



LXXVI. The analysis of the gamma rays from radium B and radium C

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To cite this article: Professor E. Rutherford F.R.S. & H. Richardson B.Sc. (1913) LXXVI. The analysis of the gamma rays from radium B and radium C , Philosophical Magazine, 25:149, 722-734, DOI: [10.1080/14786440508637389](https://doi.org/10.1080/14786440508637389)

To link to this article: <http://dx.doi.org/10.1080/14786440508637389>



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an illumination of $\frac{1}{800}$ metre-candle the maximum visibility is at $466 \mu\mu$.

Three hours was not long enough to obtain regular luminosity curves from one observer. Hence, although the mean was certainly accurate for the average eye, the individual curves were only approximate for the individual eyes.

All the observers tested had normal colour vision. Two had the shape and position of the "strong" and "weak" luminosity curves exactly the same. This is supposed to denote no rod vision. The women students tested, of whom there were nine, showed no systematic difference from the men.

LXXVI. *The Analysis of the Gamma Rays from Radium B and Radium C.* By Professor E. RUTHERFORD, F.R.S., and H. RICHARDSON, B.Sc., Graduate Scholar, University of Manchester*.

IT has long been recognized that the penetrating γ rays emitted by a γ ray salt were complex in character. The examination of the radiation has been made by the electric method in two ways :

(1) by measuring the absorption of the γ rays in different materials over a wide range of thickness ;

(2) by an examination of the absorption of the secondary and scattered γ rays which appear when γ rays traverse matter.

Initial experiments on the absorption of the γ rays of radium by different materials were made by Rutherford† and McClelland‡. These were extended by later investigations of Eve§, Tuomikoski||, Wigger¶, and S. J. Allan**. The experiments showed that the absorption of the γ rays in lead rapidly decreased for the first two centimetres of thickness, but became approximately exponential for greater thicknesses. The whole question was re-examined with great detail and thoroughness by Mr. and Mrs. Soddy and A. S. Russell††, who determined the absorption of the

* Communicated by the Authors.

† Rutherford, *Phys. Zeits.* iii. p. 517 (1902).

‡ McClelland, *Phil. Mag.* viii. p. 67 (1904).

§ Eve, *Phil. Mag.* xvi. p. 224 (1908) ; xviii. p. 275 (1909).

|| Tuomikoski, *Phys. Zeit.* x. p. 372 (1909).

¶ Wigger, *Jahrb. Radioakt.* ii. p. 430 (1905).

** Allan, *Phys. Rev.* xxxiv. p. 311 (1912).

†† Soddy and Russell, *Phil. Mag.* xviii. p. 620 (1909) ; Mr. and Mrs. Soddy and Russell, *Phil. Mag.* xix. p. 725 (1910) ; Russell, *Proc. Roy. Soc. A.* lxxxvi. p. 240 (1911).

γ rays in a number of materials and investigated the effect of different arrangements on the apparent value of the absorption coefficient. They found that the absorption of the γ rays by lead was accurately exponential for a very wide thickness, viz. from 2 to 22 cm., and concluded that over this range of thickness the γ rays were to be considered as homogeneous in type. These results were confirmed and extended by Russell, who showed that the γ rays from radium were absorbed by mercury over a range of thickness from 1 to 22.5 cm. strictly according to an exponential law. Over this range of thickness the intensity of the ionization current in the testing vessel, which served as a measure of the intensity of the γ rays, varied in the ratio of 360,000 to 1.

From an examination of the quality of the secondary γ rays set up in different materials by the γ rays, Kleeman* considered that the primary γ rays from radium could be divided into three types of widely different penetrating power. In similar experiments Madsen† found evidence of two types. On the other hand, Florance‡, who examined the character and intensity of the secondary and scattered γ rays from radiations of different materials at various angles for the primary beam, concluded that the γ rays were very complex in character and that no definite evidence could be obtained by this method of the existence of distinct groups of primary rays.

