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LI. *Collision of α Particles with Light Atoms.* I. *Hydrogen.*

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§ 1. ON the nucleus theory of atomic structure, it is to be anticipated that the nuclei of light atoms should be set in swift motion by intimate collisions with α particles. From consideration of impact, it can be simply shown that as a result of a head-on collision, an atom of hydrogen should acquire a velocity 1·6 times that of the α particle before impact, and should possess ·64 of the energy of the incident α particle. Such high speed "H" atoms should be readily detected by the scintillation method. This was shown to be the case by Marsden [†], who found that the passage of α particles through hydrogen gave rise to numerous faint scintillations on a zinc sulphide screen placed far beyond the range of the α particles. The maximum range of the H particles, set in motion by the α particles from radium C, was over 100 cm. in hydrogen or about four times the range of the colliding α particles in that gas. This range agreed well with the value calculated by Darwin [‡] from Bohr's [§] theory of the absorption of α particles by matter.

In most of the experiments of Marsden, a thin glass α-ray tube, containing purified radium emanation, was used as an intense source of rays. This was placed in a closed vessel at a suitable distance from a zinc sulphide screen, and the space

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[*] Communicated by the Author.

[†] Marsden, Phil. Mag. xxvii. p. 824 (1914).

[‡] Darwin, Phil. Mag. xxvii. p. 499 (1914).

[§] Bohr, Phil. Mag. xxv. p. 10 (1913).

between filled with compressed hydrogen. It was found that the number of H scintillations fell off approximately according to an exponential law when absorbing screens of matter were interposed, and the relative absorption of metal foils was in good accord with the square root law observed by Bragg for α particles.

In a second paper, Marsden * showed that the α-ray tube itself gave rise to a number of scintillations like those from hydrogen. Similar results were observed with an α-ray tube made from quartz instead of glass, and also with a nickel plate coated with radium C. The number of H scintillations observed in all cases appeared to be too large to be accounted for by the possible presence of hydrogen in the material, and Marsden concluded that there was strong evidence that hydrogen arose from the radioactive matter itself. Further experiments were interrupted by the departure of Mr. Marsden to New Zealand early in 1915 to fill the Professorship of Physics in Victoria College, Wellington. The quantity of radium available there was too small to continue observations, while the possibility of further work was precluded by the return of Professor Marsden to Europe on Active Service.

We have seen that Marsden in his second paper had some indications that the radioactive matter itself gave rise to swift H atoms. This, if correct, was a very important result, for previously the presence of no light element except helium had been observed in radioactive transformations.

It was thought desirable to continue these experiments in more detail, and during the past four years I have made a number of experiments on this point and on other interesting problems that have arisen during the progress of the work. The experiments recorded in this and subsequent papers have been carried out at very irregular intervals, as the pressure of routine and war-work permitted, and in some cases experiments have been entirely dropped for long intervals.

§ 2. *Source of the scintillations from active matter.*

Marsden had observed that the number of H scintillations from a nickel plate, coated with radium C, was considerably greater than for a corresponding quantity of emanation—measured by γ rays—from an α-ray tube. It thus seemed possible that H atoms might arise from the disintegration of radium C, for it is well known that this product is transformed in an anomalous manner. In order to test this point, observations were made on the variations of the number of H scintillations from an α-ray tube immediately after it was filled with emanation. It is well known that the amount of radium C in such a tube increases at first very slowly. For example, after filling a tube with emanation, the fraction of the final amount of radium C present after 10 minutes is only 2 per cent., but reaches 9 per cent. after 20 minutes †. Consequently, observations made on the number of scintillations within 10 minutes after filling should decide definitely whether the scintillations arise from radium C alone and not from the other α-ray products present, viz. the emanation and radium A. In the latter case, the number of scintillations after 10 minutes should be only 2 per cent. of the final number reached about three hours later when radium C is in transient equilibrium with the emanation.

A number of α-ray tubes were kindly made and filled for me by Mr. N. Tunstall, B.Sc. The whole process of filling and removal for testing was done as rapidly as possible, and the counting of scintillations was usually begun within four minutes after filling. The α-ray tube was placed between the poles of a strong electromagnet in order to reduce the luminosity due to β rays on the zinc sulphide screen, placed 2 centimetres beyond the range of the α rays. After every precaution had been taken to avoid radioactive contamination, the number of scintillations observed between 4 and 10 minutes was greatly in excess of the number to be expected if they had their origin in the transformation of radium C alone. The actual ratio of the maximum number varied with the thickness of the α-ray tube, but the fraction observed initially was from 20 to 40 per cent. of the maximum reached three hours later.

