CONCERNING THE ABSORPTION METHOD OF INVESTIGATING β-PARTICLES OF HIGH ENERGY: THE MAXIMUM ENERGY OF THE PRIMARY β-PARTICLES OF MESOTHORIUM 2.

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Abstract

For the primary β-particles of radium C, radium E and mesothorium 2 the maximum effective mass range, R, has been determined in paper and aluminum by the method of Chalmers. In the two former cases the maximum energy of the particles, E, is known, and these results and earlier data lead to the relation

$$R=0.511E-0.091$$

for $E>0.7$. Here R is measured in grams/cm² and E in millions of electron volts. For mesothorium 2, $R=0.955\pm0.015$ gm/cm², so that the maximum energy of the particles is $2.05\pm0.03\times10^6$ electron volts. Reasons are advanced for employing the empirical relation above quoted rather than results obtained with particles of a single velocity, as in the experiments of Varder and Madgwick, in the interpretation of absorption measurements made upon primary β-particles.

Introduction

THE earliest recognition of the emission of two distinct types of corpuscular radiation from radioactive material followed immediately upon the adoption of absorption methods of investigation; continuously throughout the development of the subject these methods have been applied afresh in the study of the radiations from the β-ray bodies. Beyond a general qualitative analysis, however, they provide little information which admits of easy interpretation. We now know, for example, that exponential absorption reflects no fundamental property of the different natural radiations—and, in consequence, exponential absorption coefficients have lost much of their significance. Moreover most of the early work was directed toward their determination.

And yet, despite this indefiniteness, absorption measurements do provide, simply and without ambiguity, the maximum effective range, in the medium employed, of the particles submitted to analysis. Now it is of considerable interest to determine the maximum energy appearing as kinetic energy in each of the cases of β-particle disintegration and it is evident that absorption measurements make this determination possible when the necessary data relating effective range with the energy of the particle are available. Such data in fact exist, and already the method has been applied to the β-ray bodies of the active deposit of thorium by Chalmers[1] and to those of the active

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[1] Chalmers, Proc. Camb. Phil. Soc. **25**, 331 (1929).

deposit of actinium by Sargent.[2] But the data in question, upon which the interpretation of these experiments depends, in themselves are ambiguous: the ranges in aluminum given by Madgwick[3] are more than 10 percent greater than the corresponding ranges as determined by Varder.[4]

Eddy[5] has recently made a more detailed study of the absorption of β-particles of somewhat less energy than those with which we are here chiefly concerned and has concluded that the discrepancies between the results of Varder and Madgwick are to a large extent due to the different arrangements of ionization chamber which these authors employed. This conclusion, coupled with the fact that the conditions obtaining in absorption measurements on the complete natural radiations are quite different from those effective in the two investigations under discussion, makes a review of the precise relevance of the data of Varder and Madgwick to the present problem of considerable interest. The results of each investigator show that the effective range is a linear function of the energy of the particle for values of the energy greater than 0.65 million electron volts, or formally

$$R = aE + b \tag{1}$$

for $E > 0.65$ (million electron volts). Varder's data for aluminum are best represented by $a = 0.469$, $b = -0.071$, R being expressed in grams/cm^2; Madgwick's figures by $a = 0.552$, $b = -0.097$. It is to be expected that a similar relation must apply to the conditions of experiment in the primary β-particle case also, but it should be pointed out that the relation in question no longer connects the effective range with the energy for particles initially homogeneous in velocity, but rather it relates the maximum effective range with the maximum energy when particles of continuously varying energy are present. It is very probable that this circumstance makes the determination of the effective range more independent of the conditions than it appears to be in the case of particles of a single velocity,[6] but obviously it cannot result otherwise than that the maximum effective range which is measured should be determined by the highest energy particles present in the beam. Nevertheless there is no simple reason for believing this range to be precisely the same as the effective range determined by extrapolation from the absorption curve taken under any arbitrary conditions with β-particles of that unique limiting velocity. For the purposes of interpretation of experiments performed upon the full natural β-radiation from different substances we ought in preference to employ a calibration curve determined under closely comparable conditions. Such a curve may be obtained by applying the absorption method to the determination of the maximum effective range of the β-particles from bodies which have already been studied in greater detail by the method of magnetic spectroscopy.