It was at first supposed that the penetrating γ rays emitted by a radium salt arose entirely from the transformation of its product radium C. Moseley and Makower§, however, showed in 1912 that radium B also emitted γ rays, although weak in intensity and penetrating power compared with those emitted from radium C. Even if radium C emitted only one type of radiation, it was clear from this result that the γ rays from a radium salt must contain at least two types of γ rays. In the meantime, the work of Barkla on X rays had shown conclusively that each of the elements emitted one or more types of characteristic or fluorescent radiations when X rays of suitable penetrating power traversed them. In some of the elements two types of characteristic radiations were observed. J. A. Gray|| extended these results to γ rays, for he found that the γ rays emitted by radium E were able to excite the characteristic

* Kleeman, *Phil. Mag.* xv. p. 638 (1908).

† Madsen, *Phil. Mag.* xvii. p. 423 (1909).

‡ Florance, *Phil. Mag.* xx. p. 921 (1910).

§ Moseley and Makower, *Phil. Mag.* xxiii. p. 312 (1912).

|| Gray, *Proc. Roy. Soc. A.* lxxxvii. p. 489 (1912).

radiations of certain elements. His results showed, as had long been supposed, that the γ rays were identical in general properties with X rays and possessed the fundamental property of exciting characteristic γ rays. In a paper entitled "The origin of β and γ rays from radioactive substances," Rutherford * put forward the view that the γ rays from radioactive substances were to be regarded as the characteristic radiations of the respective elements set up by the escape of α or β rays from them. On this basis an explanation was given of the numerous groups of homogeneous β rays emitted by radium B and C, and their connexion with the γ rays was outlined. If this were the case, each type of characteristic radiation emitted should be absorbed according to an exponential law by an absorbing substance of low atomic weight like aluminium.

The present experiments were undertaken with a view of testing this hypothesis. It will be seen that this analysis brings out that the γ radiation from radium B consists of at least two and possibly of three distinct types, and from radium C of a single type, probably corresponding in penetrating power to the characteristic radiations to be expected from elements of their atomic weight.

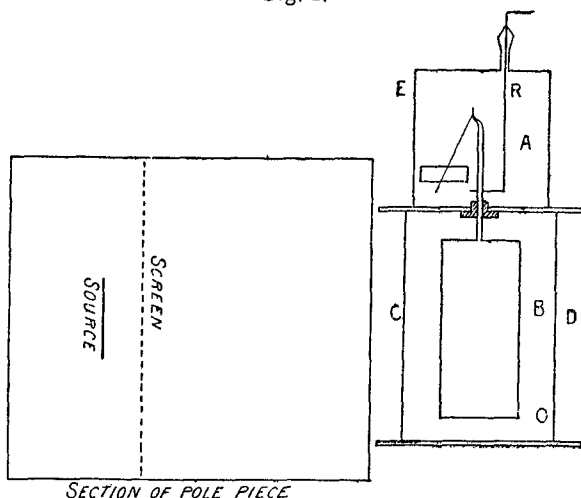
Experimental Arrangement.

In the preliminary investigations the source of γ rays consisted of about 50 millicuries of radium emanation enclosed in an α ray tube with thin walls. The thickness of glass was equal in stopping power for α rays to about 2 cm. of air. In order to get rid of the effect of the primary β rays, the source was placed between the pole-pieces of a powerful electromagnet. The γ rays passed horizontally into a thin-walled ionization vessel ($3 \times 5 \times 7$ cm.) CD, fig. 1, placed at the side of the electromagnet, in which the ionization was measured in the usual way by means of an exhausted electro-scope E of dimensions $5 \times 5 \times 5$ cm. The ionization produced by the γ rays in the electro-scope E was negligibly small compared with that produced in the ionization vessel CD. The sides of the vessel CD, through which the γ rays passed, consisted of thin sheets of mica equivalent in stopping-power for the α particles to about 2 cm. of air. This was done in order to increase relatively the ionization due to the softer γ rays that might be present. The inside of the vessel was lined throughout with aluminium. In most experiments the pole-pieces of the electromagnet were about 2 cm. apart.

* Rutherford, Phil. Mag. Oct. 1912.

The source of γ rays was in all cases more than 9 cm. distant from the vessel CD. The absorbing metal screens were placed between the pole-pieces of the magnet close to the source. The β rays escaping from the absorbing material

Fig. 1.



