Philosophical Magazine Series 6, 42:252 (1921) 923



The rise-curves obtained during these investigations throw much light on the heterogeneity of the $\gamma$ radiations from Radium B. These considerations are reserved for a further paper.

I am much indebted to Professor Sir E. Rutherford for his suggestion of this research and for his assistance in overcoming many difficulties which appeared from time to time; and to Mr. G. A. R. Crowe for his help in manipulating the radioactive material.

Cavendish Laboratory, Cambridge.
June, 1921.

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## C. *The Collisions of α Particles with Hydrogen Nuclei.* By J. Chadwick, *Ph.D., Clerk Maxwell Student of the University of Cambridge, and* E. S. Bieler, *M.Sc., 1851 Scholar of McGill University, Montreal* *.

§ 1. WHEN $\alpha$ particles pass through hydrogen gas or a substance containing hydrogen, close collisions between an $\alpha$ particle and a hydrogen nucleus occasionally take place. As a result of such a close collision, the hydrogen nucleus is set in swift motion, and can be detected by the scintillation it produces on a zinc-sulphide screen. Assuming that both the $\alpha$ particle and the hydrogen nucleus can be regarded as points, and that the forces between them arise from their charges, C. G. Darwin † calculated the number of H particles projected within any given angle to the path of the $\alpha$ particle. Sir Ernest Rutherford ‡, however, found that the numbers and angular distribution of the projected H particles did not agree with the simple theory, and he attributed the divergence to the complex structure of the $\alpha$ particle. His results indicated that the field of force between the $\alpha$ particle and the hydrogen nucleus undergoes rapid changes in magnitude, and probably also in direction, when the nuclei approach within $3{\cdot}5\times10^{-13}$ cm. of each other. These experiments were of a preliminary nature, and were not carried out to any high degree of accuracy. Further, the experimental arrangement was such that the deduction of the collision relation from the observations was very involved.

Recently, improvement of the optical conditions has made

* Communicated by Prof. Sir E. Rutherford, F.R.S.
† Darwin, Phil. Mag. vol. xxvii. p. 499 (1914).
‡ Rutherford, Phil. Mag. vol. xxxvii. p. 537 (1919).

the counting of the weak scintillations produced by these H particles much easier and more certain. The microscope used consisted of a Watson holoscopic objective of 16 mm. focal length and ·45 numerical aperture combined with a low-power eyepiece. Compared with the old system, this increased greatly the brightness of the scintillations and gave at the same time a larger field of view, *i. e.* a larger number of particles, other conditions remaining constant. This system was found to be the most suitable for these experiments; further increase of the numerical aperture with corresponding increase in brightness of the scintillations could only be obtained with a smaller field of view. Careful tests showed that with the above system, H particles with a range of more than 2 cm. could be counted with certainty under good conditions of experiment. The counts of both observers were found to be consistent over an interval of some months.

In this way, the more direct method of experiment described in this paper was rendered possible. These experiments were carried out in the hope that a detailed study of these collision phenomena would give definite information as to the size and shape of the $\alpha$ particle or helium nucleus, and as to the field of force around it.

## § 2. *The Collision Relation.*

Experiments of the kind described here can only give a statistical account of the numbers of hydrogen nuclei projected in various directions and with various velocities by a pencil of $\alpha$ particles of known velocity. If there is no loss of energy in the collision, all the hydrogen nuclei projected in any one direction have the same velocity. The experiments then lead to a relation between three variables which has been called by Darwin * the Collision Relation.

Let E, M, and V be the charge, mass, and initial velocity of the $\alpha$ particle. Let $e$, $m$ be the charge and mass of the hydrogen nucleus, initially at rest, and let $u$ be the velocity after collision, in a direction making an angle $\theta$ with the initial line of motion of the $\alpha$ particle.

If the law of conservation of energy holds, it follows that

$$u = 2\frac{\mathrm{M}}{\mathrm{M}+m}\mathrm{V}\cos\theta = \tfrac{8}{5}\mathrm{V}\cos\theta,$$

since $\mathrm{M}=4m$.

* C. G. Darwin, Phil. Mag. vol. xli. p. 486 (1921).

The maximum velocity of the H particles projected by the $\alpha$ particles of RaC has been measured by Sir Ernest Rutherford *, and found to be in accord with that relation. He has also shown that the range of the H particle is proportional to the cube of its velocity. Therefore, if $R_0$ is the range given to an H particle by a direct impact, the range R of a particle projected at an angle $\theta$ is given by $R = R_0 \cos^3 \theta$.

The validity of the assumption that the law of conservation of energy holds in these collisions can be tested by observing simultaneously the range and direction of the H particles. It will be shown later that the above relation holds within the accuracy of the experiments, and the assumption is therefore justified.

The observations then consist in counting the number of H particles produced within a given angle by a known pencil of $\alpha$ particles. This number is a direct measure of the probability of a collision which will project the H particles within an angle $\theta$, and this probability will depend on the structure of the $\alpha$ particle and of the H particle.

