was apparently continuous but had a well-marked upper limit at about Hρ 5500 (energy about 10^6 volts). In 1911, O. v. Baeyer, Hahn and Meitner† confirmed this result and Gray‡ came to a similar conclusion in the following year. Danysz,§ however, using the method of magnetic focussing, while agreeing to the main distribution including the existence of the well-marked upper limit at 5500 Hρ, made a guarded statement concerning the possibility of the existence of β-rays of far higher velocities. "Sur ces mêmes clichés, il semble y avoir des indices d'un faisceau beaucoup plus rapide, de vitesse variable comme le premier (comprise entre les limites approximatives $\beta = 0 \cdot 94$–$0 \cdot 99$). Toutefois ces indices sont tellement faibles qu'il est nécessaire de recourir à une autre methode pour être sûr de son existence. Ce faisceau est beaucoup moins visible que le faisceau le plus rapide du radium C . . ." In 1916, Kovarik and McKeehan,|| using the ionisation method, considered their results agreed with those of O. v. Baeyer, Hahn and Meitner. Curie and D'Espine,¶ in 1925, using the method of direct magnetic deviation and a photographic plate, agreed to the sharp upper limit of the main distribution, but found also a very weak band between the limits of 7000–10,000 Hρ (energy $1 \cdot 5 \times 10^6 - 3 \cdot 0 \times 10^6$ volts). It appears that there was no evidence of any direct connection between the two parts of the spectrum. The subject was considered again in 1927 by Yovanovitch and D'Espine** and

* 'Phys. Z.,' vol. 8, p. 361 (1907).
† 'Phys. Z.,' vol. 12, p. 273 (1911).
‡ 'Proc. Roy. Soc.,' A, vol. 87, p. 487 (1912).
§ 'Ann. Chim. (Phys.),' vol. 30, p. 241 (1913).
|| 'Phys. Rev.,' vol. 8, p. 574 (1916).
¶ 'C. R. Acad. Sci.,' vol. 181, p. 31 (1925).
** 'J. Physique,' vol. 8, p. 276 (1927).

the previous results of the latter were confirmed. The same year, Madgwick,* using the ionisation method, confirmed the existence of a sharp upper limit at 5000 Hρ and stated " there is no reason to doubt the accuracy of the endpoint." In a short letter to 'Nature' in 1929, Gray and O'Leary† mention an experiment, using the magnetic deflection and ionisation method, and conclude that less than one particle in 25,000 is emitted with Hρ greater than 8000.

Recently, however, F. R. Terroux,‡ using an expansion chamber, finds no indication of the sharp upper limit of the main spectrum at Hρ 5000, but a gradual tailing off to very high velocities in a manner which, he suggests, indicates a Maxwellian distribution. This would be a point of fundamental importance in attempting any theory of the primary disintegration process, for although it does not give any picture of the nucleus before emission, it imposes a strict criterion which any proposed mechanism must satisfy. In particular, he estimates the number of particles with Hρ greater than 5000 to be as high as 4 per cent. of the total number of particles emitted. This result is in direct contradiction to all previous work and it is clearly important to repeat the investigation using the same method. The advantages of the expansion chamber method are well known; in the problem in hand, the almost equal sensitivity to particles of all velocities is the point of greatest importance. The writer has recently obtained a large number of photographs of β-ray tracks in an automatic expansion chamber. The source was an old radon bulb and the experimental disposition such as to render the results suitable for the investigation of the upper half of the β-ray spectrum of radium E. The existence of the sharp upper limit at about 5000 Hρ has been fully confirmed. No evidence of any gradual tailing off was found and it is estimated that less than one particle in 2000 is emitted with Hρ greater than 5500.

2. *Experimental Method.*

The automatic expansion chamber used was a modification of that previously employed by Blackett and the writer§ for the production of α-ray photographs; it uses the disposition of two cameras mutually at right angles. The main alterations are summarised in what follows; briefly, it may be stated that the improvements in technique have consisted largely of refinements of the critical adjustments. Fast β-ray tracks are always difficult to photograph owing to

* 'Proc. Camb. Phil. Soc.,' vol. 23, p. 970 (1927).

† 'Nature,' vol. 123, p. 568 (1929).

‡ 'Proc. Roy. Soc.,' A, vol. 131, p. 90 (1931).

