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XCVIII. *The Recoil of Hydrogen Nuclei from Swift α Particles.* By A. L. McAULAY*.

1. *Objects of the Research and Experimental Method.*

SIR ERNEST RUTHERFORD † has shown that when hydrogen is bombarded by α rays the number of atoms shot forward in the direction of motion of the α particles is greatly in excess of what would be expected on the simple theory of two charged points approaching and repelling each other according to the inverse square law. It is obvious from a general survey of his curves showing the absorption of the recoil radiation, that there is a rapid change in this number, and probably in the type of the collision, as the velocity of the incident α particle approaches that of the particle of range 7 cm. from RaC.

The present research was undertaken with the object of obtaining the number of atoms recoiling at various angles from a homogeneous α ray beam, and thence of deducing information bearing on the nature of the collision, the size of the colliding particles, etc.

An ionization method was used, similar in principle to one described in a recent paper in the Philosophical Magazine ‡, but with greatly improved apparatus. The following is an outline of the method. The recoil radiation is produced in a wax film close to a source of α rays. The source is placed between the poles of a powerful electromagnet about 4.5 cm. distant from a small ionization chamber, into which the recoil radiation penetrates (see fig. 1). The electrode of the ionization chamber passes at one end into a second chamber, where the current from the first is balanced. The face of the second chamber is of brass, sufficiently thick to exclude the recoil radiation. At the other end, the electrode passes into an electroscope where the difference between the ionizations in the two chambers is measured. Between the source and the chambers and close to the former is the paraffin film in which the recoil atoms are produced. This film is fairly thick, corresponding in absorbing power to about 8 cm. of air, and is covered on one side by a thin aluminium foil equivalent to 0.69 cm. of air.

The experiment consists in observing the change in ionization in the chamber which the recoil atoms enter when the wax-aluminium film is turned so that first wax and then

* Communicated by Prof. Sir E. Rutherford, F.R.S.

† Rutherford, Phil. Mag. June 1919.

‡ McAulay, Phil. Mag. Dec. 1920.

aluminium faces the source of α rays. In the first case the ionization is due to γ rays and also to recoil atoms produced along the whole path of the α rays ; in the second the conditions are the same, except that the α particles in the first 0.69 cm. of their range are passing through aluminium, and are therefore not able to excite recoil atoms. The difference in the ionization thus represents the effect of the recoil atoms from the swiftest α particles only.

2. Apparatus. (Fig. 1.)

The separate parts of the apparatus are screwed to the under side of a wooden frame which rests on top of the electro-magnet used to remove the β -rays. The source, a small metal

Fig. 1.

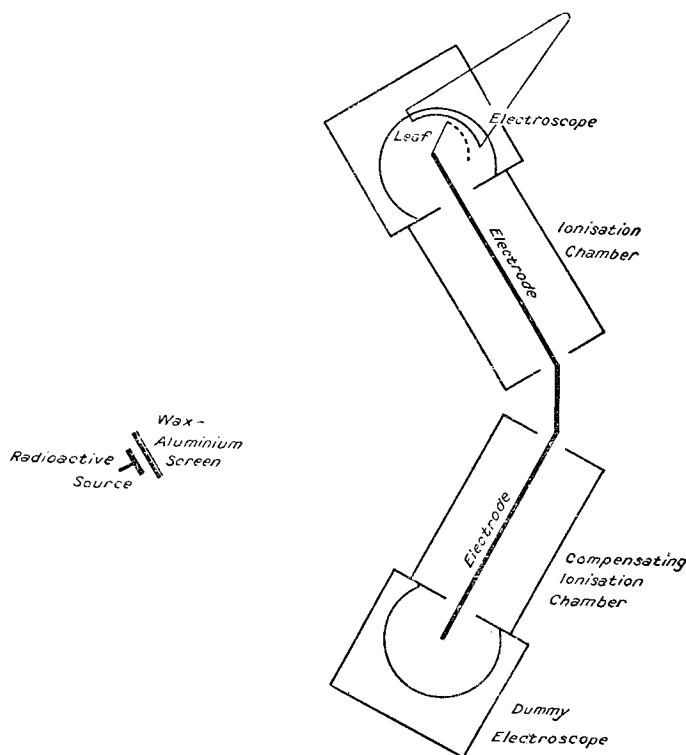


plate whose face is covered with the active deposit of radium or with thorium C, fits in a brass holder, its active surface facing the ionization chambers. The paraffin screen slips