If both particles can be regarded as point charges, it can be shown that the number of H particles projected within an angle $\theta$ by a single $\alpha$ particle in its passage through 1 cm. of hydrogen gas is

$$n = \pi N \mu^2 \tan^2 \theta,$$

where N is the number of H atoms per c.c., and

$$\mu = Ee\left(\frac{1}{M} + \frac{1}{m}\right) \cdot \frac{1}{V^2}.$$

As stated above, Sir Ernest Rutherford found that this relation did not hold, and he attributed the discrepancy between theory and experiment to the complex structure of the $\alpha$ particle. On the nuclear theory, the $\alpha$ particle is composed of four H nuclei and two electrons. For the present, therefore, it is justifiable to regard the H particle as a point charge and to ascribe the difference between experiment and the simple theory to the complexity of the $\alpha$ particle.

The experiments give a relation between $n$ and $\theta$ for a given velocity of the $\alpha$ particle, or, if observations are made with sets of $\alpha$ particles of different velocities, a relation between the three quantities $n$, $\theta$, and V.

* Rutherford, *loc. cit.*

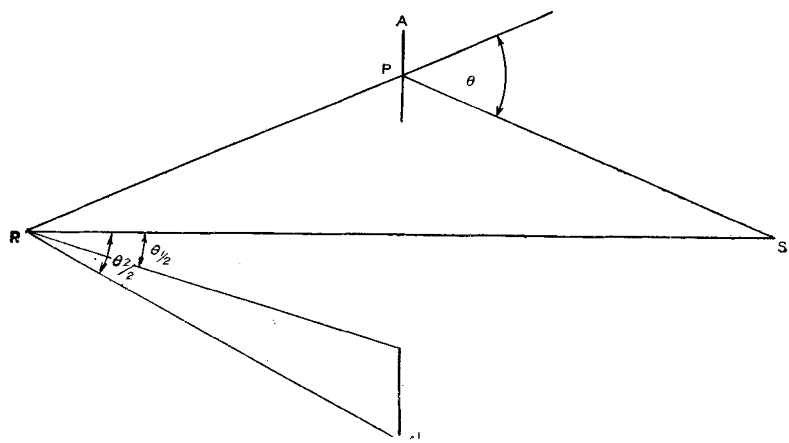
The interpretation of the experiments consists in deducing from this relation the field of force around the $\alpha$ particle, and in finding what structure of the $\alpha$ particle, or combination of four H nuclei and two electrons, will give this field of force.

## § 3. *Method of Experiment.*

In these collisions it is immaterial whether the hydrogen is present in the form of hydrogen gas or in the combined state as in paraffin wax. The use of paraffin wax as a source of hydrogen has many advantages, and was preferred in the present experiments.

In fig. 1 let R be the source of $\alpha$ particles, AA′ a thin sheet of paraffin wax in the form of an annular ring, and let a zinc-sulphide screen be placed at S on the axis of the cone RAA′, so that RA=AS.

Fig. 1.




The solid angle subtended at R by an elementary annular ring at P is $2\pi \sin \theta/2 \, . \, d\theta/2$. If Q is the number of $\alpha$ particles emitted per second by the source, then the number falling per second on this elementary ring is $Q/2 \sin \theta/2 \, d\theta/2$.

Let the number of H particles projected within an angle C by a single $\alpha$ particle in passing through 1 cm. of hydrogen gas at N.T.P. be $n=F(\theta)$. Then the number projected between $\theta$ and $\theta+\delta\theta$ is $\delta n=F'(\theta)\delta\theta$, and the number observed on a screen of unit area placed $r$ cm.

away will be $\frac{F'(\theta)}{2\pi r^2 \sin\theta}$. If the thickness of the paraffin sheet AA′ is such that it is equivalent in hydrogen content to $t$ cm. of hydrogen gas, then the number of H particles projected from the elementary ring at P to unit area at S, placed at right angles to RS, is

$$Q/2 \, . \sin\theta/2 \, . \, d(\theta/2) \, . \cos\theta/2 \, . \, t \, . \sec\theta/2 \, . \frac{F'(\theta)}{2\pi r^2 \sin\theta}$$

$$= \frac{Q}{8\pi r^2} \, . \, t \, . \sec\theta/2 \, . \, F'(\theta) \, . \, d(\theta/2).$$

For the whole angular ring of angular limits $\theta_1/2$, $\theta_2/2$ the number of H particles falling on unit area of the zinc-sulphide screen is

$$\int_{\theta_1/2}^{\theta_2/2} \frac{Q}{8\pi r^2} \, . \, t \, . \sec\theta/2 \, . \, F'(\theta) \, . \, d(\theta/2).$$

For our purpose, it is sufficient to take mean values of $r^2$ and $t \, . \sec\theta/2$. Calling these $\overline{r^2}$ and $\bar{t}$, the above number is

$$\frac{Q \, . \, \bar{t}}{16\pi \overline{r^2}} \, . \, [F(\theta_2) - F(\theta_1)].$$

