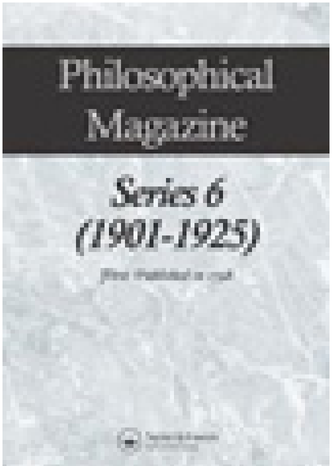

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XLI. The mass and velocity of the α particles expelled from radium and actinium

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XLI. *The Mass and Velocity of the α particles expelled from Radium and Actinium.*

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[Plate V.]

THE present paper contains an account of investigations that have been made to determine, as accurately as possible, the mass and velocity of the α particles expelled from some of the products of radium and actinium. At the present stage of our knowledge of radioactivity, such measurements have an important theoretical value in throwing light on the following questions:—

1. Has the α particle expelled from all radioactive products the same mass?
2. Does the value of e/m of the α particle vary in its passage through matter?
3. What is the connexion between the velocity of the α particle and its range of ionization in air?
4. What is the connexion, if any, between the α particle and the helium atom?
5. Is the heating effect of radium or other radioactive substance due to the bombardment of the radioactive matter by the α particles expelled throughout its own mass?

In the course of these investigations, sufficient data have been accumulated, if not to answer completely all of the above questions, at least to indicate with some certainty the relations that exist between the various quantities.

The experiments outlined in this paper have been in progress for more than a year†, but publication has been delayed in order to determine the mass of the α particle from thorium and actinium as well as from radium.

The investigations on the mass of the α particle from thorium have been made in conjunction with Dr. Hahn, and are described in a following paper.

Determinations of the mass and velocity of the α particles from radium have been made by several observers. In 1902, using the electroscopic method and radium of activity 19000, I showed that the α particles from radium consisted of positively charged particles which were appreciably deflected in

* Communicated by the Author.

† A preliminary account of the measurements of the value of e/m for the particle from radium C was given before the American Physical Society, December 1905. An abstract of the results appeared in the Physical Review, Feb. 1906.

intense magnetic and electric fields*. I deduced that the value of e/m—the ratio of the charge on the α particle to its mass—was about 6×10^3, and that the swiftest α particles emitted from radium had a velocity of about $2{\cdot}5 \times 10^9$ cms. per second. Shortly afterwards, these experiments were repeated by Des Coudres†, using the photographic method and with pure radium bromide as a source of rays. He found the value of e/m to be $6{\cdot}3 \times 10^3$, and the average velocity to be $1{\cdot}65 \times 10^9$ cms. per second.

On account of the difficulty of obtaining a sufficiently large deflexion of the α rays in passing through an electric field, the values of e/m and of the velocity of the α particles obtained by Rutherford and Des Coudres could only be considered as a first approximation to the true values.

Recently the question has again been attacked by Mackenzie‡, using the photographic method and pure radium bromide as a source of rays. Fairly large deflexions of the pencil of rays were obtained by using strong magnetic and electric fields. He showed that the α particles emitted by a thick layer of radium bromide were unequally deflected in a magnetic and electric field, and presumably consisted of α particles moving with different velocities. By assuming that the value of e/m was the same for all the α particles, he deduced that the value of e/m for the average ray was $4{\cdot}6 \times 10^3$, and that the average velocity was $1{\cdot}37 \times 10^9$ cms. per second.

It will be seen that all of these investigators have used a thick layer of radium in radioactive equilibrium as a source of rays. We know that the α particles from radium in equilibrium come from four distinct α ray products. The α particles from each of these products have different ranges of ionization in air and different velocities of projection. In addition, the α particles from each single product reach the surface from different depths of radioactive matter, and consequently have different velocities. It is thus seen that the α radiation from radium is very complex, and consists of four groups of α particles, each of which is made up of α particles which escape at widely different velocities.

On account of the dispersion of the pencil of rays in passing through an electric and magnetic field, it is difficult to interpret with certainty the deflexions observed. The difficulties which arise are clearly pointed out by Mackenzie in his paper (*loc. cit.*)

In a previous paper (Phil. Mag. July 1905) I pointed out

* Rutherford, *Phys. Zeit.* iv. p. 235 (1902); Phil. Mag. Feb. 1903.

† Des Coudres, *Phys. Zeit.* iv. p. 483 (1903).

‡ Mackenzie, Phil. Mag. Nov. 1905.

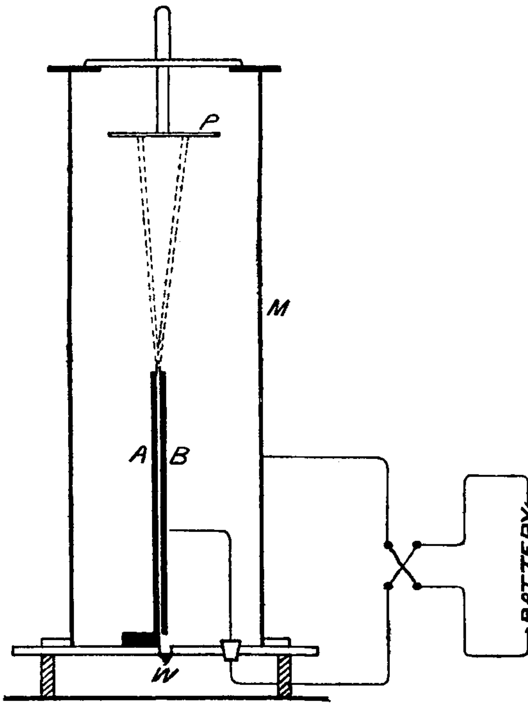
that these difficulties would disappear if a homogeneous pencil of α rays was employed. I showed that such a homogeneous pencil could be obtained by using as a source of rays a small wire which had been made very active by exposure to the radium emanation. Fifteen minutes after removal from the emanation, radium A has been transformed, and the α particles are then emitted only from radium C.