into a clip in the front of the holder, about 2 mm. from the source. Rays from the source traverse 4 cm. of a magnetic field of several thousand gauss before reaching the ionization chambers. β rays are thus almost completely removed. The chambers are the same in shape and size, and roughly symmetrically placed with regard to the source. The case of the electroscope and one of the ionization chambers are electrically connected to earth, the electrode is charged to 60 volts, and the other chamber, with a dummy electroscope attached to it, is maintained at 120 volts. In this way the charge conveyed to the electrode by the γ -ray ionization is approximately zero, but the somewhat thinner face of the earthed chamber causes a slight excess of ionization on this side. This is compensated by weak radiation from a tube containing a little radium D, placed near an aluminium window in the side of the other chamber. An exact balance can be obtained by adjusting the position of the radium D tube.

The electroscope is the result of a preliminary research, and is of a new type. The principal objects aimed at were high sensitivity and a very small volume. The design finally adopted depends for its sensitivity on the fact that the leaf when charged points upwards instead of downwards. An increase in potential causes it to move towards the vertical, and as it moves, the gravitational couple tending to restore it to its original position decreases, instead of increasing as it does in the case of the ordinary electroscope. It was found that with the right dimensions it was easy to use the electroscope in this manner without the leaf collapsing or going to the side. At the same time, if the inside of the case is not suitably designed, these and other troubles do arise. The sensitivity of such an electroscope may be made as high as 100 divisions on a microscope scale per volt, and its behaviour appears satisfactory in this condition. In the present research the sensitivity was about 30 divisions per volt. The leaf did not creep and the sensitivity varied very little from one end of the scale to the other. Greater sensitivity was not found to be an advantage without greater refinement in the rest of the apparatus. The construction of the electroscope is very simple, and it will work satisfactorily when made quite roughly. The case is 1.5 cm. in diameter and 0.6 cm. thick. The electrode enters along a diameter from below, and the leaf is attached to its top, which ends in a knife edge slightly above the centre of the case. The leaf is 4 or 5 mm. long, and when uncharged rests along the wedge-shaped side of the knife edge. When charged, it is attracted towards the edge of a plate of thin sheet brass, cut in the arc of a circle,

which slips into a saw-cut in the case. This is normally concentric with the case, but is capable of being altered in position from outside. Its object is twofold: first, it keeps the plane in which the leaf moves parallel to the sides of the case; secondly, it permits of the sensitivity being adjusted to any desired value after the instrument is set up. This is achieved by varying the eccentricity of the leaf in the circular arc of the plate. The sides of the case are of brass, in which are cut windows, about 3 mm. by 2 mm., through which the leaf is observed. These are covered with mica, which may be made conducting by painting with calcium chloride.

The capacity of the whole electrode system is 4.3 cm. Several determinations of this quantity were made, using two different methods. The final result is probably correct to 5 per cent. The first method consisted in sharing the charge on the electrode with a small lead sphere and observing the change in potential. Precautions were taken as far as possible to eliminate the effect of leads and to reduce the effect of neighbouring conductors, and the results obtained agreed well with those given by the second method. This consisted of observing the rate of leak of the electroscope under standard conditions, first with a small cylindrical condenser connected to the electrode and then with it disconnected. The condenser was so designed that its capacity was calculable.