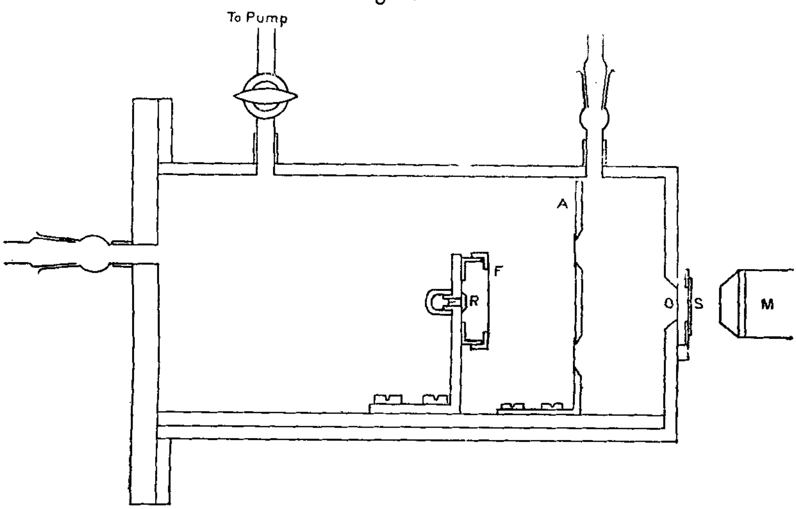
If the number of H particles observed on the screen be referred to a source of Ra(B+C), of 1 mg. $\gamma$-ray activity, Q is then the number of $\alpha$ particles emitted per second by 1 mg. Ra.

If the paraffin wax is in the form of a circular sheet, *i. e.* $\theta_1/2=0$, the number of H particles observed on the ZnS screen is directly proportional to $F(\theta_2)$. The simplest method of experiment is therefore to use circular sheets of wax of different angular limits $\theta_2/2$, $\theta_2'/2$, etc. The observations give immediately points on the curve $n=F(\theta)$ corresponding to the various angles $\theta_2$, $\theta_2'$, etc. This method, however, has the disadvantage that H particles projected at very different angles, and therefore with very different velocities, fall upon the screen during the same observation, and it is doubtful if in such a mixture of bright and weak scintillations all the weak scintillations would be counted. It was considered advisable, therefore, to use circular sheets for the smaller angles only ; for angles greater than 20°, annular rings of wax of suitable angular limits were used. The use of these has the further advantage that the "natural" H particles emitted by the source of $\alpha$-rays can be prevented from reaching the ZnS screen.

## § 4. *Apparatus.*

The apparatus was almost the same as that described by one of us* in a recent paper on the scattering of $\alpha$ particles. The general arrangement is shown in fig. 2.

Fig. 2.




The sheet of paraffin was held on a diaphragm placed at A, equidistant from the source R and the ZnS screen. The opening O was covered with aluminium foil of 3·7 cm. air-equivalent, and absorbing screens of aluminium could be inserted between the opening and the ZnS screen. These screens were necessary to prevent scattered $\alpha$ particles from hitting the ZnS screen, and were also used in measuring the range of the H particles.

The ZnS screen was observed through a microscope, M, which had a numerical aperture of 0·45 and a field of view of 7·7 sq. mm. area.

The box containing the source and diaphragm was placed between the poles of an electromagnet. This served to deflect the $\beta$-rays emitted from the source, and was only necessary with the diaphragms containing central holes.

The paraffin sheets were cut by means of a microtome, and their thickness was found by weighing.

The source of $\alpha$ particles was a brass disk of 3 mm. diameter, coated on the face with Ra(B + C). Its initial

* J. Chadwick, Phil. Mag. vol. xl. p. 734 (1920).

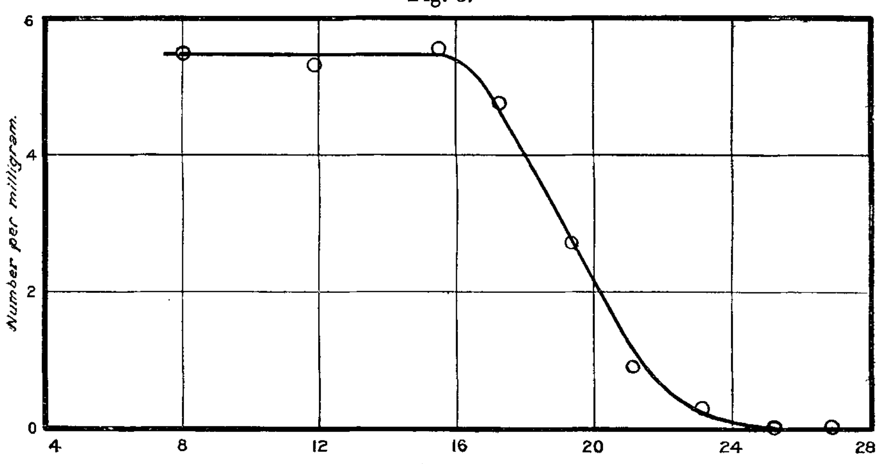
$\gamma$-ray activity was usually equivalent to from 5 to 10 mg. Ra. When the source and diaphragm were in position, the box was evacuated, and the H particles falling on the ZnS screen were counted.

### § 5. *Ranges of* H *particles projected at known Angles.*

It was stated in § 2 that, if the laws of conservation of energy and momentum hold in these collisions, the range R of an H particle projected at an angle $\theta$ is given by $R = R_0 \cos^3 \theta$, where $R_0$ is the range of the H particle projected in the line of motion of the $\alpha$ particle.

At various times during the experiments, measurements of the ranges of the $\alpha$ particles observed between known angles were made by inserting aluminium screens of known stopping-power between the opening O and the ZnS screen. It was found that the maximum range $R_0$ of the H particle, measured in aluminium and expressed in equivalent cm. of air, was 30 cm.

Fig. 3.