[2] Sargent, Proc. Camb. Phil. Soc. **25,** 514 (1929).

[3] Madgwick, Proc. Camb. Phil. Soc. **23,** 970 (1927).

[4] Varder, Phil. Mag. **29,** 725 (1915).

[5] Eddy, Proc. Camb. Phil. Soc. **25,** 50 (1929).

[6] A necessary condition for the truth of this statement is that the continuous spectrum of velocities should have a sharply defined upper limit. This seems to be the case: cf. Chalmers, reference 1, p. 337, Gurney, reference 9, p. 549.

The experiments of Chalmers[1] and Gurney[7] provide the first point on such a curve. Chalmers fixed the maximum effective range of the β-particles of thorium C at 0.98 gm/cm^2 of aluminum whilst Gurney showed that the maximum energy of the particles was 2.18×10^6 electron volts. The first portion of the present work is devoted to the determination of the maximum effective range of the radium E β-particles and of those of radium C. The limiting energies to which these ranges correspond are known from the measurements of Madgwick,[8] and Gurney,[9] respectively. Then two more points are added to the curve and the most probable values of the constants a and b of Eq. (1) may be determined.

The second part of the work consists in a similar absorption experiment upon the primary β-particles of mesothorium 2 and the newly determined range-energy relation makes possible its interpretation.

General Experimental Arrangement

The β-ray electroscope used in all the measurements consisted of a gold leaf system suspended in the usual manner at the center of a cubical aluminum case of 11 cm edge and 3 mm thickness of wall. In the base of the electroscope a hole 7.5 cm square was closed with aluminum foil weighing 6.5 mg/cm^2. The electroscope was supported on a wooden stand with a space of 24 cm between its base and the surface of the bench. A wooden slide could be inserted in various positions below the base of the instrument. This slide carried both the active material and the absorbing foils. The former was placed at the bottom of a shallow cylindrical hole (depth 1.1 cm, diameter 3.2 cm) cut in the slide and the latter, in the form of sheets 5 cm square, were placed upon the slide so as to cover the hole symmetrically. In most cases the slide was inserted in the highest position, and in these circumstances the source was about 3.5 cm below the base of the electroscope. In all the experiments the decay of the source and the varying density of the air in the electroscope were corrected for by making frequent measurements under standard conditions of absorption. In general the mean of ten independent observations was obtained for each point plotted on an absorption curve. Adopting this routine it was not found necessary to employ a magnetic field to separate β- and γ- ray effects, even in the case of radium C where the latter effect is very pronounced, and indeed it is the writer's opinion that the avoidance of such a method is much to be preferred whenever that is possible, for it is difficult to estimate the effect of the stray magnetic field on the γ-ray ionization in the electroscope in any of the simpler experimental arrangements that have been used.

Experimental Results. Part I

Radium E. Madgwick[8] has determined the upper limit of the continuous spectrum of the β-particles of radium E as 1.07×10^6 electron volts energy. This is the datum with which our range measurements are to be combined.

[7] Gurney, Proc. Roy. Soc. **112A,** 380 (1926).
[8] Madgwick, Proc. Camb. Phil. Soc. **23,** 982 (1927).
[9] Gurney, Proc. Roy. Soc. **109A,** 540 (1925).

Absorption methods have, in fact, already been applied to the determination of the range in this case. In 1912 Gray [10] first pointed out[11] the phenomenon of an end point to the β-particle absorption with a source of radium E. His measurements lead to an effective mass range between 0.45 and 0.49 gm/cm^2 of paper. Douglas[12] extended the measurements to other absorbing media and gave 0.474 and 0.460 gm/cm^2 for the effective ranges in paper and aluminum respectively. But the sources employed were weak and the logarithmic method of extrapolation was used to fix the range. It was thought worthwhile to repeat the determinations[13] with a stronger source employing the method of simple extrapolation of Chalmers. This method has been adopted as standard throughout.