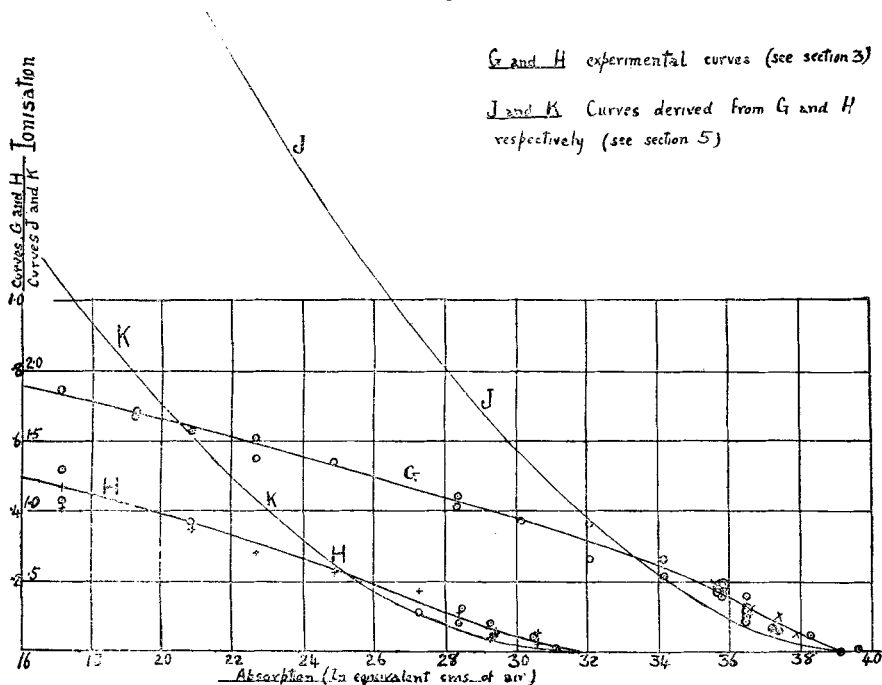
3. *The Experiments.*

As mentioned in the first section, the effect observed was the ionization due to recoil atoms produced by a nearly homogeneous beam of the swiftest α particles from the source. The velocity of the slowest was, in fact, about 3 per cent. less than that of the fastest. The experiment consisted of making such observations with different thicknesses of absorbing material between source and ionization chamber. The observed ionizations were then plotted against the absorption. Curves G and H (fig. 2) were obtained in this way. The ionization is in arbitrary units, but a knowledge of the constants of the apparatus makes it possible to analyse the curves and actually to obtain from them the number of recoil atoms thrown within selected angles of the incident α ray.

Curve G was made with a nickel plate coated with thorium C as a source of α rays. There was an air-gap of about 2 mm. between source and wax screen, so that the maximum range of the α particles incident on the

wax screen was 8.4 cm. Curve H was made with two types of radioactive source. One was a plate coated with the active deposit from radium, giving α rays of range about 6.8 cm. incident on the screen. The points obtained

Fig. 2.



in this way are plotted on the curve as crosses. The other source was of thorium C, the plate being covered with an aluminium foil of stopping-power 1.5 mm. The α -rays had a maximum range of from 6.9 to 6.7 cm. when they reached the wax, according to the angle at which they passed through the foil. The points so obtained are plotted on the curve as circles.

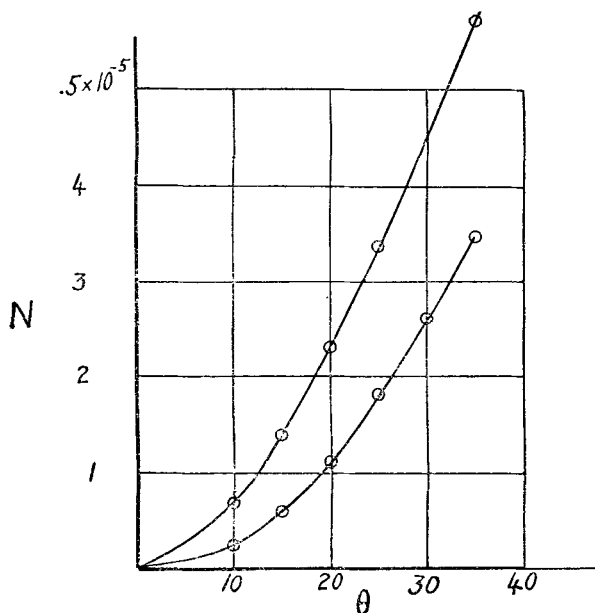
The number of α particles emitted from the source per second was deduced from its γ -ray activity as measured through 6 mm. of lead. No data could be found for the relation between the α - and γ -ray activities of thorium C, so a preliminary investigation was made for its determination. This is described in a note at the end of the paper. The fact that both sets of points on curve H fall about the same line shows that the value obtained was sufficiently accurate for the purpose.