§ 'Proc. Roy. Soc.,' A, vol. 130, p. 380 (1931).

the very small limits between which the expansion ratio can be varied for the production of fine clear tracks and to the very small amount of light scattered by the few individual drops per centimetre of the fast β-ray track. These difficulties become very great indeed when a large number of fast β-ray photographs is required in a reasonably short time. The expansion chamber was of the standard pattern, being about 16 cm. in diameter and about 6 cm. deep ; a small window in the cylindrical wall was about $\frac{1}{2}$ cm. in diameter and was covered with a thin piece of aluminium foil, equal in stopping power for α-particles to about 4 cm. of air. The shutter was a simple brass bar arrangement with a lead strip attached to one end. It was actuated by a spring and released by a Bowden wire attached to the main driving mechanism, as already described by Blackett.* The source was an old radon bulb and was placed behind a lead slit, 5 mm. broad, 10 mm. long, and 0·5 mm. high. This served to define a flat beam of rays in the plane of the chamber. The source itself was placed in a small brass holder which was open at the end facing the chamber, thus producing very few scattered particles in the forward direction. The holder slid to and from the chamber window on a steel rod, thus rendering it possible to adjust easily the number of tracks per photograph. The whole source and slit arrangement rotated about a brass support, so that the entering beam of rays could be inclined at any mean angle to the window.

The rate of taking photographs was about one per minute and one intermediate expansion was found quite sufficient to clear the field from the old tracks of the previous expansion. Any attempt to increase the speed of taking photographs was unsuccessful, as a chamber of the above dimensions does not reach thermal equilibrium in less than 1 minute. The expansion ratio is then no longer constant and successive photographs show marked differences in appearance. The writer found that the diatomic gases (nitrogen and oxygen) functioned best when the expansion ratio was just under 1·31, the actual method of procedure being to raise the expansion ratio to that value and then to make the final adjustments, using the visibility of the tracks as a guide. At a certain critical value, the tracks take on a particularly fine beady appearance which is strikingly different from their appearance when the expansion ratio is even 0·005 away from this critical value. The nature of the gas in the chamber, of course, strongly affects the appearance of the tracks. Oxygen gives fine tracks over a comparatively wide range of expansion ratio, but in nitrogen, unless special precaution is taken over this factor and the timing of

* 'Proc. Roy. Soc.,' A, vol. 123, p. 613 (1929) ; 'J. Sci. Inst.,' vol. 4, p. 433 (1927) ; etc.

the shutter, the tracks tend to be diffuse. Although early experiments were made in oxygen, all the tracks analysed here were taken in nitrogen. The reason for this was the persistent appearance of general cloud in the chamber when the former gas was used. This contamination is no doubt due to the formation of chemical condensation nuclei, owing to the high chemical activity of the oxygen.* The result is, that about half-an-hour after the apparatus has been working, the tracks commence to be formed against a considerable and continually increasing background of drops; to reduce this background it is necessary to lower the expansion ratio with a consequent increase of diffuseness in the appearance of the tracks. With nitrogen in the chamber, the trouble was very much less in evidence and this gas was therefore used throughout the present experiment. The nitrogen was changed once a day.

For illuminating the tracks, the usual method of a powerful electrical discharge through two mercury vapour lamps, was used; the capacity of the condenser supplying the two lamps was about one-tenth of a microfarad, the voltage about 40,000, and the internal diameter of the quartz capillary about 3 mm. It was necessary to employ oblique illumination to obtain adequate intensity of the photographic image. The illuminating beam was inclined at about 30° to the axes of the cameras and therefore at about 15° to the horizontal plane of the chamber. With such an experimental disposition and a chamber of the dimensions used here, the beam of light illuminated the peripheral parts of the glass roof of the chamber. Careful screening was therefore necessary and a circular annular black screen of about 12 cm. internal diameter was fixed to the roof of the chamber (see fig. 1).