The results are shown in Fig. 1. They refer to a source of radium D, E and F in equilibrium[14] deposited by evaporation on a small platinum dish. The

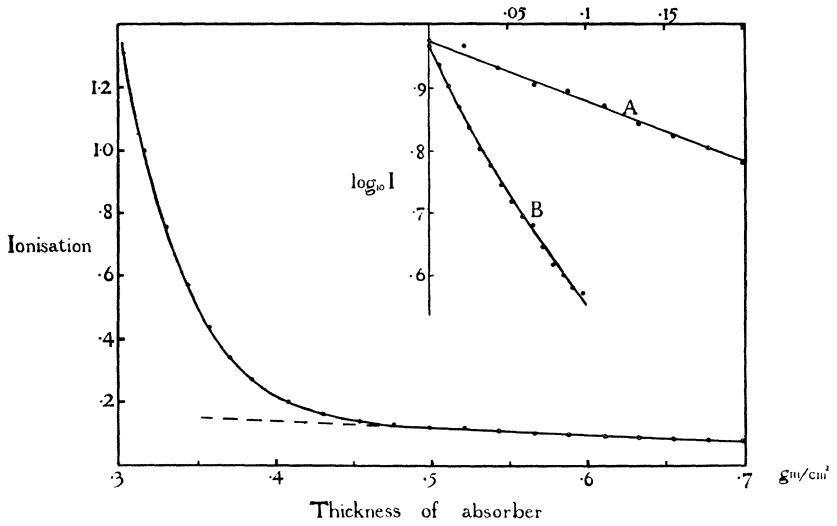

Fig. 1. Radium E.

weight of deposit, more than 1 cm^2 in extent, was a few milligrams only. Unwhitened paper was used as absorber and the maximum effective mass range in this medium may be taken as 0.475 ± 0.005 gm/cm^2.

A simple experiment was also made upon the radiation unabsorbed by this thickness of material. The source was covered with sheets of paper repre-

[10] Gray, Proc. Roy. Soc. **87A,** 487 (1912); Trans. Roy. Soc. Canada **16 III,** 125 (1922).

[11] The end point is clearly shown in absorption curves published by Schmidt in 1907 (Phys. Zeits. **8,** 362 (1907)).

[12] Douglas, Trans. Roy. Soc. Canada, **16 III,** 113 (1922).

[13] Absorption measurements by Aston (Proc. Camb. Phil. Soc. **23,** 935, (1927)) and by Fournier and Guillot (Comptes rendus **189,** 1079 (1929)) also have reference to a region including the β-particle end point but, being concerned chiefly with the weak γ-radiation, permit of no accurate range values being drawn from them.

[14] The writer wishes to thank Dr. C. F. Burnam of the Kelly Hospital, Baltimore, for a supply of old radon tubes from which this material was extracted.

senting (together with the air gap and the base of the electroscope) 0.499 gm/cm^2 of absorber. Aluminum foils were then added and the further progress of the absorption followed. The curve *B*, Fig. 1, exhibits these results, the logarithm of the corrected ionization being plotted against the foil thickness. Curve *A* represents the parallel case where the absorption was in paper throughout. A mass absorption coefficient of 2.3 cm^2/gm is a sufficiently good approximation here; the initial absorption in aluminum, however, is roughly five times as great, for equal mass of absorber. This is what we should expect if the absorption were chiefly photoelectric, and the numerical values also suggest that the effective radiation is for the most part the very soft component, probably the *LX*-radiation of radium D, for which a mass absorption coefficient of 16.5 cm^2/gm in aluminum is accepted as correct.[15] The smaller value (11.3 cm^2/gm) found with the present arrangement is to be attributed largely to the fact that the first 0.5 gm/cm^2 of paper has already reduced this soft component to about a quarter of its original intensity, so that the influence of the less intense though harder components is no longer negligible. It is of interest to record that the last point on the curve *B*, representing the smallest ionization current involved in this series of measurements, yet represents a current about forty times as great as the natural leak of the electroscope effective at the time.