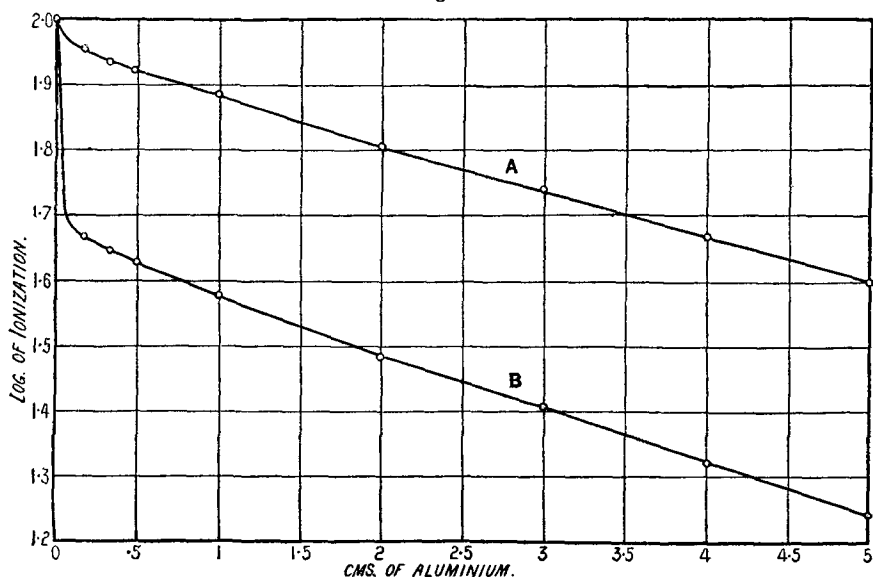
were removed by the magnetic field before entering the ionization vessel. The γ rays which entered the ionization vessel passed nearly normally through the absorbing screens, so that no correction for obliquity was necessary in determining the absorption coefficient of the rays.

Preliminary experiments showed that if the ionization vessel were filled with air, the effect of the penetrating γ rays from radium C was large compared with that due to the softer types of radiation that were present. When air was used, the reduction of the ionization by using absorbing screens of aluminium of different thicknesses is shown in fig. 2 A (p. 726), where the logarithms of the ionization are plotted as ordinates and the thickness of aluminium as abscissæ. It will be observed that in this case there is a rapid drop of the ionization corresponding to about 10 per cent. of the whole effect.

In order to bring out prominently the effect of the softer types of γ radiation present, the vapour of methyl iodide was used instead of air. As it was impossible to exhaust the ionization vessel on account of the thin mica covering of

the sides, the vapour was introduced by means of a slow current of hydrogen which bubbled through the liquid. Under these conditions, the ionization vessel was filled with a mixture of hydrogen and vapour of methyl iodide at atmospheric pressure. The ionization in the vessel was almost entirely due to the methyl iodide, and for the hard γ rays from radium C was usually about three times as great as for air at atmospheric pressure. Some difficulty was at first experienced on account of the absorption of the vapour by the wax used in fixing the mica plates and in sealing the

Fig. 2.



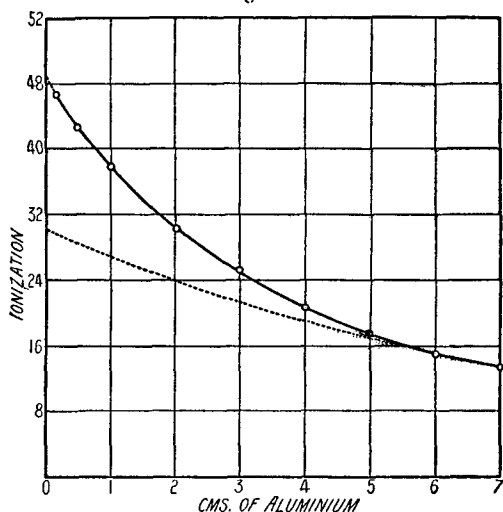
various parts of the vessel. This effect was got rid of by reducing the amount of wax to a minimum, and covering it with a non-absorbing layer of gum. This was kindly prepared for us by Dr. Lapworth, F.R.S., by special treatment of the ordinary gum sold commercially. By this method the absorption of the vapour was so much reduced that measurements extending over several hours could be made with certainty and accuracy.