The magnetic field which was used for determining the velocities of the β-particles was supplied by a pair of Helmholtz coils with their common axis perpendicular to the plane of the chamber. The field was tested over the area and depth occupied by the illuminated tracks and found to be constant to $\frac{1}{2}$ per cent. A field of about 250 gauss was used in this experiment; it was measured independently with a fluxmeter and a ballistic galvanometer. The method of analysis of the tracks utilises two cameras at right angles; consequently, the circles into which the β-ray tracks are bent by the applied field project into ellipses on the photograph. The measurement of these ellipses and their computation back into circles is laborious; a series of about 120 artificial tracks of known curvature (drawn on white paper in Indian ink)

* In particular, the growth of bacteria in the gelatin used for sealing part of the chamber and for covering the floor, is a disturbing factor. In growing, the bacteria liberate carbon dioxide, alcohols and other fermentation products.

were therefore photographed in the position of the natural tracks and the resulting ellipses, corresponding to circles of known radius of curvature, simply slipped over the photographs of the natural tracks, until a fit was obtained.

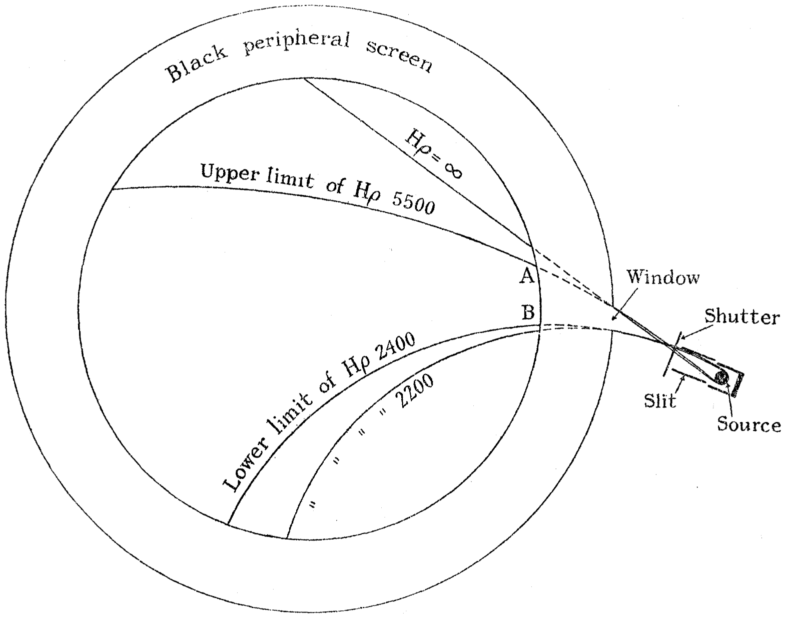


Fig. 1.

The method was tested by drawing random tracks, photographing them, computing the radius of curvature by the above method and subsequently measuring the actual curvatures. The accuracy is from 2 to 4 per cent. over the range of curvatures required in this work. It is desirable to have as little nuclear deflection of the tracks as possible, for the accuracy of the measurements will clearly depend on the length of the track which is a smooth curve. From this point of view, hydrogen would be the ideal gas to use in the chamber but the diffuseness of the tracks and the small ionisation make it very difficult to obtain good results; nitrogen was therefore used throughout.

The approximate position of the source is shown in fig. 1, which is drawn for $H = 250$ gauss. It is essential to have a rigorous criterion governing which tracks are to be counted and to abide by that criterion throughout, rejecting firmly all tracks which do not satisfy it. The initial criterion adopted was that all tracks measured must have a measurable length of undisturbed track for at least 6 cm. from the edge AB of the black screen. It is observed in the figure that all particles with $H\rho$ equal to or greater than 2200 will be fully represented under such a criterion. As a special precaution, a few photographs were taken with the magnetic field off, and the presence of a bundle of "straight" β-ray tracks in the neighbourhood of $H\rho = \infty$, showed that very fast particles would have been adequately photographed when the field was on. The fulfilment of the criterion required the rejection of about 1 in 10 tracks. The effect of this rejection on the relative numbers of particles found in different parts of the spectrum and its connection with the velocities is discussed later.

3. *Results and Discussion.*

The maximum number of particles in the spectrum is found by all experimenters to occur at about $H\rho$ 2200. It has been shown that with the experimental disposition employed here, particles with a velocity corresponding to this value would just have been adequately represented. The lower limit of tracks investigated was therefore raised, for further safety, to $H\rho$ 2400. One thousand tracks with $H\rho$ greater than 2400 have been examined in detail; of these, none has been found with $H\rho$ greater than 5500 and only five with $H\rho$ greater than 5000. The estimated error in a single determination of $H\rho$ in the region of the upper limit is ± 5 per cent., so the results are in complete agreement with the earlier workers. The actual distribution found is shown in Table I. Each reading on the left, in the first column, gives the mean value of $H\rho$ over a range of 400 $H\rho$; thus the first reading 2600 corresponds to a range 2400–2800. The second column gives, on the left, the number of tracks

Table I.