4. *Quantities derived from the Absorption Curves giving information as to the nature of the collision.*

If it be assumed that all the energy of a hydrogen nucleus thrown forward by collision with an α particle is dissipated in producing ions (an assumption that is almost certainly approximately true), the actual number of recoil atoms thrown within various angles of the incident α ray can be calculated from curves such as G and H. From these numbers, information may be obtained relative to the nature of the collision and the size of the α particle. This question will be considered further in section 6. The steps in the calculation by which the numbers are derived from the absorption curves are outlined in the next section.

The quantities in Table I. are as follows:—The first column gives the number of recoil atoms whose path after collision makes an angle less than ϕ with the incident α ray. These numbers refer to one α particle passing through 1 cm. of hydrogen gas at N.T.P. The second column gives ϕ . The third gives the highest potential that the recoiling nucleus reaches in the field (assumed purely electrostatic) of the α particle.

Fig. 3.



N , the number of recoil atoms thrown within ϕ of the direction of motion of the α particle, is shown plotted against ϕ in fig. 3.

TABLE I.

From curve G, α particles of range 8.4 cm.			From curve H, α particles of range 6.8 cm.		
N.	ϕ .	V.	N.	ϕ .	V.
1.39×10^{-5}	15	5.50×10^6	$.60 \times 10^{-5}$	15	4.79×10^6
2.30	20	5.16	1.13	20	4.50
3.38	25	4.82	1.81	25	4.20
4.53	30	4.48	2.61	30	3.90
5.71	35	4.03	3.48	35	3.51

5. *Deduction from the Absorption Curves of the results given in the last section.*

The ordinates of curves G and H (fig. 2) multiplied by .772 give the number of pairs of ions produced in the ionization chamber divided by the number of α particles involved in the production of the recoil radiation, and the curves are obtained directly by experiment.

Curves J and K are derived from G and H. J corresponds to G, and K to H. The ordinate for abscissa R in the case of the new curves represents the total ionization produced by all atoms that pass R during the whole of the rest of their course. J and K are obtained from G and H as follows:—The absorption curves are marked off by vertical lines drawn at intervals of 1.5 cm. (the depth of the ionization chamber) starting from the maximum range. Thus G, whose end is at 39 cm, is cut into sections by lines at 37.5, 36.0, 34.5, 33.0, etc. If the ordinates at these points are a, b, c, d , etc., the new curve is constructed by drawing ordinates $a, a+b, a+b+c, a+b+c+d$, and so on, at abscissæ 37.5, 36.0, 34.5, 33.0. As 1.5 cm. is the depth of the ionization chamber, 'a' represents the total ionization produced by those atoms which pass 37.5. In the same way, 'b' represents the total ionization produced by those which pass 36.0 but not 37.5, plus the ionization produced by those which pass 37.5 in the part of their course between 36.0 and 37.5. Thus $a+b$ represents the total ionization produced by the atoms which pass 36.0. Similarly, it can easily be seen that $a+b+c, a+b+c+d$, etc., represent the total ionization due to those atoms that pass 34.5, 33.0, etc.

A consideration of the geometry of the experimental arrangement shows that the number of atoms entering the ionization chamber which recoil at an angle θ with the

direction of the incident α ray is approximately proportional to $p \sec \theta$, where p is the probability that an atom will recoil at an angle θ from a single α particle.

Combining the assumption that the whole energy of the recoil atom is dissipated in the production of ions with the experimental fact that the velocity of a recoil atom is proportional to the cube root of its remaining range, it is easy to show that the ordinates of the total ionization curves are given by

$$I_{\phi} = \int_0^{\phi} K R_0^{2/3} (\cos^3 \theta - \cos^3 \phi)^{2/3} \sec \theta F'(\theta) d\theta,$$

where $F(\theta)$ is the number of atoms recoiling at an angle less than θ from a single α particle as it passes through 1 cm. of hydrogen gas at N.T.P., ϕ is the angle at which an atom is shot that just reaches the range at which I_{ϕ} is measured, θ is any angle less than ϕ , R_0 is the maximum range of the recoil atoms, and K is a constant involving the dimensions of the apparatus and the ionizing power of a recoil atom. Beside the assumption that the whole energy of a recoil atom is dissipated in producing ions, the conservations of energy and momentum are assumed to hold during the collision.