The absorption curve using methyl iodide instead of air is shown in fig. 2 B. An absorbing screen of 1.6 mm. of aluminium reduced the ionization to about 50 per cent. It will also be seen that the latter part of the absorption curves A and B are not linear and are not parallel to one another.

This will be shown to be due to the fact that two penetrating types of radiation are present, the relative ionizations of which differ in air and in methyl iodide.

After passing through about 6 cm. of air, the absorption curves, both for air and methyl iodide, became exponential with a value of the absorption coefficient $\mu=0.115$, or $\mu/D=0.0424$, where D is the density. This is practically identical with the absorption coefficient found by Russell and Soddy for the γ rays from radium C after passing through 2 cm. of lead. The absorption curve of the γ rays for thicknesses of aluminium between .05 and 7 cm. is shown in fig. 3, where the ionization itself is plotted as ordinates.

Fig. 3.

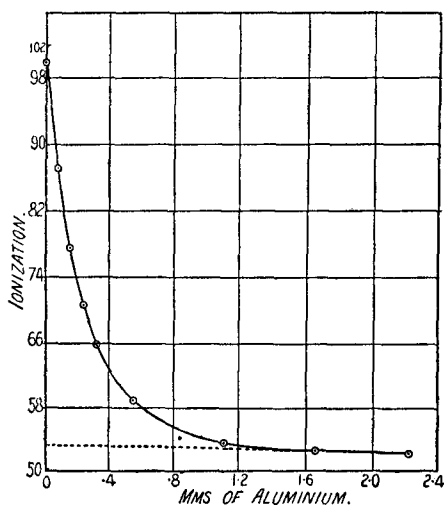


After 6 cm. of aluminium the curve is exponential with a value of $\mu=.115$. It will be shown later that the absorption curve in aluminium of the γ rays from radium C is practically exponential from the beginning with a value of $\mu=0.115$. Consequently, if the curve is produced backwards from a thickness of 6 cm. corresponding to radiations for which $\mu=.115$, it gives the ionization due to the γ rays from radium C alone. This is shown in the dotted curve fig. 3. If the difference between the ordinates of these curves be plotted, it is found to be an exponential curve with a value of $\mu=0.51$ in aluminium. This radiation is undoubtedly due to radium B. A similar result was obtained when air was used instead of methyl iodide, but the effect due to this radiation is relatively smaller compared with that from radium C.

Analysis of the soft radiation.

In order to find the absorption coefficient of the very soft radiation, which is shown so prominently in fig. 2 B, sheets of aluminium $\cdot 042$ and $\cdot 084$ mm. thick were used. The curve obtained is shown in fig. 4. In deducing the ionization due to these soft rays, it is necessary to subtract the

Fig. 4.
Absorption of γ rays from radium B+C. Initial portion
of curve $\lambda = 40$.



ionization due to the harder rays. This can easily be done since the absorption of the harder rays over the thickness of 1.51 mm. of aluminium is practically linear. The difference curve is exponential and gives an absorption coefficient in aluminium $\mu = 40$. The source of γ rays in this case was about 15 cm. from the ionization chamber. In these experiments, the pole-pieces were covered with thick cardboard in order to reduce the excitation of secondary γ rays to a minimum. With the bare pole-pieces close together, the radiation entering the ionization vessel was distinctly softer with a value of μ between 40 and 45.

Attempts to detect very soft γ radiation.

Special experiments were made to examine whether radium B or radium C emitted any very soft types of γ radiation in addition to the type already discussed for which $\mu = 40$. In the experiments with the emanation tube, the γ rays before entering the ionization vessel passed through