An examination of the deflexion of the rays in a magnetic field showed that such an active wire fulfilled the conditions necessary for a homogeneous source of rays. The α particles all escaped from the thin film of radioactive matter at the same speed, and all suffered the same reduction of velocity in passing through an absorbing screen. On account of the rapid decay of the activity of the active deposit, it is necessary to employ an intensely active wire to obtain a strong photographic effect. In most of the experiments described later, the active deposit was concentrated on the wire by making it the only negatively charged surface in a vessel containing a large quantity of the radium emanation. In this way, very active wires were obtained which served as suitable sources of homogeneous α rays.

Electric Deflexion of the α Rays.

The determination of e/m and of the velocity of the α particle was made in the usual way by measuring the deflexion of a pencil of rays in passing through both a magnetic and electric field of known strength. The method employed for measuring the magnetic deflexion has already been described in a previous paper. After some preliminary experiments, the following arrangement was adopted to determine the deflexion of the α rays in passing through an electric field. The rays from the active wire W (fig. 1), after traversing a thin mica plate in the base of the brass vessel M, passed between two parallel insulated plates A and B about 4 cms. high and 0·21 mm. apart. The distance between the plates was fixed by thin strips of mica placed at the four corners, and the plates were rigidly held together by rubber bands. The terminals of a storage-battery were connected with A and B so that a strong electric field could be produced between the two plates. The pencil of rays, after emerging from the plates, fell on a photographic plate P. The latter was rigidly fixed to a ground-brass plate which fitted accurately on the top surface of the vessel. The ground surfaces were air-tight, and the photographic plate could thus easily be placed in position or removed without disturbing the rest of the apparatus. The vessel was connected to a mercury pump and exhausted to a low vacuum. If necessary, the exhaustion was completed by means of a side tube filled with cocoanut charcoal and immersed in liquid air.

Fig. 1.



The plates A and B were placed close together for several reasons. In the first place, a strong electric field could be produced between the plates for a comparatively small voltage. The greatest P.D. necessary in the experiments was about 500 volts. Since the plates were about one-fifth of a millimetre apart, this voltage produced an electric field between the plates corresponding to 25000 volts per cm. One advantage of the arrangement lies in the fact that, provided the P.D. is below about 350 volts, there is no danger of a discharge between the plates, even if there is not a good vacuum. This is particularly convenient where it is found necessary to expose the photographic plate to a weak source of radiation for several days, for there is no necessity to continually watch the state of the vacuum.

On account of the small distance between the plates, there is no necessity to correct for the disturbance of the electric field near the ends of the plates. In addition, the parallel plates acted as a slit in order to obtain a narrow pencil of rays. In its passage through the electric field each α particle describes a parabolic path, and after emergence travels in a straight line to the photographic plate. By reversing the electric field at intervals, the direction of deflexion of the pencil of rays is reversed.

The general effect of the electric field in altering the appearance of the trace of the pencil of rays impinging on the photographic plate is shown in fig. 2 (Pl. V.) A shows the natural width of the line without an electric field, B for a P.D. of 255 volts, C for 340 volts, and D for 497 volts. These are reproduced from the actual photographs (magnification about 1·4 times). When a small P.D. is applied, the natural width of the photographic trace is broadened. Above a certain voltage, the single band breaks into two. As the voltage is further increased, the distance apart of these bands increases while the width of each band steadily narrows. The outside edge of each band is sharply defined, but it is difficult to fix with certainty the inner boundary of the bands.

Theory of the Experiment.

The theory of the experimental arrangement where the parallel plates act both as a slit and a means of applying the electric field, is more complicated than the ordinary case where a narrow pencil of α rays is made to pass between the two parallel plates of the condenser without impinging on the sides.

A diagram of the experimental arrangement is shown in fig. 3. AB and CD are the two charged parallel plates, and CE the radiant source which was of greater width than the distance between the plates. It is required to find the width of the trace on the photographic plate when a P.D. V is applied between the plates.

Let m = mass of α particle,

e = charge on α particle,

u = velocity of α particle in passing between plates,

$AB = l_1$, $CD = l_2$, $Bb = l_3$,

d = distance between plates,

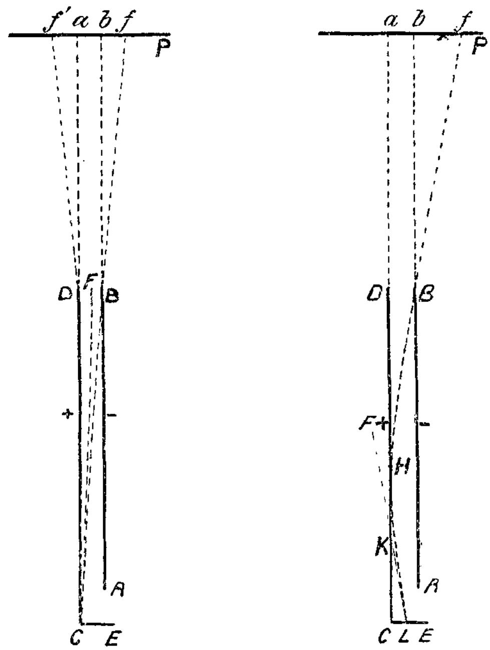
D = distance between extreme edges of the photographic trace for reversal of the electric field.

There are two cases of the theory which must be separately considered :—

Case 1, when the deflexion of the α particle in passing through the electric field is less than d, the distance between the plates,

Case 2, when the deflexion is greater than d.

Fig. 3 A. Fig. 3 B.



Case 1. Case 2.

Case 1.—We shall now consider the theory for the first case. On entering the electric field at A, each α particle describes a parabolic path, and on emergence from the field moves in a straight line, the direction of which is a tangent to the parabolic path at the moment of emergence. The distance between the plates (0·21 mm.) is so small compared with the length AB (3·77 cms.), that we may assume without sensible error that the electric field is everywhere normal to the path of the rays. Suppose that the electric field is applied in such a direction that the α particle is urged in the direction of the plate AB. Some of the α particles, which before the field was applied fell on the photographic plate, are now stopped by the plate AB, but other α particles previously stopped by the plate CD are able to emerge.