A solution could not be found for the above integral, so $F(\theta)$ was assumed to have the form $A\theta + B\theta^2 + C\theta^3 + D\theta^4$, and the values of the constants were calculated by evaluating the integral by a Simpson's Rule method for four different values of ϕ and equating it to the appropriate value of I_{ϕ} taken from curves J and K. The equations obtained were as follows:—

Radium C.

$$\begin{aligned} \phi = 10^\circ & \dots\dots 03 \times 10^{-2} = 1950[A + 3.4 \times 2B + 17 \times 3C + 86 \times 4D], \\ \phi = 20^\circ & \dots\dots 37 \times 10^{-2} = 1950[A + 35.9 \times 2B + 323 \times 3C + 5080 \times 4D], \\ \phi = 25^\circ & \dots\dots 85 \times 10^{-2} = 1950[A + 74.5 \times 2B + 1040 \times 3C + 16660 \times 4D], \\ \phi = 35^\circ & \dots\dots 2.48 \times 10^{-2} = 1950[A + 215.8 \times 2B + 4322 \times 3C + 97350 \times 4D], \end{aligned}$$

Thorium C.

$$\begin{aligned} \phi = 10^\circ & \dots\dots 115 \times 10^{-2} = 2240[A + 3.4 \times 2B + 17 \times 3C + 86 \times 4D], \\ \phi = 20^\circ & \dots\dots 88 \times 10^{-2} = 2240[A + 35.9 \times 2B + 323 \times 3C + 5080 \times 4D], \\ \phi = 25^\circ & \dots\dots 1.725 \times 10^{-2} = 2240[A + 74.5 \times 2B + 1040 \times 3C + 16660 \times 4D], \\ \phi = 35^\circ & \dots\dots 4.49 \times 10^{-2} = 2240[A + 215.8 \times 2B + 4322 \times 3C + 97350 \times 4D], \end{aligned}$$

which give the following values for the constants :—

RaC.		ThC.	
$A = -2.1 \times 10^{-8}$	$C = 6.25 \times 10^{-10}$	$A = 1.3 \times 10^{-7}$	$C = -4 \times 10^{-11}$
$B = 2.16 \times 10^{-8}$	$D = -1.19 \times 10^{-11}$	$B = 5.56 \times 10^{-8}$	$D = -.92 \times 10^{-11}$

From these constants and the equation

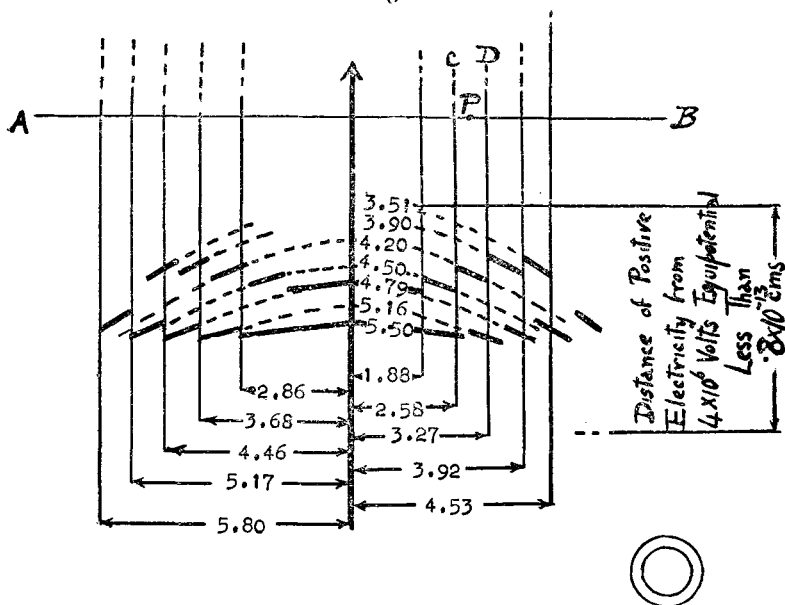
$$N = F(\theta) = A\theta + B\theta^2 + C\theta^3 + D\theta^4$$

the curves of fig. 3 have been plotted.