Radium C. The primary β-particles of this body comprise a continuous spectrum of energies having a sharp upper limit at 3.15×10^6 electron volts (Gurney[9]). On the other hand no data have hitherto been available concerning the maximum effective range of these particles as determined in the present type of experiment. The problem here presented is considerably more difficult than in the case of radium E, on account of the very great intensity of the γ-radiation from radium C and of the rapid decay of this body. The latter difficulty may be overcome by using a radon tube as a β-particle source, although this procedure increases the γ-ray effect, by adding the γ-rays of radium B to those of its subsequent product. Moreover the radiation thus added is in general much less penetrating than the latter, and it is the softer components of the radiation which constitute the greater source of error. An attempt was made to minimise this effect in the arrangement finally adopted.

A small glass bulb, about 3 mm in diameter, originally containing about 800 equivalent milligrams of radon was employed as the source of β-particles at the stage when its activity had fallen to a few thousandths of its initial value.[16] In this way the points of Fig. 2 were obtained. The absorbing material consisted of aluminum to the extent of 1.012 gm/cm^2 placed directly over the source, with sheets of paper for the remainder. By using the aluminum it was hoped to cut down the softer components of the γ-rays to reasonable proportions whilst the use of paper for the rest of the absorption was governed by considerations of ease of manipulation and of the sharper type of absorption

[15] Rutherford and Richardson, Phil. Mag. **26,** 324 (1913). Curie and Fournier, Comptes rendus **176,** 1301 (1923).

[16] For this material also the writer is indebted to Dr. Burnam.

limit thereby obtained. Moreover Chalmers failed to find any appreciable difference between the mass ranges of the thorium C β-particles in paper and aluminum. The equivalence of these materials in this respect has been assumed in the present experiments. The walls of the radon tube were not negligibly thin and an estimate of their thickness was made in two ways, by direct weighing, and by a subsequent absorption experiment after the lapse of a few weeks, when the radium E β-particles were responsible for the greater proportion of the ionization as measured through small thicknesses.[17] The difference

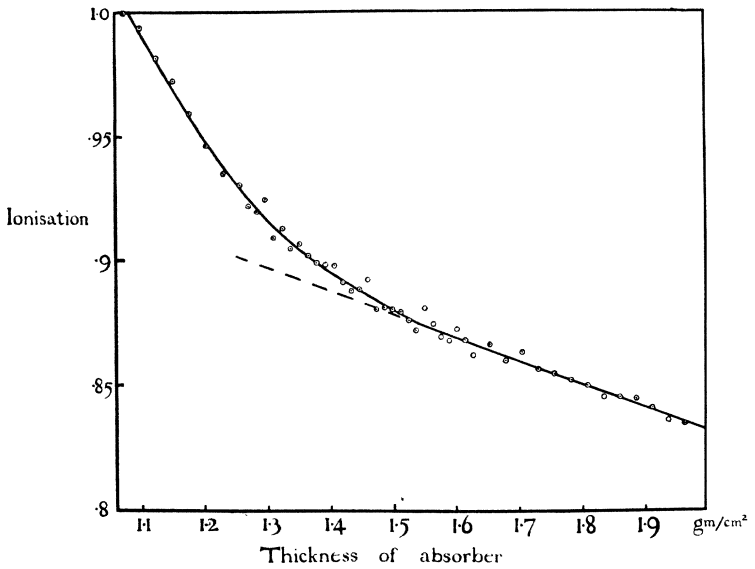

Fig. 2. Radium C.

between the apparent maximum effective range of these particles as determined with this source and in the direct experiments on radium E described above was attributed to absorption in the glass walls of the bulb. Both methods suggested an equivalent thickness of glass of 0.03 gm/cm^2. So corrected the maximum effective mass range of the primary β-particles of radium C in aluminum or paper may be given as 1.54 ± 0.02 gm/cm^2, as indicated in the figure.

The range-energy relation. The data which are to be employed in constructing our calibration curve are given in Table I.