Suppose that the α particle in passing through the electric field is deflected normally through a distance S represented by FB. All the α particles which before the application of the electric field passed through the point F now just emerge at B at grazing incidence. The α particle which forms the extreme edge of the photographic trace at f must obviously be projected initially in the direction CF, and after emergence will travel along the line B f.

Since the normal acceleration of the α particle in passing through the electric field is $\frac{Ve}{dm}$, and the time occupied in passing between the charged plates is $\frac{l_1}{u}$, the distance

$$\mathrm{FB} = s = \frac{Ve}{2dm} \cdot \frac{l_1^2}{u^2},$$

or

$$s = \lambda l_1^2, \quad \text{where } \lambda = \frac{e}{2m} \cdot \frac{V}{du^2}.$$

At the moment of leaving the electric field, the tangent of the angle θ, which the direction of motion makes with the initial direction of projection CF, is given by $\tan\theta = 2\lambda l_1$.

If the angle $\mathrm{DCF} = \theta_1$, the emerging ray makes an angle $\theta + \theta_1$ with the direction of the plates B b. The distance $bf = l_3 \tan(\theta + \theta_1)$. Since the angles θ and θ_1 are small,

$$\begin{aligned} bf &= l_3(\theta + \theta_1) \\ &= l_3\left(2\lambda l_1 + \frac{d-s}{l_2}\right). \end{aligned}$$

In a similar way when the electric field is reversed, the corresponding distance

$$af' = l_3\left(2\lambda l_1 + \frac{d-s}{l_1}\right).$$

In this case, the α particle which is most deflected enters the electric field at grazing incidence at the point A.

The distance D between the extreme edges ff' of the photographic impression is consequently given by

$$\begin{aligned} \mathrm{D} &= bf + ab + af' \\ &= 4\lambda l_1 l_3 + l_3(d-s)\left(\frac{1}{l_1} + \frac{1}{l_2}\right) + d. \end{aligned}$$

Substituting the value $s = \lambda l_1^2$,

$$\mathrm{D} = \lambda l_1 l_3\left(3 - \frac{l_1}{l_2}\right) + \left(\frac{l_3}{l_2} + \frac{l_3}{l_2} + 1\right)d.$$

But it is easily seen that the natural width of the photographic band without the electric field is given by

$$\left(\frac{l_3}{l_2}+\frac{l_3}{l_1}+1\right)d.$$

Therefore the *increase* D_1 of the breadth of the band by the reversal of the electric field is given by

$$D_1=\lambda\, l_1\, l_3\left(3-\frac{l_1}{l_2}\right).$$

Substituting the value of λ,

$$\frac{mu^2}{e}=\frac{V\, l_1\, l_3}{2dD_1}\left(3-\frac{l_1}{l_2}\right). \quad . \quad . \quad . \quad . \quad (1)$$

This gives the formula required for determining the value of $\frac{mu^2}{e}$ for case 1.

Case 2.—In this case the electric field is supposed to be sufficiently strong to deflect the α particle in passing between the charged plates through a distance greater than d.

Suppose the electric field urges the α particle towards the plate AB (fig. 3 B). A little consideration shows that the α particle which forms the extreme edge of the photographic impression at f must touch at grazing incidence the plate CD. Let LKF be the direction of projection of such an α particle, intersecting the plate CD at K. The path of the α particle under the action of the electric field is shown by the dotted line in the figure. The path touches the plate CD at H and emerges at B at grazing incidence.

Let $DH=y$.

Then with the same notation as before, $d=\lambda y^2$.

The angle θ which the tangent to the parabola at B makes with the direction of the plate AB is given by

$$\tan\theta=2\lambda y.$$

The distance $bf=l_3\tan\theta=2\lambda y l_3$.

The total distance D between the extreme edges of the photographic impression on the plate P by reversal of the field is consequently given by

$$D=4\lambda y l_3+d.$$

Then $$(D-d)^2=16\lambda d l_3^2.$$

Substituting the value of λ as before,

$$\frac{mu^2}{e}=\frac{8Vl_3^2}{(D-d)^2}. \quad . \quad . \quad . \quad . \quad . \quad (2)$$

It is interesting to note that this formula for the determination of $\frac{mu^2}{e}$ does not involve l_1 or l_2, and only involves the distance d to a subordinate extent. For example, in one experiment where $l_3=10$ cms., the value of d was only 1/15 D. This is a great advantage, as the distance d is difficult to measure with accuracy.

While the distance l_1 is not involved in the final formula, it must be remembered that the formula (2) only applies when the α particle is deflected through a distance greater than d in passing between the plates. If l_1 is made smaller, the value of V must be made correspondingly greater before the formula can be applied.

It has been mentioned that the width of two deflected traces obtained by reversal of the electric field decreases in width with increase in strength of the electric field. The reason of this can readily be shown from theoretical considerations. For example, it is seen that the inside edge of the deflected pencil (fig. 3 B) is produced by the α particles whose paths touch at grazing incidence the plate AB at A and also touch the plate CD. These conditions determine the direction of the α particle in entering the electric field at A. All α particles passing through A which make a greater angle with the plate AB than the above α particle are stopped by the plate CD. As the width of the trace is not required in the experiment, it has not been thought necessary to include here the connexion between the width of the deflected pencil and the strength of the electric field. The calculations, though a little long, are not difficult.

It is now necessary to consider how we are able to know from the photographs obtained whether the formula (1) or (2) is to be applied. The formula (1) holds provided the distance of deflexion of the α particle is not greater than d. Suppose that the α particle is deflected through a distance d in passing between the charged plates. The outside edge of the photographic impression, for example, on the right of the plate P (fig. 3) is due to the α particles which start from the point C parallel to the plate CD. With the same notation as before,

$$d=\lambda l_1^2.$$

Following the same method of calculation as for case (2), it is seen that the value of D is given by

$$D=4\lambda\, l_1\, l_3+d.$$

Substituting the value $\lambda = \frac{d}{l_1^2}$,

$$D = d\left(\frac{4l_3}{l_1} + 1\right).$$

In most of the experiments to be described later,

$$l_3 = 3{\cdot}94 \text{ cms.,} \quad l_1 = 3{\cdot}77 \text{ cms.,} \quad d = {\cdot}21 \text{ mm.}$$

Consequently, $D = 1{\cdot}09$ mm.