absorbing material equivalent in amount to about 14 cm. of air. Any very soft type of γ radiation which might be present would be largely absorbed in traversing this material. It is essential, however, in the experiments to use sufficient absorbing material to stop completely the α rays from radium C, which have a range of 7 cm. in air. Since it is well known that, for equal masses, X rays pass with much less absorption through elements of small atomic weight, arrangements were made to absorb the α rays mainly by hydrogen and carbon. The source of radiation was the active deposit of radium deposited from the emanation on both sides of a very thin mica plate. This was placed in a brass vessel which was closed at one end by a thin mica plate equal in stopping power to 1.5 cm. of air. This mica plate also formed one side of the ionization chamber, shown in fig. 1. The active matter was deposited on mica to avoid the excitation of detectable characteristic X rays. For a similar reason, the inside of the brass vessel was lined entirely with thick cardboard. A continuous current of hydrogen was sent through the brass vessel. Sheets of india-paper were interposed in the path of the rays of just sufficient thickness to stop entirely the α rays. The ionization in the detecting vessel filled with methyl iodide was then carefully examined when thin aluminium screens were introduced. It was found that the ionization at first decreased more rapidly than corresponded to an exponential law of absorption of the radiation for which $\mu=40$ in aluminium. This initial drop could be accounted for by assuming the presence of a very soft γ radiation for which $\mu=230$ about in aluminium. Since the ionization in methyl iodide due to this radiation corresponded to only 10 per cent. of the total effect, the initial slope of the curve could not be determined with much certainty. It is difficult to decide whether this soft radiation has an independent existence, or whether it is due to an initial drop in the absorption curve of the radiation corresponding to $\mu=40$. It will be seen later that a rapid initial drop of the absorption curve is always observed when lead is used as an absorbing material. It is possible that aluminium may show a similar effect for a comparatively soft radiation.

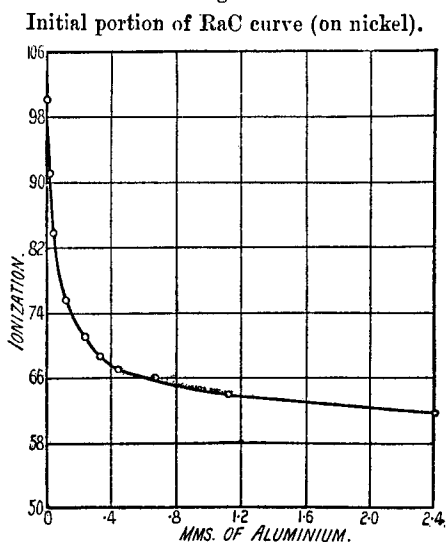
From the rate of decay of this very soft radiation it was clear that it arose from radium B. It was always proportional in amount to the radiation $\mu=40$. It should be pointed out that decay of the active deposit measured under these experimental conditions is initially far more rapid than that calculated by Moseley and Makower (*loc. cit.*). This is

due to the fact that radium B initially provides about 70 per cent. of the total ionization due to radium B + C instead of the 12 per cent. observed by Moseley and Makower under their experimental conditions with air in the testing vessel.

Analysis of the rays from radium C.

Experiments were next made to settle which of the types of γ radiation were to be ascribed to radium B and which to radium C. It is not convenient to use radium B itself as a source, as there is a rapid growth of radium C from it. By von Lerch's method, however, it is possible to obtain a strong deposit of pure radium C on a metal plate placed in an acid solution of the active deposit radium B + C. Since radium C loses half its activity in 19.7 minutes, a large number of experiments were necessary to determine with accuracy the absorption curves for the γ rays emitted from it. The type of curve obtained with radium C on nickel is shown in fig. 5.

Fig. 5.



It is seen that a very soft γ radiation is present, but after passing through two millimetres of aluminium the absorption is exponential with a value of $\mu = .115$. This soft radiation was much more readily absorbed than the γ radiation, $\mu = 40$, obtained when the emanation was used as a source. It thus seemed probable that this soft radiation was excited in the nickel by the radiation from the radium C deposited on it.

This conclusion was confirmed by using a deposit of radium C on silver instead of nickel. A sufficiently active preparation was obtained by using the method outlined by v. Hevesy* of placing a silver plate in a silver nitrate solution containing the radium B+C in solution. With the silver plate, no appreciable amount of soft radiation was observed, but the absorption curve in aluminium was exponential from the beginning with a value of $\mu = \cdot 115$.

There appears to be no doubt that this soft radiation from nickel consists mainly of the "characteristic X radiation" of nickel excited probably by the α rays, although some rays of a more penetrating type were also present. It was observed that the amount of this soft radiation varied markedly with the orientation of the nickel plate, and was much less when the plate was parallel to the face of the pole-pieces than when it was perpendicular. Chadwick† first showed that γ rays were excited by α rays traversing different materials. The method employed by him, however, was not suitable for the detection of such a soft type of γ radiation. It is intended to make further experiments by the method outlined in this paper to examine whether the characteristic radiations of all elements are excited under similar conditions.