In one set of experiments, a sheet of paraffin wax of effective thickness 8·0 $\mu$ or 8·7 mm. stopping-power was used on a diaphragm of angular limits 21°·4 to 31°·3. The greatest range of the H particles observed on the screen should then be 24·2 cm., corresponding to an angle of 21°·4 and an $\alpha$ particle of range 7·0 cm., and the least range should be 16·3 cm. for an angle of 31°·3 and an $\alpha$ particle of range 6·13 cm.

The curve of fig. 3 shows the experimental results.

Within the accuracy of experiment, the measured ranges, after allowing for the fact that the H particles travel through the screens at an angle, agree with the calculated ranges, indicating that there is no appreciable loss of energy in these collisions, such as might occur owing to radiation or to the conversion of translational energy into rotational energy.

## § 6. *Angular Distribution of the* H *particles.*

The relation $n=F(\theta)$ has been investigated carefully up to an angle of 48°·4 for the impact of $\alpha$ particles of average range 6·6 cm.

The following diaphragms were used :—

| | | | | | |
|---|---|---|---|---|---|
| Diaphram | A, | for which $\theta=0$ | | and $\theta=$ | 11°·3, |
| „ | B, | „ | 0 | „ | 21°·4, |
| „ | C, | „ | 21°·4 | „ | 31°·3, |
| „ | D, | „ | 31°·3 | „ | 41°·0, |
| „ | E, | „ | 41°·5 | „ | 48°·4. |

Each diaphragm carried a sheet of paraffin wax of effective thickness equal to 8·0 $\mu$, equivalent to 1·22 cm. of hydrogen gas at N.T.P. Its stopping-power was equal to 8·7 mm. of air. The range of the incident $\alpha$ particles was 7·0 cm., and their average range in the paraffin sheet was 6·6 cm.

The distance from source to diaphragm, and from diaphragm to screen, was 26·8 mm.

In the case of diaphragms A and B, the H particles observed on the screen consisted partly of the so-called "natural" H particles *. These are supposed to be due to a slight hydrogen contamination of the source or any absorbing foils in the path of the $\alpha$ rays. All foils which were exposed to the $\alpha$ rays were heated *in vacuo* to reduce the number of these "natural" particles to a minimum. Their number was found by observations when the diaphragm and paraffin were removed, and was usually about 1·5 per minute per mgm. activity of the source.

With the other diaphragms no correction of this kind was necessary, for the central disk of the diaphragm stopped the "natural" H particles completely.

The second column of the following table gives the

* Rutherford, *loc. cit.* p. 544.

number of H particles observed on the screen per minute per mg. activity of the source for each diaphragm:—

| Diaphragm. | No. of H particles per mg. per min. | $F(\theta_2)-F(\theta_1)$. | $\theta$. | $n$. |
|---|---|---|---|---|
| A .. ......... | 1·7 | $\cdot 29\times 10^{-5}$ | 11°·3 | $\cdot 39\times 10^{-5}$ |
| B ............ | 7·1 | $1\cdot 23\times 10^{-5}$ | 21°·4 | $1\cdot 63\times 10^{-5}$ |
| C ............ | 5·5 | $\cdot 99\times 10^{-5}$ | 31°·3 | $2\cdot 94\times 10^{-5}$ |
| D ............ | 4·0 | $\cdot 76\times 10^{-5}$ | 41°·0 | $3\cdot 94\times 10^{-5}$ |
| E ............ | 2·4 | $\cdot 48\times 10^{-5}$ | 48°·4 | $4\cdot 58\times 10^{-5}$ |

The third column gives the values of $F(\theta_2)-F(\theta_1)$ calculated according to the final result of § 3, putting

$$Q = \text{No. of } \alpha \text{ particles emitted by 1 mg. Ra per second} = 3\cdot 7\times 10^{7}$$

$$\overline{t} = 1\cdot 22$$

and substituting for $\overline{r^2}$ the values pertaining to each diaphragm.

The fifth column gives the numbers of H particles projected within various angles, as calculated from the data of column 3. These are also given in curve B of fig. 4. In this calculation, a correction is necessary for the fact that all the H particles which fall within the field of view of the microscope do not hit a ZnS crystal, and therefore do not produce a scintillation. The efficiency of the screen was determined by comparison with a standard screen, which had been carefully calibrated by sources of RaC, and found to be 76 per cent.

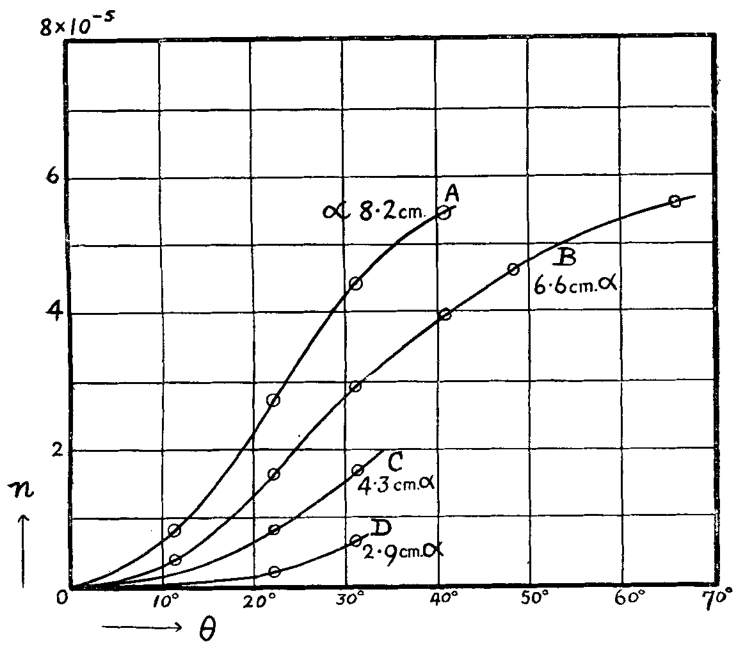
The values of $n$ are probably correct to within 5 per cent.