From the data given below it will be seen that the formula (2) applies for all voltages greater than about 300, while the formula (1) applies for all values smaller than this.

Results of Experiments.

The electrostatic deflexion of the α rays from radium C was first determined for different voltages between the plates. The rays from the active wire passed through a mica plate in the base of the vessel, equivalent in stopping power to about 3·5 cms. of air. The extreme distance D between the outside edges of the photographic impressions obtained on the plate by reversal of the electric field was measured by the lantern method described in a previous paper*.

In most of the experiments, the value l_3 of the distance of the photographic plate above the parallel plates was 3·94 cms. In one experiment this distance was 10·00 cms.

$$l_1 = 3{\cdot}77 \text{ cms.,} \quad l_2 = 4{\cdot}165 \text{ cms.,} \quad d = 0{\cdot}210 \text{ mm.}$$

The values of $\frac{mu^2}{e}$ obtained for different voltages and distances of the photographic plate are tabulated below.

Volts between plates.	l_3.	D.	$\frac{mu^2}{e}$.
171	3·94 cms.	0·857 mms.	$5{\cdot}1 \times 10^{14}$
255	" "	0·995 "	$4{\cdot}9 \times 10^{14}$
340	" "	1·136 "	$4{\cdot}93 \times 10^{14}$
497	" "	1·346 "	$4{\cdot}79 \times 10^{14}$
508·6	10·00 "	3·10 "	$4{\cdot}87 \times 10^{14}$

Each of the values of D given above is the mean of a large number of separate measurements which agreed closely among

* Rutherford, Phil. Mag. August 1906.

themselves. The values for 171 and 255 volts are calculated from formula (1), the natural width of the photographic trace being 0·61 mm., and for the higher voltages from formula (2). Some of the photographs from which the measurements were made are reproduced in fig. 2, magnification about 1·4.

Two good photographs were obtained with a P.D. of 340 volts. In each case two active wires were used successively to give a strong photographic impression. On account of the greater distance, the photographic impression was not so strongly marked for the distance 10 cms.

Giving a weight 1 to the measurement of $\frac{mu^2}{e}$ for 497 volts, and a weight 2 for both 340 and 508·6 volts, the mean value is given by

$$\frac{mu^2}{e}=\underline{4\cdot 87\times 10^{14}}\text{ electromagnetic units.} \quad . \quad . \quad . \quad (3)$$

By measurement of the magnetic deflexion, the maximum value of $\frac{mu}{e}$ for the α rays from radium C was found to be $4\cdot 06\times 10^5$. The mica screen cut down the velocity of the rays to ·763 of the initial velocity, so that the value of $\frac{mu}{e}$ for the rays which passed through the electric field is given by

$$\frac{mu}{e}=3\cdot 10\times 10^5. \quad . \quad . \quad . \quad . \quad . \quad (4)$$

By combining equations (3) and (4)

$$u=1\cdot 57\times 10^9 \text{ cms. per second,}$$
$$e/m=\underline{5\cdot 07\times 10^3}\text{ electromagnetic units.}$$

I think that the values of u and e/m are certainly correct within two per cent.

The initial velocity of the α particles expelled from radium C is consequently $\underline{2\cdot 06\times 10^9}$ cms. per second.

Does the value of e/m *for the α particle vary in its passage through matter?*

In order to test this point, the value of e/m for the α particle was determined under the following conditions:—

(1) The active wire was placed on top instead of under

the mica screen, so that the electrostatic deflexion was determined for the α particle from the unscreened wire.

(2) The α particles passed through a mica screen equivalent in stopping power to 3·5 cms. of air. The value of e/m under these conditions has been determined in the previous section.

(3) The α particles passed through a screen of mica and aluminium equivalent to about 6·5 cms. of air.

The magnetic and electrostatic deflexion were separately determined. The former gives the value of $\frac{mu}{e}$ and the latter $\frac{mu^2}{e}$. The results of the measurements are collected in the following table, where D has the same meaning as before. The value of l_3 in all cases was 3·94 cms.

Interposed absorbing screen in terms of air.	Volts.	D.	$\frac{mu}{e}$.	$\frac{mu^2}{e}$.	$\frac{e}{m}$.
0	340	0·88 mm.	$4{\cdot}06\times10^5$	$9{\cdot}4\ \times10^{14}$	$5{\cdot}7\ \times10^3$
3·5 cms.	...	...	$3{\cdot}10\times10^5$	$4{\cdot}87\times10^{14}$	$5{\cdot}07\times10^3$
6·5 cms.	340	1·62 mm.	$2{\cdot}11\times10^5$	$2{\cdot}11\times10^{14}$	$4{\cdot}8\ \times10^3$

The deflexion for the rays from the bare wire was small, but could be measured with fair certainty. I think the value of e/m obtained in this case, viz. $5{\cdot}7\times10^3$, is undoubtedly too high. On removing the active wire after completion of the experiment, it was noticed that its position was displaced somewhat to the side of the opening of the parallel plates. This would tend to make the observed width of the photographic trace too small, and consequently to give too great a value of e/m, when calculated from formula (1), which is based on the assumption that the active source completely covers the opening between the parallel plates.

The impression on the photographic plate due to the α particles which have passed through an absorbing screen equivalent to 6·5 cms. of air was weak but clearly defined, and admitted of fairly accurate measurement. Allowing for an error in the estimation of e/m for the α particles from the bare wire, I think the agreement of the values of e/m obtained under the different conditions is sufficiently close to prove definitely that the value of e/m for the α particle is unaltered in its passage through matter.

Value of e/m *for the* α *particles from Radium* A.

In a previous paper (*loc. cit.*) I gave the results of the measurements by the photographic method of $\frac{mu}{e}$ for the α particle emitted from radium A. For the unscreened wire the value of $\frac{mu}{e}=3{\cdot}67\times10^5$, and for the wire covered with a mica plate of the same thickness as that over the opening in the base of the electrostatic apparatus, I found the value of $\frac{mu}{e}=2{\cdot}19\times10^5$.