6. The Field near an α Particle.

Fig. 4 is a diagram of the field near an α particle deduced from the figures given in section 4 on the assumption that the forces are purely electrostatic. The simple form taken for the field is purely arbitrary, but the results represented graphically by the diagram are quite independent of this.

Fig. 4.



The dotted lines represent surfaces, close to the α particle, whose potentials (in millions of volts) are given by the numbers marked on them. The α particle is moving in the direction of the large arrow, and the short heavy lines

represent diametral sections of annular disks described on the equipotential surfaces and having the arrow as a common axis. The lines parallel to the arrow are sections of corresponding cylindrical shells. The dimensions below the figure refer to the radii of the annuli. They are given in cms. $\times 10^{-13}$.

The diagram can best be explained by means of a definite example. Suppose a hydrogen nucleus, assumed to be a point, is situated in front of the α particle at P. Then, if the velocity of the α particle is such that the nucleus reaches a potential of 4.2 million volts during the collision, it will be thrown at an angle of between 20° and 25° of the α ray. This is indicated in the figure by the annulus on the 4.2 million volt equipotential being drawn with its normal inclined at an angle of $22\frac{1}{2}^\circ$ to the direction of the arrow. In order that the nucleus may be thrown between 20° and 25° , it must lie within a certain area on a plane at right angles to the α -ray. AB in the diagram is such a plane, and the area, determined by calculation from the experiments, is that marked out by the cylindrical shell CD on AB.

The annuli described on the equipotentials consist of two sets, one derived from curve G (dimensioned on the left of the figure), the other from curve H (dimensioned on the right). The nearest annulus to the axis in each case represents nuclei recoiling between 0° and 15° , the next those between 15° and 20° , the third between 20° and 25° , the fourth between 25° and 30° , and the last between 30° and 35° .

If interpreted as above, the diagram represents the experimental results correctly whatever the form assumed for the field, provided that it is purely electrostatic. If the recoil of the nucleus is partly due to electromagnetic or other forces, the potentials will not be true electrostatic potentials, but will still describe the maximum potential energy of the collision in a convenient manner.

If the recoil be due only to electrostatic forces, a rough estimate of the dimensions of the field in the direction of motion of the α particle can be made, and an upper limit set with certainty to distances in this direction. One arrives at this by consideration of the field round a point charge of magnitude equal to that of an α particle. The 5.5 and 3.5 million volt equipotentials round the point are spheres of radius .52 and .82 $\times 10^{-13}$ cm. respectively (indicated in the bottom right-hand corner of fig. 4), and it is easy to show that for any distribution of charge other than a point

the equipotentials must be closer than this to some of the electricity. It is evident that to make fig. 4 in any way a correct picture of the field the scale must be reduced at least ten times in the direction of the arrow, and the positive electricity must be pictured as lying close under the 6 million volts equipotential.

A consideration of the difficulties in the way of constructing such a diagram suggests arguments against the purely electrostatic field. The electricity must be spread over a relatively large area, and therefore the density of charge must be low, and the nuclei must approach extremely close to attain the required potential. At the same time the inertia of the whole of the α particle must come into play during the collision; consequently there can be no disruption, and the forces between the nuclei at their points of intimate contact must be transmitted to the rest of the mass. If the hydrogen nucleus is pictured as a point charge flung at a stationary α particle, the structure of the latter would seem to be analogous to a strong heavy flexible sheet. This would offer a large target, yet oppose all its inertia to a small missile, exerting an impulsive force on it in a direction almost directly opposed to its line of flight.

If the recoil is not due to a simple electrostatic field, it would seem that the choice of structures for the nuclei would be much larger. At the same time, it is difficult to picture a mechanism which gives sufficiently large electromagnetic forces. Perhaps the simplest combined field would be one in which the magnetic field deflected the nuclei towards one another, in which case they may both be of small volume and the actual recoil be due to electrostatic repulsion. The same effect might be produced electrostatically by an α particle composed of two electrons and four hydrogen nuclei, the electrons deflecting the recoil nucleus towards the positive part of the α particle.

It must be remembered that the field considered is probably enormously different from that of the normal α particle. At the same time the great energy of the collision will ensure that the geometry of the system is that which gives minimum potential energy, and is therefore almost certainly the same in every collision, so that conclusions arrived at represent more than merely a statistical average.