A number of experiments were made to test whether radium C itself emitted more than one type of radiation. For this purpose, the absorption curve in aluminium was very carefully examined over a thickness of aluminium from 0.2 to 4 cm. Over this range the absorption of the γ rays appeared to be exponential within the margin of possible experimental error with a value of $\mu = \cdot 115$. No evidence was obtained that a radiation for which $\mu = \cdot 5$ about was present. At the same time, it should be pointed out that it would be very difficult by direct measurement to detect with certainty the presence of a few per cent. of this radiation mixed with the more penetrating type for which $\mu = \cdot 115$.

Absorption of the γ rays by Lead.

In the experiments so far described aluminium has been used as an absorbing material. Since it is well known that the absorption of γ rays in a heavy element like lead is abnormal, it was thought desirable to determine the absorption curves for this material.

The curve obtained for pure radium C on nickel is shown in fig. 6, Curve B. The soft radiation from the nickel was first

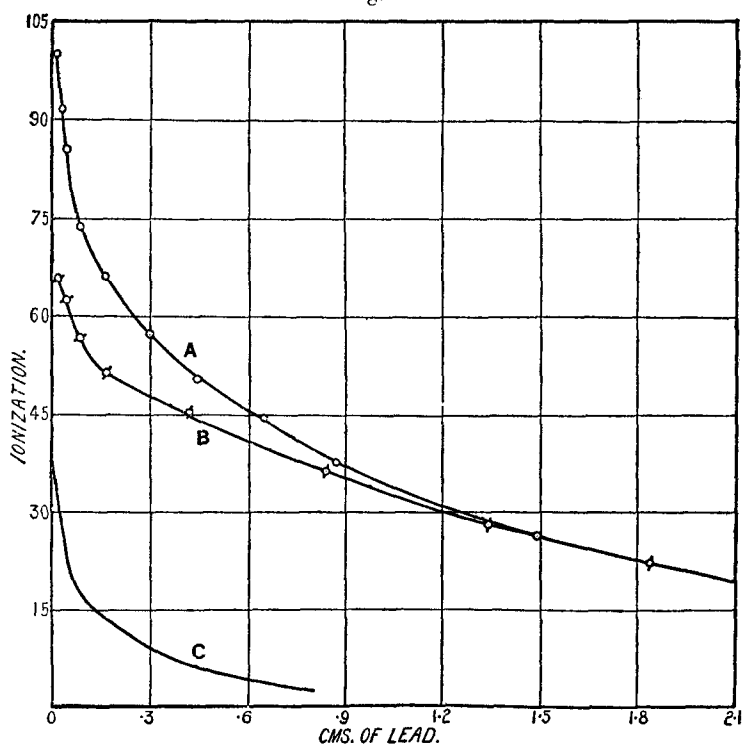
* Hevesy, Phil. Mag. xxiii. p. 628 (1912).

† Chadwick, Phil. Mag. xxv. p. 193 (1913).

cut out by a thin sheet of lead. The ionization initially fell more rapidly than was to be expected for an exponential law of absorption, but after traversing 1 cm. of lead the absorption of the rays in lead became accurately exponential with a value of $\mu=0.50$.

The absorption of the γ rays, using the emanation tube as a source, was also determined. In this case, before beginning the measurements, a thickness of lead was used sufficient to absorb completely the γ rays for which $\mu=40$ in aluminium. The curve obtained is shown in fig. 6, Curve A. After a thickness of 1.5 cm. of lead the absorption became exponential with a value of $\mu=0.50$. Since the radiation $\mu=0.50$ comes entirely from radium C, the curve B (fig. 6) represents the

Fig. 6.



part of the γ radiation due to radium C alone. The difference curve C given in fig. 6 shows the absorption in lead of the γ rays from radium B. It is seen that the curve shows a rapid initial drop, which is far more marked than in the case of radium C. The value of the absorption

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appears to vary from $\mu=11$ to $\mu=2.8$ about, but it is difficult by this method to fix the values with much accuracy. These results are in general agreement with the experiments of Moseley and Makower, who showed that the absorption coefficient of the γ rays from radium B for lead varied between $\mu=6$ and $\mu=4$ about.