In addition to the numbers of column 5 above, one point is plotted on curve B of fig. 4, corresponding to an angle of 66°. Owing to the fact that, at large angles, the $\alpha$ particles scattered from the C atoms in paraffin wax have a range almost equal to that of the projected H particles, it was found impossible to use paraffin wax in the determination of this point. Hydrogen gas was used instead, and two diaphragms of angular limits 48°·4 and 66° were so arranged that the second one cut out any $\alpha$ particles scattered in the direction of the screen by the first one.

The number of H particles projected at various angles by $\alpha$ particles of mean ranges 8·2, 4·3, and 2·9 cm. was determined in a similar way.

The source of $\alpha$ particles of mean range 8·2 cm. was a deposit of thorium C, obtained on one side of a nickel disk by immersion in a strong solution of radiothorium. Thorium C gives complex $\alpha$-rays, viz. 65 per cent. of range 8·6 cm., and 35 per cent. of range 5·0 cm. The number of particles of range 8·6 cm. emitted by ThC has been

Fig. 4.




compared recently in this laboratory by Professor Schlundt and Mr. Shenstone with the number of $\alpha$ particles emitted by Ra(B+C) of equal $\gamma$-ray activity. Under the conditions of measurement in our experiments, the number of 8·6 cm. particles per milligram activity of ThC is taken as 0·75 of the number of 7 cm. $\alpha$ particles per milligram activity of Ra(B+C).

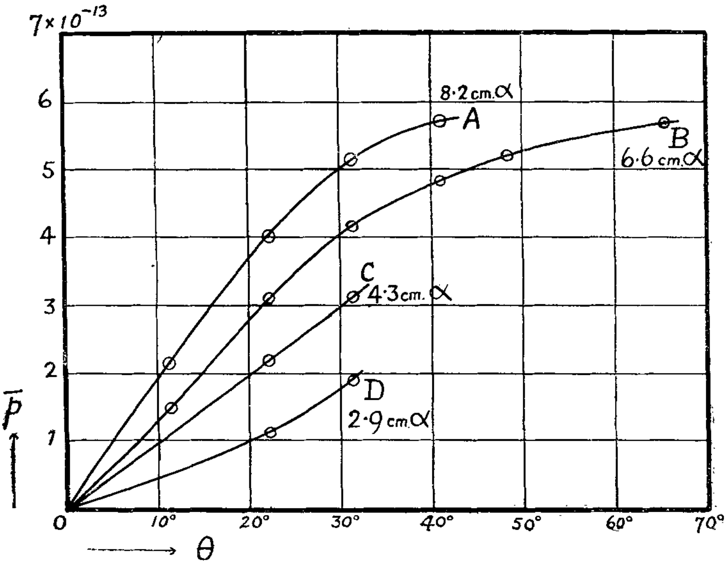
The H particles due to the $\alpha$ particles of range 5·0 cm. were cut out by absorbing screens placed in front of the ZnS screen.

Sources of $\alpha$ particles of smaller range than 7 cm. were obtained by placing gold or silver foils of known stopping-power over a source of radium (B+C), as at F in fig. 2.

The results are shown in curves A, C, and D of fig. 4. It will be noted that the observed numbers of H particles are greatly in excess of those which would be given by point charges and the inverse square law of force. On this theory, the value of $n$ for an angle of 30° and an $\alpha$ particle of mean range 8·2 cm. is $4{\cdot}4\times10^{-7}$; for an $\alpha$ particle of mean range 2·9 cm. it is $15{\cdot}8\times10^{-7}$. The corresponding observed values are $4{\cdot}3\times10^{-5}$ and $0\ 6\times10^{-5}$ respectively: in the first case 100 times as great as the inverse square number, in the second not quite 4 times as great. This suggests that the inverse square forces would hold for the collisions of $\alpha$-rays of still lower velocity, and it may be stated here that this anticipation is borne out by the results to be described in the next section.

It will frequently be necessary to compare our results with the collision relations calculated by Darwin * for various models of the $\alpha$ particle; and for convenience of comparison, the $n$, $\theta$ curves of fig. 4 are translated into the $p$, $\theta$ curves of fig. 5, as this is the form in which Darwin

Fig. 5.




expresses his results. If we define a quantity P as the probability of the collision of a single $\alpha$ particle with a single H nucleus resulting in the projection of the H nucleus within an angle $\theta$, the quantity $\bar{p}$ is given by $P=\pi\bar{p}^2$. Hence $\bar{p}=\sqrt{\frac{n}{\pi N}}$, where $N=5{\cdot}41\times10^{19}$, the number of H atoms per c.c. of hydrogen gas at N.T.P.

* Darwin, Phil. Mag. vol. xli. p. 486 (1921).