Mean $H\rho$.		Number of tracks.				
		Champion.		Madgwick.		Terroux.
2600		374		346		
3000		267		267		
	3200		437		451	230
3400		170		184		
3800		112		112		
	4000		165		161	161
4200		53		49		
4600		17		16·5		
	4800		24		19·5	79
5000		7		3		
5400		2		—		
	5600		2		—	33
5800 and onwards to 12,000		—		—		Total here = 106

found with velocities falling within the range indicated in the first column. The third column gives, on the left, the values estimated from Madgwick's curve, which was obtained using the ionisation method and the fourth column gives the results obtained by Terroux. For the purposes of comparison with the last-named, the intervals of 800 Hρ are used; the mean values of Hρ are represented on the right-hand side of column 1, and the corresponding numbers of tracks on the right-hand side of the other columns.

The results of Madgwick have been adjusted numerically to fit the present results at Hρ 3000; in the comparison with Terroux, the adjustment has been made to fit the present results at Hρ 4000. This value of Hρ is, for safety, much above Terroux's estimate of the value at which his particles of lower velocity are adequately represented. It is observed that the present results

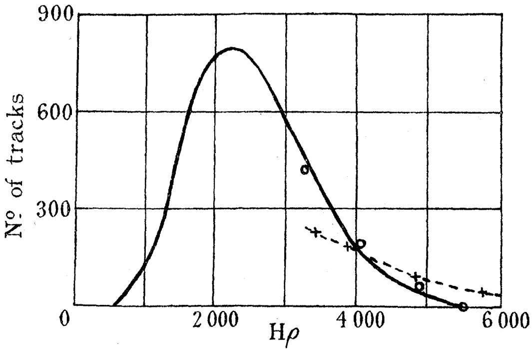


Fig. 2.

are in good agreement with those of Madgwick.* Madgwick's curve is reproduced in fig. 2. The present results are represented by circles and those of Terroux by crosses. This curve was obtained from ionisation measurements and somewhat uncertain data were employed in converting the ionisation readings to a representation of the number of particles with a particular value

* Let $\overline{N_r}$ be the number of particles with a given value of Hρ as given by Madgwick. Since this number is very large it may be used as a standard against which to test the statistical fluctuation of the present results. If N_r is the number of particles found at any mean value of Hρ on the present results and the whole of these results is divided into n groups, then we may apply the usual criterion that the distribution actually found is a probable one, if

$$F = (n-1) = \frac{(N_r - \overline{N}_r)^2}{\overline{N}r}.$$

The number of groups used in this comparison is $n = 6$ over the range 2600–4600 Hρ. Hence, $F = (n-1) = 5$ in this case. Actually, F is found to be nearly 4, so the distribution may be considered probable.

of Hρ. Further, the actual distribution in the region below Hρ 600 is very uncertain. However, using this curve for the particles of Hρ less than 3000 and fitting the present results on to the curve at that point, it is possible to form the rough estimate that less than 1 particle in 2000 is emitted with Hρ greater than 5500.

It remains to discuss the various results and to attempt some explanation of the discrepancy. First, with regard to the accuracy of the absorption experiments, Feather* has considered these in detail and concludes that certainly less than 1 per cent. of the total number of particles emitted have a value of Hρ greater than 5000. Further, in those experiments in which the existence of a band of high Hρ has been reported, it has always been considered to be of very feeble intensity. No estimate seems to have been made of its intensity relative to that of the main band and it may well be of the order indicated by the present expansion experiment. Gray and O'Leary estimate that less than 1 particle in 25,000 is emitted with Hρ greater than 8000. The only results that are in real discord with the present and previous results are therefore those of Terroux. He estimated that 4 per cent. of the total number of particles emitted had Hρ greater than 5000. Such a distribution would be in disagreement, not only with previously obtained spectral distributions but also with the experiments of Ellis and Wooster,† and Meitner and Orthmann,‡ on the mean energy of disintegration of the radium E atom as determined from the heating effect. These results give the mean energy of disintegration n good agreement with Madgwick's curve; the results of Terroux predict a mean energy definitely greater than this. Since the present method is essentially that of Terroux, a few possibilities of the causes of the discrepancy will be considered.