I pointed out in that paper the difficulty of accurately measuring the magnetic deflexion of the α particles from such a rapidly changing product as radium A, which is half transformed in three minutes. The difficulty of obtaining a sufficiently marked photographic impression, in order to measure the electric deflexions of the rays, was still greater. It was found necessary to place twenty active wires successively in position under the base of the apparatus, in order to obtain a measurable darkening of the photographic plate. Each wire was exposed for two minutes as negative electrode in a vessel containing a large quantity of the radium emanation. For such a short exposure, the initial radiation from the wire mainly comes from radium A. The wire was rapidly removed from the emanation vessel and placed in position and left for six minutes. In that time, the α ray activity of radium A is reduced to one quarter of its initial value. The α rays from the active wire passed through the standard mica plate before entering the electric field. The electric deflexion of the α rays from radium A is considerably greater than that for the swifter α particles from radium C; so that there is no danger of confusion between the two types of rays, even though the photographic impression of the rays from radium C present on the active wire is comparable with that due to the rays from radium A.

In the experiment the voltage was 255; $l_3=3{\cdot}94$ cms.; and $D=1{\cdot}30$ mm. This gave

$$\frac{mu^2}{e}=2{\cdot}67\times10^{14}.$$

The value $\frac{mu}{e}$ for the α rays from radium A after traversing the standard mica was $2{\cdot}19\times10^5$. This gives the values

$$u = 1{\cdot}22\times10^9 \text{ cms. per sec.}$$
$$e/m = 5{\cdot}6\times10^3.$$

It was found by experiment that the measured value of D—the distance between the extreme edges of the trace—was always underestimated for a very feeble photographic trace. An underestimate of the value of D gives too large a value for e/m. Taking this factor into consideration, the values of e/m obtained for the α particles from radium A and from radium C agree within the limit of experimental error. This shows that the α particles expelled from radium A and C have the same mass and differ only in their initial velocities of projection.

Mass of the α particle from Radium F.

A bismuth rod coated with radiotellurium was used as a source of α rays. It is now definitely established that the active constituent in both radiotellurium and polonium is the same and consists of the transformation product of radium, radium F. The active matter is deposited in the form of a thin film on the bismuth rod, and the α particles all escape from the surface at practically the same velocity. A piece of the rod was placed in position inside the electrostatic apparatus, and the photographic plate exposed for four days to the action of the α rays from the bare rod. The value $l_3 = 10{\cdot}00$ cms, the voltage $= 443$, and the observed value $D = 2{\cdot}72$ mm.

This gives a value $\frac{mu^2}{e} = 5{\cdot}63 \times 10^{14}$ for the α rays from the unscreened source. The value of $\frac{mu}{e} = 3{\cdot}2 \times 10^5$ was deduced by me in a previous paper from measurement of the range of the α particles from radium F in air. The experimental value found directly by Mackenzie (*loc. cit.*) was $3{\cdot}3 \times 10^5$. Taking the mean value $\frac{mu}{e} = 3{\cdot}25 \times 10^5$, we find that $e/m = 5{\cdot}3 \times 10^3$, and $u = 1{\cdot}73 \times 10^9$ cms. per second.

The actual photograph obtained was very weak in intensity, and, for the reasons previously mentioned, there is no doubt that the value e/m obtained is too large. We may consequently conclude that the α particle from radium F has the same mass as that expelled from radium C. Using a more active rod or a longer time of exposure, the value of e/m should be obtained with much greater precision; but there can be no doubt that it would be found identical with that observed for the α particle from radium C.

Mass of the α particles from Actinium.

In order to obtain a homogeneous source of α rays, the active deposit of actinium was used. The active deposit was concentrated on a small copper plate by making it the negative electrode in a small vessel containing the emanating actinium compound. This active deposit consists of two products, actinium A and B, the former of which is rayless. The activity imparted to a plate, ten minutes after removal from the emanation, decays exponentially with a period of 36 minutes. The rays emitted are all of one kind and have a range in air, found by Dr. Hahn in this laboratory, of 5·5 cms.

The preparation of actinium * employed was not very active, and the activity imparted to the copper plate was too weak to produce appreciable photographic action at the distances required. With the experience gained in the previous experiments with weak radioactive sources, it was recognized that at least twenty active wires, placed successively in position, would have been required to produce a measurable photographic effect in the magnetic deflexion apparatus. Three or four times this number would have been necessary in the electrostatic experiment. In order to avoid the necessity of such a procedure, the apparatus was constructed so that the copper plate could be kept active in the position required for any length of time. The actinium compound, wrapped in thin paper, was placed round the sides of a small brass vessel, which was attached to the base of the magnetic or electric deflexion apparatus. A small insulated copper plate, with its plane slightly inclined to the vertical, was placed below a narrow slit covered with mica in the base of the apparatus and was kept negatively charged. The activity on the plate reached a maximum after three hours and then remained constant. The radiation passing through the slit into the magnetic deflexion apparatus was mainly due to the α rays from actinium B. The photographic effect of the radiations from the emanation close to the active plate was too weak to be observed. The magnetic deflexion of the pencil of the α rays was determined under identically the same conditions as in the experiments using radium C as a source of rays. The photographic plate was exposed for ten hours in a constant magnetic field which was reversed at intervals. Two fine well-defined lines were obtained on the plate. The amount of the magnetic deflexion

* I am indebted to Mr. H. Lieber of New York for his kindness in lending me the sample of actinium used in this experiment.

was then directly compared with that due to the rays from radium C under the same conditions. For this purpose, the copper plate was removed and made active by exposure to the radium emanation. It was then placed back in its original position, and another photograph taken. The mica plate, covering the opening in the base of the magnetic apparatus, was of the same thickness as that used in the base of the electrostatic apparatus. The following numbers illustrate the results obtained :—

Distance between centres of deflected bands due to rays from actinium B = 1·85 mm.

Distance between centres of deflected bands due to rays from radium C = 1·53 mm.