TABLE I. *Data used in constructing calibration curve.*

Source of β particles	Maximum energy electron volts $\times 10^{-6}$	Maximum effective mass range gm/cm^2
RaE	1.07	0.475
ThC	2.18	0.98
RaC	3.15	1.54

[17] The final decay of the emanation originally contained in the bulb is responsible for the production of about 0.3 equivalent milligrams of radium D, E, and F.

Within experimental error this material is consistent with a linear relation such as that given by Eq. (1) and is best represented by the straight line

$$R = 0.511E - 0.091 \quad (2)$$

which, by analogy with the relations of Varder and Madgwick, may probably be regarded as valid for values of E greater than 0.7 (million electron volts). It may be remarked that the present straight line occupies a position intermediate between those of Varder and Madgwick—and it may be pointed out that the results of Eddy occupy a similar position in the region of smaller energies where the curve is no longer linear. But the intention of any very close comparison between the present results and results having reference to particles of a single velocity has already been disclaimed, so that no primary importance is attached to this apparent agreement. Moreover, not only was the work of Eddy concerned with particles of a single velocity, but it was carried out by the method of electrical counting, providing a further reason for caution in its comparison with the results of ionization measurements.

Experimental Results. Part II

Mesothorium 2. The β-particles of mesothorium 2 have been studied by Yovanovitch and d'Espine[18] by the direct deviation method of magnetic spectroscopy. These authors suggest that the high energy limit of the continuous spectrum occurs in the region of 1.6 million electron volts energy. It is not unreasonable to suppose, from a knowledge of the general characteristics of the method, however, that this represents merely a lower limit to the maximum energy of the particles.[19]

The difficulties in the way of absorption measurements with mesothorium 2 are similar to those obtaining with radium C: there are γ-rays of considerable intensity and the pure substance is of fairly rapid decay. The broad scheme of the experiments, therefore, was first to determine an absorption curve in full detail with a source of mesothorium 1 and 2 in equilibrium and then to make confirmatory tests with a small number of selected thicknesses of absorber and a source of pure mesothorium 2, in order to be certain that the main features of the former curve, in the region of the β-particle end point at least, were due to the latter body alone.

A solution of mesothorium 1, freed from radiothorium by repeated precipitation with iron, and from a large fraction of the ammonium chloride which accumulates as a result of such operations, was allowed to stand so that the thorium X should decay. Being neutralized the solution was electrolysed with platinum anode and silver cathode at a temperature of about 90°C.[20]

[18] Yovanovitch and d'Espine, J. de Physique. **8,** 276 (1927).

[19] For a constant value of the field the dispersion decreases rapidly as the energy of the particles increases, and this, together with the peculiarities of photographic registration, must necessarily introduce considerable distortion. Both in the case of the primary β-particles of radium C and for those of radium E this method has given too low a value for the maximum energy (2.74×10^6 electron volts in the former case and 0.94×10^6 in the latter).

[20] Meitner, Phys. Zeits. **12,** 1097 (1911).

Mesothorium 1 and 2 were obtained together, the latter in about 90 percent of its equilibrium amount. The silver plate (about 2 cm² in area), carrying the deposit on one surface only, was enclosed in an airtight container to prevent the diffusion of emanation. A thin sheet of mica was employed for the upper face of the vessel which fitted neatly in the whole cut in the electroscope slide already described. Since originally the mesothorium was extracted directly from monazite, radium was known to be present as "impurity." But the duration of the previous heat treatment of the solution, and of the electrolysis, was such that immediately after its preparation the β-particle source could be regarded as free from all contamination except by radium element itself. Provided, therefore, that measurements were carried out within the