The adoption of a rigorous criterion for the rejection of tracks of which the curvature is doubtful, is of fundamental importance. This implies, however, a considerable amount of data, if the experimenter is to be in a position to adhere strictly to this criterion. Now, about a dozen tracks were found by the writer to have Hρ apparently greater than 5500, but on closer examination these were all found to suffer from one or more deflections due to passage near an atomic nucleus and simply to be tracks near the upper limit, which, as a result of these nuclear deflections, exhibited a spurious straightness. The total number of tracks rejected by the writer, over the whole range of spectrum, was

* 'Proc. Camb. Phil. Soc.,' vol. 27, p. 430 (1931).

† 'Proc. Roy. Soc.,' A, vol. 117, p. 109 (1928).

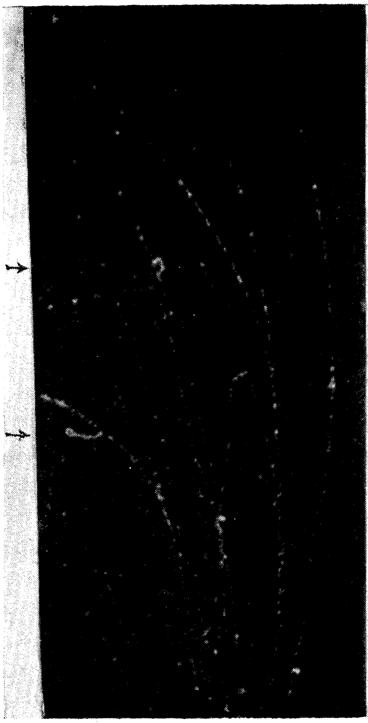
‡ 'Z. Phys.,' vol. 60, p. 143 (1930).

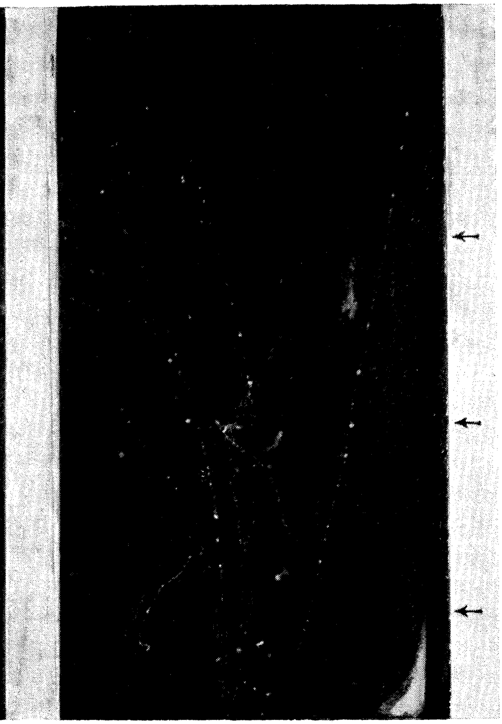
about 100 out of a total of 1100. It is well known that, to a first approximation, the chance of a nuclear deflection for equal distances traversed by different particles is inversely proportional to the fourth power of their respective velocities. Over the range of velocities examined in these experiments, it may easily be shown that this will mean the rejection of about one and a half times as many tracks near the lower limit at $H\rho$ 2400 as near the upper limit at $H\rho$ 5000, if we make the criterion that only those tracks which are perfect over equal distances (say, 6 cm. from the commencement of the photograph) are to be counted.* The final correction that would have been necessary had this criterion been employed, was avoided in practice, by using the criterion that tracks near the upper limit must have the first 9 cm. of the track undisturbed and the tracks near the lower limit, the first 6 cm. This second scheme is preferable, as the use of 9 cm. of the undisturbed track, assists the accuracy of the determination of the curvatures at the higher end of the spectrum. The failure to adopt some such criterion may therefore account for part of the discrepancy. Again, the ratios of the numbers of tracks at mean $H\rho$ 4000 and 4800 for the three experimenters, are 161 : 23·5, 161 : 21, and 161 : 79, respectively. The rapid change in gradient which Terroux observes here is taken by him to indicate a definite kink in the curve at the point $H\rho$ 4000, but the writer suggests it may be due to incorrect fitting of the results to Madgwick's curve. If these slopes are adjusted to fit, by supposing the particles of lower velocity to be inadequately represented in Terroux's measurements, the percentage of fast tracks above 5000 $H\rho$ falls to about one-quarter of that previously indicated. The fact that Terroux's results in these regions of lower velocities fall so much below the accepted values of other experimenters, indicates that the fit has been made too soon, even at $H\rho$ 4000. Further, the number of tracks above these values is so small numerically that the probability fluctuations are very large and the attempt to fit them on to a smooth curve and deduce a Maxwellian tail does not seem justifiable.