We have previously shown that the value of $\frac{mu}{e}$ for the α particles of radium C after passing through the standard mica screen, absorbing-power equal to 3·5 cms. of air, is $3{\cdot}10\times10^5$. Consequently the value of $\frac{mu}{e}$ for the α particles from actinium B is given by

$$\frac{mu}{e}=\frac{1{\cdot}53}{1{\cdot}85}\times3{\cdot}10\times10^5=2{\cdot}56\times10^5.$$

It is interesting to note that the comparative magnetic deflexions observed for the rays of actinium B and of radium C agree with those to be expected from their known ranges in air, assuming the value of e/m for the α particle to be the same in both cases.

I have shown in a previous paper that the velocity V of an α particle of range r cms. in air is given by

$$\frac{V}{V_0}=\cdot348\sqrt{r+1\cdot25},$$

where V_0 is the maximum velocity of the rays from radium C which have a range of 7·06 cms. Now, after passing through the mica screen, the rays from actinium B have a range $5{\cdot}5-3{\cdot}5=2{\cdot}0$ cms., while those from radium C have a range $7{\cdot}06-3{\cdot}5=3{\cdot}56$ cms.

Consequently,

$$\frac{\text{velocity of rays from radium C after passage through mica}}{\text{velocity of rays from actinium B after passage through mica}}=$$

$$=\sqrt{\frac{3{\cdot}56+1{\cdot}25}{2{\cdot}0+1{\cdot}25}}=1{\cdot}22.$$

The experimental ratio is 1·21. From the agreement between the experimental and the theoretical ratios, it could be concluded with confidence that the mass of the α particle from actinium is the same as that from radium C. This, however has been experimentally verified by measuring the electric deflexion of the α rays from actinium B.

The apparatus for determining the electric deflexion of the α rays was the same as that used in the radium experiments. The copper plate which served as a source of α rays was kept active by an arrangement similar to that used for the magnetic deflexion. The photographic plate was exposed for six days. Through an accident in the connexions, the electric field was not acting between the plates for the first three days. The photographic plate consequently showed the undeflected trace of the rays and the deflected trace on one side of it. The distance between the centre of the undeflected trace and the outside edge of the deflected trace gives the value of $\frac{D}{2}$. The value of l_3 was 10·00 cms.; the voltage 340, and D was 3·174 cms. Consequently the value of $\frac{mu^2}{e}$ for the rays after passing through the standard mica was

$$\frac{mu^2}{e} = 3{\cdot}10 \times 10^{14}.$$

We have previously shown that

$$\frac{mu}{e} = 2{\cdot}56 \times 10^5,$$

Therefore

$$\frac{e}{m} = 4{\cdot}7 \times 10^3,$$

and

$$u = 1{\cdot}21 \times 10^9 \text{ cms. per second.}$$

We may thus conclude that the α particle from actinium has the same mass as that from radium.

Connexion of the α particle with the helium atom.

We have seen that, within the limit of experimental error, the mass of the α particle expelled from radium A, radium C, radium F, or actinium B is the same. In a later paper, in conjunction with Dr. Hahn, it will be shown that the mass of the α particle expelled from thorium C is also identical with that expelled from the radium products. We have also shown in a previous paper that the amount of the magnetic deflexion of the α particle from radium itself is in agreement with that to be deduced from its range in air—a result which is only to be expected if the α particle from radium has the same mass as that from radium C.

There then remains only one α ray product of radium, viz. the emanation, whose radiation has not been closely examined. There is, however, no reason to suppose that the α particles from the emanation differ in mass from those of the other products. An examination of the complex pencil of rays from a layer of radium in equilibrium shows no evidence of the presence of α rays which suffer an abnormal amount of deflexion. I think there can be no doubt that the α particles emitted from the various products of radium have an identical mass, but differ only in the initial velocities of projection. Although the mass of the α particles has been determined for only a single product of thorium and of actinium, the analogy with radium would lead us to expect that the α particle has the same mass for all the products of these substances.

We may thus reasonably conclude that the α particles expelled from the different radio-elements have the same mass in all cases. This is an important conclusion; for it shows that uranium, thorium, radium, and actinium, which behave chemically as distinct elements, have a common product of transformation. The α particle constitutes one of the fundamental units of matter of which the atoms of these elements are built up. When it is remembered that in the process of their transformation radium and thorium each expel five α particles, actinium four, and uranium one, and that radium is in all probability a transformation product of uranium, it is seen that the α particle is an important fundamental constituent of the atoms of the radio-elements proper. I have often pointed out what an important part the α particles play in radioactive transformations. In comparison, the β and γ rays play quite a secondary rôle.

It is now necessary to consider what deductions can be drawn from the observed value of e/m found for the α particle. The value of e/m for the hydrogen ion in the electrolysis of water is known to be very nearly 10^4. The hydrogen ion is supposed to be the hydrogen atom with a positive charge, so that the value of e/m for the hydrogen atom is 10^4. The observed value of e/m for the α particle is $5{\cdot}1 \times 10^3$, or, in round numbers, one half of that of the hydrogen atom. The density of helium has been found to be 1·98 times that of hydrogen, and from observations of the velocity of sound in helium, it has been deduced that helium is a monatomic gas. From this it is concluded that the helium atom has an atomic weight 3·96. If a helium atom carries the same charge as the hydrogen ion, the value of e/m for the helium atom should consequently be about $2 \cdot 5 \times 10^3$. If we assume that the α particle carries the same charge as the hydrogen ion, the mass of the α particle is twice that of the hydrogen atom. We are here unfortunately confronted with several possibilities between which it is difficult to make a definite decision.

The value of e/m for the α particle may be explained on the assumptions that the α particle is (1) a *molecule* of hydrogen carrying the ionic charge of hydrogen, (2) a helium atom carrying *twice* the ionic charge of hydrogen, or (3) *one half* of the helium atom carrying a single ionic charge.