It is thus seen that the two types of γ radiation which are exponentially absorbed by aluminium both show irregular absorption curves when lead is used as absorbing material. It is intended in a later paper to discuss in more detail the relative absorption curves in lead and aluminium, and their bearing on the question of the homogeneity of the radiations concerned.

General discussion of results.

The results of the analysis of the γ radiation from radium B and radium C are included in the following table. The density D of the aluminium was taken as 2.71.

	Absorption coefficient in aluminium.	Mass absorption coefficient in aluminium.	Absorption coefficient in lead.
Radium B.....	$\left\{ \begin{array}{l} 230 ? \\ 40 \text{ (cm.)}^{-1} \\ 0.51 \text{ ,,} \end{array} \right.$	$\left\{ \begin{array}{l} \cdot \cdot \cdot \cdot \cdot \\ 14.7 \text{ (cm.)}^{-1} \\ 0.188 \text{ ,,} \end{array} \right.$	varying from 11 to 2.8 (cm.) ⁻¹ .
Radium C.....	0.115 ,,	0.0424 ,,	0.50 (cm.) ⁻¹ after traversing 1 cm. of lead.

It is seen that radium C emits essentially only one type of γ radiation, while radium B certainly emits two, and possibly three. In a previous paper, one of us pointed out that the rays from radium C correspond in penetrating power to the "characteristic X radiation" of the K series to be expected from an element of atomic weight 214. The soft radiation from radium B ($\mu/D=14.7$) undoubtedly corresponds closely in penetrating power to the radiation of the L series to be expected from an element of atomic weight 214. For example, Chapman * found that the value of μ/D in aluminium for the characteristic X radiation from bismuth (atomic weight 208.5) was 16.1, while the value of μ/D for thorium (atomic weight 232) was 8.0. It seems reasonable to suppose that the second type of γ radiation from radium B ($\mu/D=1.88$) also corresponds to a type of characteristic radiation from heavy elements which has not so far been

* Chapman, Proc. Roy. Soc. A. lxxxvi. p. 439 (1912).

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observed with X rays on account of the difficulty of obtaining X rays of sufficient penetrating power to excite it. It is of interest to note that Chadwick and Russell* have found that three types of radiation were excited by the α rays in ionium. Two of these types, $\mu/D=8.35$ and $\mu/D=0.15$, appear to be analogous to the two types of radiation from radium B, but it is doubtful whether the very soft type ($\mu/D=400$) observed by them in ionium is given out by radium B or radium C, although, as we have seen, careful experiments have been made to test this point. There appears to be little room for doubt that the γ rays at any rate from radium B+C are to be regarded as types of characteristic radiation from these elements. It is of interest to note that the energy of the soft γ radiation from radium B is very small compared with the energy of the more penetrating types of γ radiation from radium B and radium C. Chadwick and Russell, on the other hand, found that the soft types of γ rays excited by the α rays in ionium were relatively far more prominent. The bearing of these results on the general theory of the connexion between β and γ rays which led to these experiments will be discussed in detail in a later paper.

Summary.

The γ rays from radium B consist of at least two distinct groups, each of which is absorbed exponentially in aluminium with absorption coefficients $\mu=40$ and $\mu=0.51$ (cm.)⁻¹ respectively. The first group of γ rays is much less penetrating than the X rays excited in an ordinary focus-tube. The γ rays from radium C consist essentially of one type which are absorbed exponentially in aluminium with a value $\mu=0.115$. No evidence was obtained of the emission from radium C of the groups of radiation observed from radium B. The absorption of the rays by lead does not follow an exponential law.

The general evidence indicates that these radiations are to be regarded as types of characteristic radiation from the elements in question analogous to the characteristic X radiations excited in elements by X rays.

Experiments are now in progress to analyse by the methods outlined in this paper the γ radiations from all the radioactive elements which emit β and γ rays. The analysis of the γ radiation from α ray products is being undertaken by Chadwick and Russell in this Laboratory.

University of Manchester,
March 6, 1913.

* Chadwick and Russell, Proc. Roy. Soc. A. lxxxviii. p. 217 (1913).