With regard to radioactive β-ray emitters other than radium E, it may be observed that an experiment made by Cave,† using a thin-walled radon tube at the centre of the circular pole-pieces of a large Weiss electromagnet and attempting to detect with an electroscope the fast β-particles which should

* The result of applying no correction would have been to have over-represented the fast tracks at the expense of the slower tracks and consequently the error introduced would have favoured the estimate of the number of fast tracks.

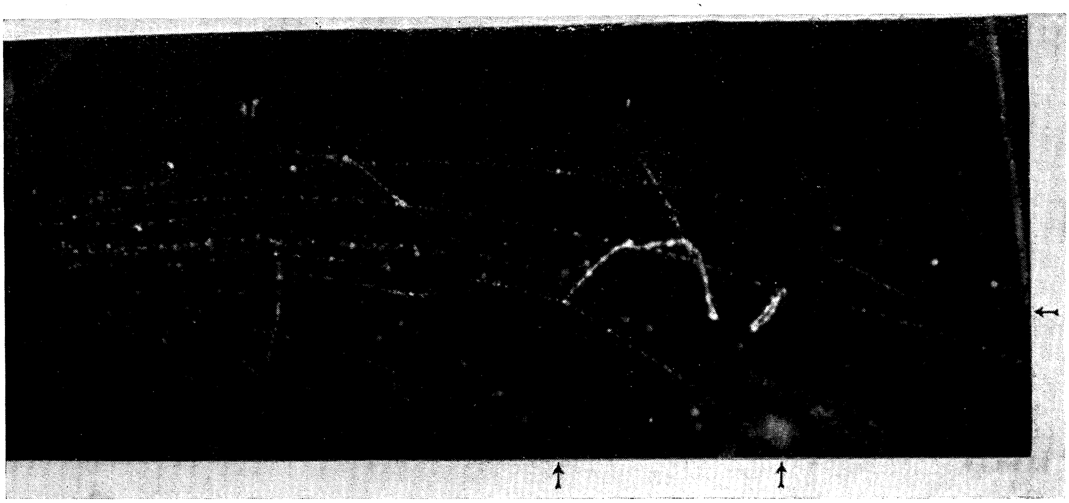
† 'Proc. Camb. Phil. Soc.,' vol. 25, p. 222 (1929).





a. *b.*

Tracks natural size at N.T.P. (*a*) This shows one of the typical β-ray "fans." There are 8 to 10 measurable tracks, which is about the maximum number which can be clearly separated. All the tracks here obey the criterion; two small collisions showing slow ejected secondary electrons are seen on the left along the lines indicated by the arrows. (*b*) This shows another typical "fan," but more particularly one of the tracks of spurious straightness in a region of the chamber corresponding to Hρ greater than 5500. The arrows indicate points at which the misleading nuclear deflections occur; the track, not obeying the criterion, was, of course, rejected.



c.

(*c*) Twice natural size at N.T.P. This shows another typical "fan" with the absence of tracks in the regions of the chamber where Hρ would be greater than 5500, that is, along the top part of the photograph. Two well-marked collisions with electrons are observed at the points indicated by the arrows; both give rise to slow secondary electrons and the difference in the ionisation along the tracks corresponding to slow and fast electrons is brought into strong contrast.