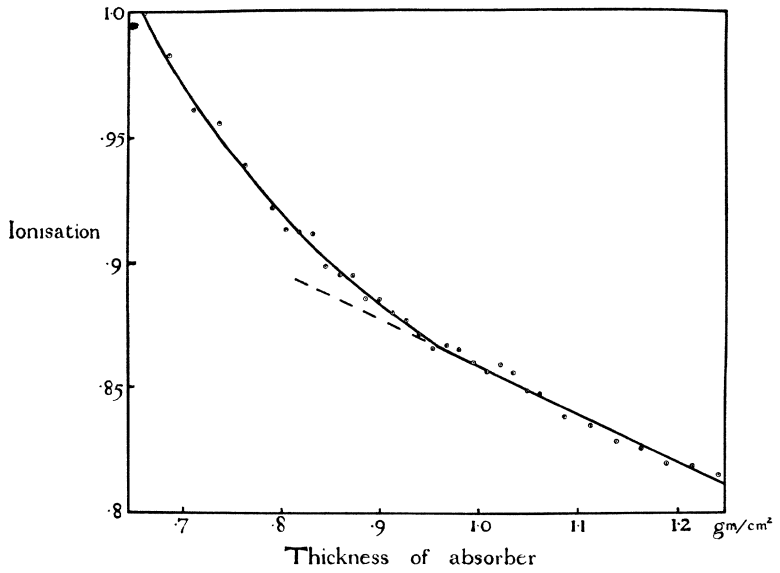

Fig. 3. Mesothorium 2.

first 24 hours after the source was prepared they were unlikely to be seriously affected by the growing β-particle activity arising from the active deposit of radium.

The results of measurements with this source are shown in Fig. 3, the last measurement being completed 22 1/2 hours after the source was obtained on the plate. As in the experiment on radium C roughly the first two-thirds of the absorption was in aluminum—a thickness of 0.646 gm/cm² of this metal being succeeded by sheets of paper. In an attempt to detect any possible effect of the gradual building up of radium C in the source during the period of observation measurements were made in the following order, namely through

44, 40, ... ,0,
11, 15, ... ,27,
2, 6, ... ,42,
29, 25, ... ,13

sheets of paper, in turn. This sequence was, of course, interrupted periodically to permit of measurements with a standard absorber in place. It will be seen from the figure that no such effect as was sought was observed.[21] In this way the β-particle end point was fixed at 0.955 ± 0.015 gm/cm^2 and it only remained to confirm its identification with the maximum effective mass range of the primary β-particles of mesothorium 2 by an independent experiment.

A source of mesothorium 2 was prepared in the usual manner by precipitation with a trace of iron from a solution containing mesothorium 1 and 2 in equilibrium. Three thicknesses of absorber, corresponding respectively to the first and last points in Fig. 3 and to the point nearest the absorption discontinuity, were chosen and two sets of measurements made, separated in time by about 3 1/2 hours. Table II contains the results.

TABLE II. Results

Thickness of absorber	Relative ionizations	
gm/cm^2	(1)	(2)
0.660	1.000	1.000
0.952	0.867	0.870
1.241	0.825	0.824

The decay of activity, corresponding to a half period of 6.4 hours, showed that the source was sufficiently pure for the test to be conclusive, and the figures given, when compared with the values 1.000, 0.868, 0.812 read directly from the curve, establish the identity which was in question. The exact agreement in the second instance is probably fortuitous but it is obvious first of all that no appreciable amount of unrecognized radioactive impurity was present in the orginal source, and secondly that any γ-rays emitted by mesothorium 1 were of little or no consequence in the measurements made with that source.

Inserting the value 0.955 gm/cm^2 for R in Eq. (2) we have $E = 2.05$ million electron volts and consequently, as the result of these experiments, may adopt this as the most probable value for the maximum energy of the primary β-particles of mesothorium 2. As was pointed out earlier in the discussion, a value considerably in excess of that given by Yovanovitch and d'Espine was almost to be expected.

Finally, in addition to acknowledgements already made, the writer wishes to record his appreciation of help received from the Rumford Fund of the American Academy of Arts and Sciences, a grant from which made possible the purchase of the mesothorium employed in these researches.

[21] Further measurements were made on the source at three different absorptions within the range of the figure after 4 and 10 days, respectively. Also a rough absorption curve extending over this range was determined for a source of radium B+C in equilibrium. All the measurements could be explained simply by assuming that 8.7 percent of the ionization through 0.66 gm/cm^2 of aluminum at the end of 4 days, and 17.0 percent at the end of 10 days, was due to the β and γ-rays of radium B+C which had grown in the interim.