## § 7. *Variation of the Number of* H *particles with the Velocity of the* $\alpha$ *particle.*

The variation of the number of H particles projected within a given angle with the velocity of the incident $\alpha$-rays can be deduced from the curves of fig. 4 for a range of velocities from $2 \cdot 02 \times 10^9$ to $1 \cdot 43 \times 10^9$ cm. per sec. As previously mentioned, these results suggested that the inverse square law would be valid for the collisions of $\alpha$-rays of still lower velocity. It was found impracticable, however, to determine the whole $n$, $\theta$ curve for $\alpha$-rays of very small range; for, when using the diaphragms A and B, the "natural" H particles coming from the source and absorbing screens in the path of the $\alpha$-rays were more numerous than those produced in the paraffin film. Consequently, the effect of particles of low range was investigated with diaphragm C; that is, between $21^{\circ} \cdot 4$ and $31^{\circ} \cdot 3$.

The results for $\alpha$-rays of mean range varying from 6·6 to 1·0 cm. are collected in the following table. The second column gives the value of $(V_0/V)^2$, where $V_0 = 1 \cdot 92 \times 10^9$ cm. per sec., the velocity corresponding to a range of 7 cm., and V is the velocity corresponding to the range given in the first column. The third column gives the observed number of H particles per mgm. activity of the source, and the fourth the values of $F(31^{\circ} \cdot 3) - F(21^{\circ} \cdot 4)$ after correction for the efficiency of the screen.

In the case of the counts with $\alpha$-rays of range 1·6 cm. and 1·0 cm., a further correction was necessary to take into account the stoppage of $\alpha$ particles by the absorbing screens of gold which were used to cut down the range. This was determined by a second experiment, in which the $\alpha$ particles from a weak source of Ra(B + C) were counted through the same thickness of gold. It was found that the effective number of $\alpha$ particles in the count at a range of 1·6 cm. was 84 per cent. of the number emitted by the source, while in the count at 1 cm. range the effective number was only 50 per cent. The numbers observed at these ranges were therefore multiplied by factors of 1·2 and 2·0 respectively.

For comparison, the values of $F(31^{\circ} \cdot 3) - F(21^{\circ} \cdot 4)$ which would be given by point charges and the inverse square law are shown in the last column.

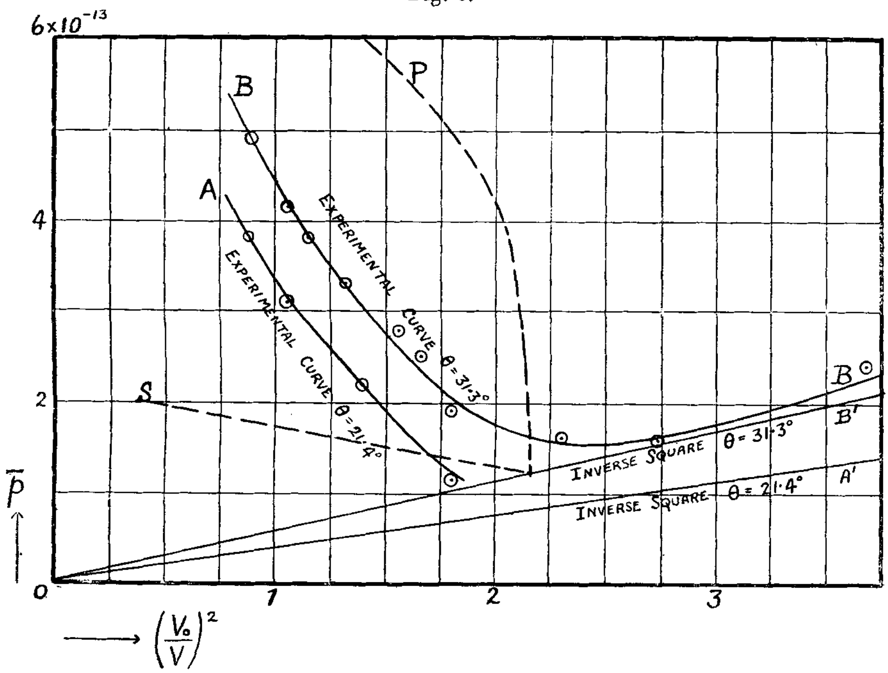
It is seen that as the range of the $\alpha$-rays is diminished, there is a very rapid decrease in the observed number of H particles, until, for an $\alpha$ particle of range about 2 cm., a minimum is reached at which the number is about that to be expected on the inverse square law. As the velocity of the α particle is further reduced, the number of H particles increases in the way demanded by this law of force.

| Range of α particle. | $(V_0/V)^2$. | No. of H particles per mgm. | F(31°·3)–F(21°·4). | Inverse Square Law. |
|---|---|---|---|---|
| 6·6 | 1·04 | 5·5 | $9·9\times10^{-6}$ | $0·34\times10^{-6}$ |
| 5·6 | 1·16 | 4·6 | 8·4 | 0·43 |
| 4·6 | 1·32 | 3·7 | 6·7 | 0·55 |
| 3·6 | 1·55 | 3·1 | 5·6 | 0·76 |
| 3·3 | 1·65 | 2·8 | 5·1 | 0·86 |
| 2·9 | 1·80 | 1·7 | 3·0 | 1·0 |
| 2·0 | 2·32 | 1·1 | 1·9 | 1·8 |
| 1·6 | 2·70 | 0·8 | 1·8 | 2·3 |
| 1·0 | 3·69 | 1·4 | 4·9 | 4·3 |

It appears from these results that the inverse square law holds, at least approximately, for the collisions of α particles of low velocity, that is, for large distances of collision. It was clearly of great importance to make certain of this point. The experiments with the low-range α-rays were therefore repeated several times, all possible precautions being taken. The observations were naturally difficult, owing to the weakness of the scintillations produced by the low-range H particles concerned, but we estimate that the error is within 30 per cent. The fact that H particles due to α-rays of 1 cm. mean range could still be counted consistently would indicate that the count with α-rays of 2 cm. range must certainly be reliable ; and the latter count agrees within the error of experiment with the inverse square number.