(*Facing p.* 681.)

have escaped, showed that on the average less than one of the high energy particles was emitted in every 500 disintegrations. In later experiments, Cave and Gott, using an absorption method and a radon source, estimated that the fast β-rays were less than 1 in 1000 disintegrations. Indirect evidence shows that the number of fast electrons in the radium C line Hρ 10,020 is about 20 in every 10^6 disintegrations. To return to the consideration of radium E, it is clear that expansion chamber experiments with strong sources and magnetic fields of about 1000 gauss are required to investigate the qualitative existence of any particles with Hρ greater than 5500. It is concluded at present that if they exist, the number is certainly less than 1 in 2000 of the main band.

Summary.

(1) The conditions for the production of a large number of good β-ray photographs, using an automatic expansion chamber, are discussed.

(2) The energy distribution of the β-ray spectrum of radium E is investigated from Hρ 2400 onwards, using 1000 tracks obtained with an automatic expansion chamber.

(3) The spectrum is found to end sharply at about Hρ 5500.

(4) It is estimated that less than 1 particle in 2000 is emitted with Hρ greater than this value.

(5) A review of the experimental results previously obtained with other methods is given and causes of the discrepancy previously observed by Terroux, using the expansion chamber method, are suggested.

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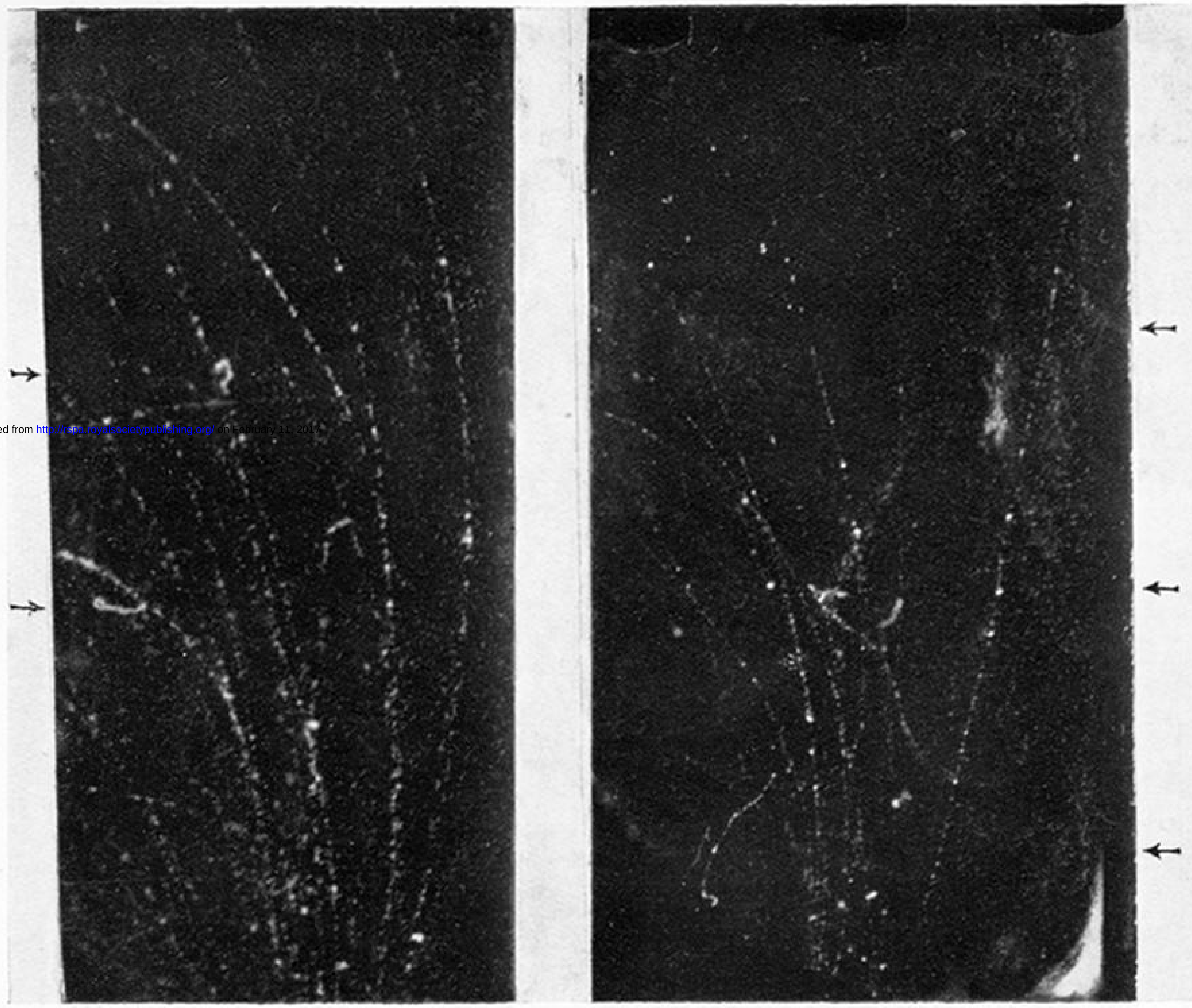