The hypothesis that the α particle is a molecule of hydrogen seems for many reasons improbable. If hydrogen is a constituent of radioactive matter, it is to be expected that it would be expelled in the atomic, and not in the molecular state. In addition, it seems improbable that, even if the hydrogen were initially projected in the molecular state, it would escape decomposition into its component atoms in passing through matter, for the α particle is projected at an enormous velocity, and the shock of the collisions of the α particle with the molecules of matter must be very intense, and tend to disrupt the bonds that hold the hydrogen atoms together. If the α particle is hydrogen, we should expect to find a large quantity of hydrogen present in the old radioactive minerals, which are sufficiently compact to prevent its escape. This does not appear to be the case, but, on the other hand, the comparatively large amount of helium present supports the view that the α particle is a helium atom. A strong argument in support of the view of a connexion between helium and the α particle rests on the observed facts* that helium is produced by actinium as well as by radium. The only point of identity between these two substances lies in the expulsion of α particles of the same mass. The production of helium by both substances is at once obvious if the helium is derived from the accumulated α particles, but is difficult to explain on any other hypothesis. We are thus reduced to the view that either the α particle is a helium atom carrying twice the ionic charge of hydrogen, or is half of a helium atom carrying a single ionic charge.

The latter assumption involves the conception that helium, while consisting of a monovalent atom under ordinary chemical and physical conditions, may exist in a still more elementary state as a component of the atoms of radioactive matter,

* Debierne, *C. R.* cxli. p. 383 (1905).

and that, after expulsion, the parts of the atom lose their charge and recombine to form atoms of helium; while such a view cannot be dismissed as inherently improbable, there is as yet no direct evidence in its favour. On the other hand, the second hypothesis has the merit of greater simplicity and probability.

On this view, the α particle is in reality a helium atom which is either expelled with a double ionic charge or acquires this charge in its passage through matter. Even if the α particle were initially projected without charge, it would certainly acquire one after the first few collisions with the molecules in its path. We know that the α particle is a very efficient ionizer, and there is every reason to suppose that it would itself be ionized by its collisions with the molecules in its path, *i. e.* it would lose one or more electrons and retain a positive charge. If the α particle can remain stable with the loss of two electrons, these electrons would almost certainly be removed as a result of the intense disturbance set up by the collision of the α particle with the molecules of matter. The α particle would then have twice the normal ionic charge, and the value of e/m, as found by measurement, would be quite consistent with the view that the α particle is an atom of helium.

In a previous paper* I showed, from measurement of the charge carried by the α rays, that $6\cdot2 \times 10^{10}$ α particles were expelled per second from one gram of radium at its minimum activity. This was based on the assumption that each α particle carried a positive charge equal to the ionic charge of hydrogen, viz. $3\cdot4 \times 10^{-10}$ electrostatic units. Assuming that the α particle carries two ionic charges, the corresponding number is reduced to one half of the above, viz. $3\cdot1 \times 10^{10}$. This would make the calculated period of radium 2600 years instead of 1300 years (see 'Radioactivity,' second edition, 1905, p. 457). In a similar way, the calculated volume of the emanation released from one gram of radium would be 0·4 cubic mm. instead of 0·8 cubic mm. The calculated volume of helium produced per year per gram of radium would be 0·11 cubic cms. ('Radioactivity,' p. 481).

On the hypothesis that the α particle is a helium atom, the atomic weight of each product is diminished by four units, in consequence of the expulsion of an α particle. On the hypothesis that the α particle is half a helium atom carrying a single ionic charge, the atomic weight is diminished by two units instead of four. Taking the latter hypothesis, the number of α particles expelled per second from one gram of

* Phil. Mag. August 1905.

radium at its minimum activity is $6{\cdot}2\times10^{10}$. The calculated volume of the emanation is 0·8 cubic mms., while the production of helium per year is 0·11 cubic cms. per gram. The two hypotheses thus lead to the same rate of production of helium by radium.

Age of Radioactive Minerals.

I have previously pointed out that the age of the radioactive minerals can be calculated from the amount of helium contained in them. The method is based on the assumption that, in a compact mineral, the greater part of the helium is mechanically imprisoned in the mineral and is unable to escape. Let us consider, for example, the mineral fergusonite, which was found by Ramsay and Travers to contain 1·81 c.c. of helium per gram of the mineral. The fergusonite contains about 7 per cent. of uranium. The amount of helium per gram of uranium is consequently 26 c.c. Now we have seen that one gram of radium produces 0·11 c.c. of helium per year. The content of radium per gram of uranium is $3{\cdot}8\times10^{-7}$ gram *. Supposing that uranium emits only one α particle corresponding to the five emitted by radium in equilibrium where the product radium F is present, the production of helium per year per gram of uranium is $\frac{6}{4}\times{\cdot}11\times3{\cdot}8\times10^{-7}$ or $6{\cdot}3\times10^{-8}$ c.c. per year. Assuming as a first approximation that the rate of production of helium has been constant since the formation of the mineral, the time required for a production of 26 c.c. of helium is about 400 million years. This is a minimum estimate, for some of the helium has probably escaped from the mineral.

As another example, consider the mineral thorianite, which contains about 72 per cent. of thorium and 10 per cent. of uranium. The evolution of helium per gram of the mineral was found by Ramsay to be 9·5 c.c. Bragg (Phil. Mag. June 1906) has shown that thorium breaks up at ·26 of the rate of uranium. This was based on measurements made with ordinary commercial thorium. Boltwood (Amer. Journ. Sci. June 1906) has, however, drawn attention to the fact that ordinary commercial thorium has in many cases only about one half of the activity obtained by direct preparation of the thorium from the radioactive minerals. This would double the rate of breaking up of thorium observed by Bragg. Remembering that a thorium atom during its transformations emits five α particles, and assuming that thorium breaks up at half the rate of uranium, it is seen that 72 per cent. of thorium in a mineral corresponds as a producer of helium to

* Rutherford and Boltwood, Amer. Journ. Sci. July 1906.

about $\frac{5}{6} \times \frac{72}{2} = 30$ per cent. of uranium. The amount of helium corresponding to one gram of uranium or its equivalent in the mineral is consequently 24 c.c. As before, the age of the mineral works out to be about 400 million years.

Numerous other examples may be given, but these serve to illustrate the method of calculation from radioactive data of the age of some radioactive minerals, and indirectly, in some cases, of the geological strata in which they are found.

Velocity and Energy of the α particles expelled from Radium products.

If the value of e/m is the same for the α particle expelled from the various radium products, the maximum velocity of each set of α particles can be deduced from their range in air, knowing the velocity of the α particles expelled from radium C. The velocities so determined are probably more accurate than those obtained by direct measurement under difficult conditions. In the following table, the second column gives the range in air of the α particles from the radium products, found by Bragg and Kleeman; in the fourth column is given the value of $\frac{mu^2}{e}$, where u is the initial velocity of projection of the α particles.