The variation of the number of H particles with the velocity of the α-rays is shown very clearly in fig. 6, where Darwin's $\bar{p}$ is plotted against $(V_0/V)^2$. For α-rays of range less than 2·9 cm. [$(V_0/V)^2 > 1·80$], the numbers between 0° and 21°·4 could not be determined directly, for the reason stated above. To obtain the total numbers between 0° and 31°·3, it was assumed that within this range these numbers follow the same law of variation with angle as that given by the inverse square law, viz. $n \propto \tan^2\theta$, and the results obtained for the angles between 21°·4 and 31°·3 were multiplied by the factor $\tan^2 31°\cdot 3 / (\tan^2 31°\cdot 3 - \tan^2 21°\cdot 4)$.

Fig. 6.




The curves of fig. 4 lead one to expect that this would be very closely true at the smaller ranges. From the values of $n$ so calculated, the values of $\bar{p}$ were obtained according to the formula at the end of § 6.

## § 8. *Discussion.*

The results of the experiments described in this paper are crystallized in the curves of figs. 5 and 6. From these we should be able to deduce information about the field of force around the $\alpha$ particle or helium nucleus, and also about its structure.

In the first place, our results are in strong contrast to those to be expected if the nuclei behaved as point charges repelling each other with forces varying as the inverse square of the distance between them. Not only is the angular distribution of the H particles different, but the numbers projected at small angles are, for $\alpha$ particles of high velocity, many times greater than those for point nuclei. For example, the observed number of H particles projected within 30° of the direction of incident α-rays of range 8·2 cm. is more than 100 times as great as the theoretical number; the number projected within the same angle by α-rays of range 4·3 cm. is 15 times the theoretical number. Again, the observed variation of the numbers of H particles with velocity of the α particle is in the opposite direction from that given by the point-charge theory. For example, α-rays of range 8·2 cm. project within an angle of 30° nearly 3 times as many H particles as α-rays of range 4·3 cm.; on the point-charge theory, the α-rays of 4·3 cm. range should give nearly 3 times as many as the 8·2 cm. α-rays.

It seems clear, then, that in the collisions of high-velocity α particles with H atoms the forces between the α particle and the H nucleus do not vary according to the inverse square law. On the other hand, the results obtained with α particles of low velocity show that this law is approximately true for larger distances of collision. It is our task to find some field of force which will reproduce these effects.

A similar task has been undertaken by C. G. Darwin * for the experimental results of Sir E. Rutherford. In his paper, he has worked out the collision relations for all possible models of the α particle which give integrable orbits.

He showed that a square nucleus, in which the H nuclei are arranged at the four corners of a square and the two electrons together at the centre, would give a field of force very similar to that of a bipole; the collision relation of the bipole was roughly similar to that deduced from Rutherford's experiments.

Comparison of the $\bar{p}, \theta$ and $\bar{p}, (V_0/V)^2$ curves for the bipole with those of figs. 5 and 6 shows clearly that such a system does not give our collision relation. Simple calculations show that the forces around the bipole are much too small to give the observed effects. It appears, indeed, that any combination of four H nuclei and two electrons with inverse square law forces cannot give our collision relation, for this indicates that, at a certain distance, the forces around the α particle increase with great rapidity.

The simplest representation of such a field of force is afforded by the hard elastic sphere. An H particle projected towards the sphere moves under inverse square forces until it strikes the sphere, when it rebounds elastically. The $\bar{p}, \theta$ curves for the elastic sphere are given by Darwin on p. 502 of his paper, and it will be seen that they are, at

* Darwin, *loc. cit.*

first sight, very similar to the curves of fig. 5. The curves for $\alpha$ particles of different velocities are, however, much closer together than our experimental curves: in other words, the elastic sphere gives a much smaller variation in number of projected H particles with velocity of the $\alpha$-rays than we require. By comparison of the two sets of $\bar{p}$, $\theta$ curves, it is easy to find the radius of an elastic sphere which will give approximately both the observed number and the distribution of the H particles for any one velocity of the $\alpha$ particle. For $\alpha$ particles of range 6·6 cm. this radius is $8 \times 10^{-13}$ cm.; while for $\alpha$ particles of range 4·3 cm. it is $5 \times 10^{-13}$ cm. If we consider the elastic sphere as a simple representation of a discontinuous field of force, in which the repulsive forces increase very rapidly at a short distance from the $\alpha$ particle, we should expect an effective radius smaller at high velocities than at low. Since the effective radius varies in the opposite way, we are forced to reject the elastic sphere. If, as Darwin suggests, the elastic sphere represents in a general way systems of any shape, but orientated equally in all directions, we may conclude that the $\alpha$ particle is probably an orientated system so arranged as to throw more of the H particles forwards.