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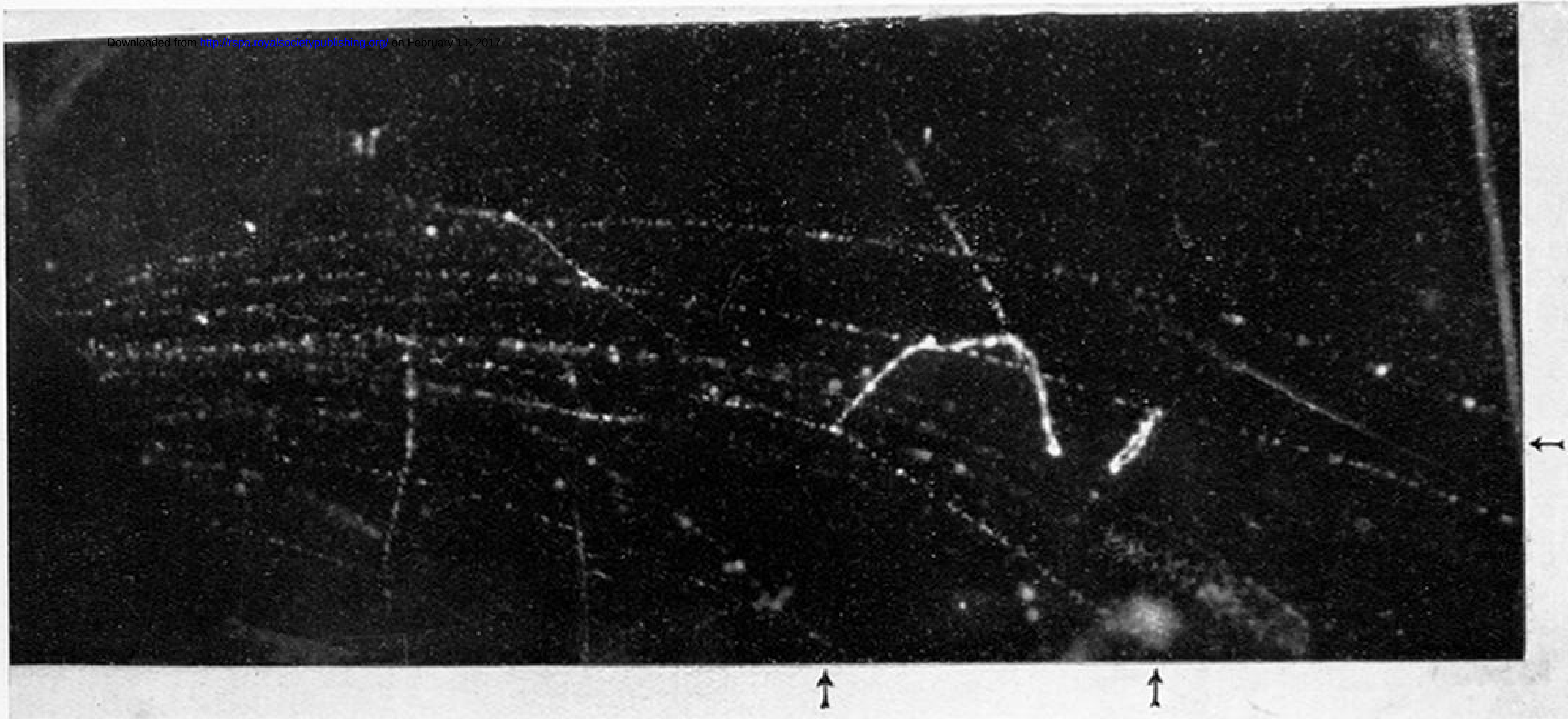

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