I wish to thank Dr. A. Pontremoli, of the University of Rome, for his assistance in the counting operations necessary to obtain the relation between the α - and γ -ray activities of thorium C, and also Mr. Chadwick and Mr. Bieler of the

Cavendish Laboratory for suggesting the method finally adopted for deducing the numbers of recoil atoms from the experimental curves. My best thanks are due to Professor Rutherford for his continued interest and advice during the course of this research.

NOTE.

An Experiment to determine the relation between the α - and γ -Ray activities of Thorium C.

The standard of γ -ray activity was the ionization produced by 1 mg. of radium in equilibrium with its products, in an electroscope with sides of lead 6 mm. thick. The γ -ray activity of a source of thorium C, which had been allowed to come into equilibrium with thorium D, was measured on the standard electroscope and then placed in an exhausted glass tube. To the end of this was waxed a brass plate in which was a mica window of about 2 mm. diameter. Outside the tube was a zinc-sulphide screen on which the α particles, passing through the window from the source, produced scintillations. These were observed and counted by means of a scintillation microscope. Between window and screen was mounted a wheel with a hole near the circumference, which when rotated reduced the number of scintillations in a known ratio. This wheel was kindly lent me by Mr. Chadwick, who has given a full description of its use in a recent paper*. The stopping-power of the mica window was just sufficient to prevent the α particles of range 4.8 cm. from reaching the screen.

The number of long-range α particles projected within a definite solid angle by a thorium C source of known γ -ray activity was deduced from the above experiment. Precisely the same measurements were then made, using a source of radium C in place of thorium C. The number of α particles given off by the radium C in equilibrium with 1 mg. of radium is known; and the ratio of the numbers from thorium C and radium C sources of equal γ -ray activities can be deduced from the foregoing. From these values the relation between the α - and the γ -ray activity of thorium C can be obtained.

In the present research the quantity actually required was the ratio of the number of α particles given off by equal γ -ray activities (as measured through 6 mm. of lead) of radium active deposit and thorium C. Radium active deposit has a slightly greater γ -ray activity than its radium C constituent

* Chadwick, Phil. Mag. Dec. 1920.

alone, owing to the relatively weak γ -rays from radium B, and in consequence the ratio for equal γ -ray activities of thorium C and radium C, as obtained above, must be multiplied by a correction factor. This factor was taken from a paper by Moseley and Makower *. The results were as follows :—

	Radium C.	Thorium C.
Number of α particles per min. per mg. (if wheel were removed)	3350	2180
Number of particles counted.....	940	899
Ratio $\frac{\text{No. per mg. of ThC}}{\text{No. per mg. of RaC}} \dots\dots\dots$	$\frac{2180}{3350}$	
Ratio $\frac{\text{No. per mg. of ThC}}{\text{No. per mg. of Ra act. dep.} \dots\dots\dots}$	$\frac{2180}{3350} \times \frac{106}{100} = .69.$	

This ratio is now being determined accurately by Professor Schlundt and Mr. Shenstone in this laboratory.

XCIX. *The Excitation of γ Radiation by α Particles from Radium Emanation.* By F. P. SLATER, B.A., M.Sc.†

INTRODUCTION.

PART I.

CHADWICK ‡ has shown that the α -rays of Radium C excite a small but detectable quantity of γ radiation when they impinge on matter. From the character of his experiments this radiation could arise solely from the bombardment of atoms of matter, and not from the radioactive material itself. The radiation was of a comparatively soft nature, and it would have been almost impossible to have detected a small quantity of penetrating radiation among the intense and highly penetrating primary γ radiation always associated with radium C.

In a later paper Chadwick and Russell § using ionium sources, which emit practically no primary β and γ rays, were able to make a detailed examination of the γ radiation excited by the α particles, and found three types of soft, medium, and hard penetrating power. This radiation was excited in the active material itself or the thorium mixed with it.

* Moseley and Makower, *Phil. Mag.* 1912.

† Communicated by Prof. Sir E. Rutherford, F.R.S.

‡ Chadwick, *Phil. Mag.* xxv. p. 193 (1913).

§ Chadwick and Russell, *Proc. Roy. Soc. A.* vol. lxxxviii. (1913).