This view is strengthened by consideration of the collision relation for the elastic plate, worked out by Darwin. This model of $\alpha$ particle repels the H particle with a force varying as the inverse square of the distance from the centre, and the centre is surrounded by a circular plate from which the H particle rebounds elastically. The $\bar{p}$, $\theta$ curves for such an elastic plate (Darwin, p. 504) show a greater variation with the velocity of the $\alpha$ particle than our experimental curves: that is, they differ in the opposite sense to the curves for the elastic sphere.

In fig. 6, curve S is the $\bar{p}, (V_0/V)^2$ curve for $\theta = 31°·3$ for an elastic sphere of radius $4 \times 10^{-13}$ cm., and curve P that for an elastic plate of radius $8 \times 10^{-13}$ cm. At the point of intersection they turn into the inverse square law line B′. The dimensions are so chosen as to give a deviation from the inverse square law in the region given by the observations. The corresponding experimental curve lies about midway between these curves.

As a first approximation, we may say that the $\alpha$ particle behaves in these collisions as a body with properties intermediate between the elastic sphere and the elastic plate, and compare it with an elastic oblate spheroid of semi-axes about $8 \times 10^{-13}$ cm. and $4 \times 10^{-13}$ cm. respectively, moving in the direction of its minor axis. On this view, an H particle projected towards an $\alpha$ particle would move under the ordinary electrostatic forces governed by the inverse square law, until it reached a spheroidal surface of the above dimensions. Here it would encounter an extremely powerful field of force and recoil as from a hard elastic body. The effect of this model of $\alpha$ particle will be studied further, and an attempt will be made to obtain its collision relation.

It is not possible to say from these experiments whether there is any actual discontinuity in the law of force between the nuclei. The absence of a flat part in the $\bar{p}$, $\theta$ curves, and the general shape of the $p$, $(V_0/V)^2$ curves, would suggest that these new forces merge gradually into the inverse square law forces.

As regards the structure of the $\alpha$ particle, it will be apparent at once that no system of four H nuclei and two electrons united by inverse square law forces could give a field of force of such intensity over so large an extent. We must conclude either that the $\alpha$ particle is not made up of four H nuclei and two electrons, or that the law of force is not the inverse square in the immediate neighbourhood of an electric charge. It is simpler to choose the latter alternative, particularly as other experimental, as well as theoretical, considerations point in this direction. The present experiments do not seem to throw any light on the nature or the law of variation of the forces at the seat of an electric charge, but merely show that the forces are of very great intensity.

It is of interest to note that, assuming an $\alpha$ particle composed of four H nuclei and two electrons, the present experiments provide the only direct evidence we have as to the size of the electron. These results show that the radius of the electron cannot be greater than about $4 \times 10^{-13}$ cm.

## § 9. *Summary.*

In this paper, the relations which hold in the collisions between $\alpha$ particles and H nuclei have been investigated.

(1) The angular distribution of the H particles projected by $\alpha$ particles of mean range 6·6 cm. has been determined up to an angle of 66°. The distribution for $\alpha$-rays of mean ranges 8·2, 4·3, and 2·9 cm. has been obtained over a smaller range of angle. It is shown that the number of H particles projected within these angles by $\alpha$-rays of high velocity is greatly in excess of that given by forces varying as the

inverse square of the distance between the centres of the two nuclei.

(2) The variation in the number of H particles projected within a given angle with the velocity of the $\alpha$-rays has been observed over a wide range. It is shown that for $\alpha$-rays of high velocity the variation is in the opposite direction to that given by the inverse square law; for $\alpha$-rays of range less than 2 cm., velocity less than $1{\cdot}26 \times 10^9$ cm. per sec., however, the collision relation is about the same as that given by the inverse square law.

(3) The experimental collision relation is compared with those calculated by Darwin for various models of $\alpha$ particle, and the conclusion is reached that the $\alpha$ particle behaves in these collisions as an elastic oblate spheroid of semi-axes about $8 \times 10^{-13}$ and $4 \times 10^{-13}$ cm., moving in the direction of its minor axis. Outside this surface the force varies approximately as the inverse square of the distance from the centre of the spheroid.

In conclusion, we desire to express our best thanks to Sir Ernest Rutherford for his interest and advice throughout the course of the experiments.

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## CI. *The Mutual Action of the Convection Currents arising from two fine heated Platinum Wires.* By J. S. G. Thomas, *D.Sc. (Lond.), B.Sc. (Wales), A.R.C.S., A.I.C., Senior Physicist, South Metropolitan Gas Company, London**.

### *Introduction.*

A TYPE of hot-wire inclinometer wherein two fine heated platinum wires, parallel to one another, were subjected to the mutual thermal effects due to their respective free convection currents, such thermal effects being dependent upon the inclination to the horizontal of the plane of the wires, was recently described by the author †. The effects to which attention was directed in that paper are of some consequence in a variety of directions, *e. g.* in connexion with the theory of the hot-wire microphone as described by Tucker and Paris ‡. Likewise in the design

* Communicated by the Author.

† Proc. Phys. Soc. vol. xxxii. Part v. pp. 291–314 (1920).

‡ Phil. Trans. Roy. Soc., A.592, vol. 221, pp. 389–430 (1921).