Product.	Range of α particle in cms.	Velocity in cms. per sec.	$\frac{mu^2}{e}$.
Radium	3·50 cms.	$1{\cdot}56 \times 10^9$	$4{\cdot}78 \times 10^{14}$
Emanation.........	4·36 ,,	$1{\cdot}70 \times 10^9$	$5{\cdot}65 \times 10^{14}$
Radium A.........	4·83 ,,	$1{\cdot}77 \times 10^9$	$6{\cdot}12 \times 10^{14}$
Radium C.........	7·06 ,,	$2{\cdot}06 \times 10^9$	$8{\cdot}37 \times 10^{14}$
Radium F*	3·86 ,,	$1{\cdot}61 \times 10^9$	$5{\cdot}15 \times 10^{14}$

* The range of the rays for polonium (radium F) has been recently measured by Levin (Amer. Journ. Sci. July 1906).

Disregarding radium F, the average energy of the α particle expelled from radium in equilibrium is $3{\cdot}11 \times 10^{14} e$, where e is the charge carried by the α particle. Assuming that the heating effect of radium is a measure of the kinetic energy of the expelled α particles, we can at once deduce the total number of α particles expelled per second per gram of radium in equilibrium. One gram of radium in equilibrium emits 100 gram-calories of heat per hour. This rate of emission of energy is mechanically equivalent to $1{\cdot}16 \times 10^{6}$ ergs per second. Since the average energy of the expelled α particle is $3{\cdot}11 \times 10^{14}\, e$, the number of α particles expelled per second from one gram of radium in equilibrium is $\frac{3{\cdot}65}{10^{9}\, e}$. The number previously found by the writer by measuring the total charge carried by the α particles was $\frac{2{\cdot}82}{10^{9}\, e}$, *i. e.* 77 per cent. of the theoretical number. The agreement between theory and experiment is thus fairly good. In the above estimate, it is assumed that the heating effect is due entirely to the kinetic energy of the expelled α particles. It is known experimentally that the heating effect of the β and γ rays is only a small percentage of that due to the α rays. The expulsion of an α particle from an atom should lead to the recoil of the residue of the atom. Assuming that the momentum of the atom is equal and opposite to that of the α particle, the velocity of recoil of the atom can be simply calculated. Taking the mass of the α particle as 4 and of the radium atom as 225, the velocity of recoil of the disintegrated radium atom, for example, is $1/55 \times 1{\cdot}56 \times 10^{9}$ or $2{\cdot}8 \times 10^{7}$ cms. per second. The heating effect resulting from this recoil is thus only about 2 per cent. of that due to the α particle.

Assuming that each α particle carries a single ionic charge of $1{\cdot}13 \times 10^{-20}$ electromagnetic units, the number of α particles which must be expelled per second from one gram of radium in order to account entirely for the heating effect is $3{\cdot}2 \times 10^{11}$. The experimental number is $2{\cdot}5 \times 10^{11}$. If it is assumed that the α particle carries twice the usual ionic charge, each of these numbers is reduced by one half.

It is of interest to calculate the distribution of the heating effect of radium in equilibrium amongst the various α ray products. The theoretical percentages of the total heating effect are given in column 1. These are calculated from the known energy of the α particles expelled from each product. The observed percentages are deduced from the experimental numbers and curves given by Rutherford and Barnes (Phil. Mag. Feb. 1904).

Product.	Calculated heating effect.		Observed heating effect.
Radium	19·2		23
Emanation......	22·7	47·2	45
Radium A	24·5		
Radium C	33·6		32

The observed heating effects of the emanation and radium A are given together, as it is very difficult experimentally to determine their separate effects. It will be seen that there is a substantial agreement between the calculated and observed values.

Connexion between the Velocity and Amount of Ionization produced by the α particle.

Bragg (Phil. Mag. Nov. 1905) has shown that the ionization produced by a single α particle increases with the distance from the source to nearly the end of its range, when the ionization falls off very abruptly. He has shown that the ionization produced by the α particle at a distance r cms. from the end of the path is inversely proportional to $\sqrt{r+c}$, where c is a constant equal to 1·33. In a previous paper (Phil. Mag. Aug. 1906) I have shown that the velocity of an α particle at a distance r cms. from the end of its range is proportional to $\sqrt{r+d}$, where d is a constant equal to 1·25. The close agreement between these two expressions shows that the ionization produced per unit path by the α particle is inversely proportional to its velocity. This is in agreement with the theoretical views of Bragg, who supposed that the rate of expenditure of energy of the α particle in ionization at any point is inversely proportional to the energy of motion which it possesses.

A comparison of the velocities of the α particles expelled from the various products of the radio-elements, and a discussion of the connexion that exists between the velocity of expulsion of the α particle and the character of the transformation will be given in a later paper.

I desire to express my thanks to Dr. Hahn and Dr. Levin for their assistance in the measurement of the numerous photographs obtained in this investigation.

Berkeley, California, July 20, 1906.

XLII. *Mass of the α particles from Thorium.*

By E. Rutherford, *F.R.S., Macdonald Professor of Physics, McGill University, Montreal, and* O. Hahn, *Ph.D.**

[Plate V. figs. 1–3.]

THE present investigation, which has involved the determination by the photographic method of the deflexion of the α rays from the active deposit of thorium in a magnetic and electric field, has been rendered possible by

* Communicated by the Authors.

RUTHERFORD.]

FIG. 2.

A B C D

RUTHERFORD & HAHN.

FIG. 1.

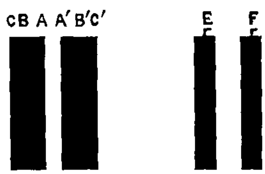
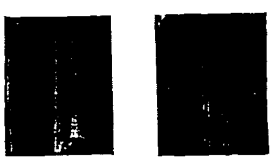
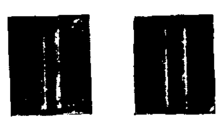


FIG. 2.



A B

FIG. 3.



A B