These results showed conclusively that, if the H atoms from a glass α-ray tube were a product of radioactive disintegration, they arose not only from radium C but also from radium A or the emanation or both. It is hoped to discuss in a later paper the results of a number of experiments to test whether hydrogen is a product of radioactive change. It is not easy to give a decisive answer to this important problem on account of the numerous factors involved. It will be seen later that the number of scintillations from hydrogen is much greater than is to be expected on the simple theory, and it is difficult to be sure of the absence of hydrogen as a contamination in the source and absorbers of the radiation. In addition, both nitrogen and oxygen atoms are set in such swift motion by collision with α particles that they cause

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* Marsden, Phil. Mag. xxx. p. 240 (1915).

† 'Radioactive Substances and their Radiations,' Rutherford, p. 499.

scintillations outside the range of the α particles. It seems probable that the large number of scintillations observed by Marsden (*loc. cit.*) from a nickel plate coated with radium C were mainly due, not to H atoms, but to high-velocity N and O atoms produced from the air between the source and the screen.

§ 3. *Source of radiation.*

While the use of α-ray tubes as an intense source of radiation has many advantages, it has the drawback that the α radiation is heterogeneous arising from the three products radium A, radium C, and the emanation. In addition, it is difficult to make α-ray tubes of uniform thickness whose stopping power is less than two centimetres of air. For these reasons, I have discarded the use of α-ray tubes and have conducted the majority of the experiments with a homogeneous source of radiation, consisting of the active deposit of radium. Twenty minutes after removal from the emanation, the α radiation arises entirely from radium C and is homogeneous with a range in air of 7 cm. A brief account will now be given of the method for obtaining an intense source of radiation of convenient dimensions. The source usually consisted of a circular bevelled brass disk which was screwed on the lower end of a glass stopcock. The emanation, after removal from the radium solution, was sparked with oxygen to remove excess of hydrogen until the volume was reduced to about 0·5 c.c. This emanation was introduced by means of a mercury trough into a small transfer pump and the mercury raised until its level was 1 or 2 mm. below the disk to be activated. The disk was connected through the stopcock with the negative pole of the lighting circuit and the mercury with the positive pole, in order to concentrate to some extent the active matter on the surface of the disk. After two hours' exposure, the emanation was pumped out and the active disk removed. Theoretically, in order to obtain the maximum activity, the exposure to the emanation should be more than three hours, but in practice it is found that an exposure of two hours gives more activity, while an exposure of twenty-four hours gives much less than an exposure of two hours. This anomalous effect had been previously observed by Ratner*, and is apparently due to the loss of active matter from the disk through the intermediary of the electric wind.

Using a large quantity of emanation, it is possible to

obtain in this way a disk, coated on one side with radium C, which has a gamma-ray activity equal to 80 mg. of radium. In most experiments, sources were employed of activity between 5 and 80 mg. of Ra.

The active disk after removal was washed in alcohol and then heated for a minute in an exhausted tube inside an electric furnace at about 300° C. As Ratner (*loc. cit.*) has pointed out, the treatment with alcohol reduces greatly the loss of active matter by so-called volatilization, while the heating tends to remove the surface gases and the emanation occluded in the disk during its exposure. The quantity of active matter on the disk was determined with the aid of a standardized gamma-ray electroscope. The decrease of intensity with time is known from the well-known curve of decay.

§ 4. *Counting scintillations.*

As the systematic counting of H scintillations under varied conditions is a rather difficult and trying task, it may be of some value to mention the general arrangements found most suitable and convenient in practice. Using the excellent zinc sulphide screens, specially prepared by Mr. Glew, the scintillation due to a high-speed H atom appears as a fine brilliant star or point of light, very similar in appearance and intensity to that produced by an alpha particle about 3 mm. from the end of its range. Near the end of the range of the H atom, the scintillation becomes very feeble, and can only be observed on a dark background. Consequently, in a heterogeneous beam of H atoms, the actual number counted per minute is to some extent dependent on the luminosity of the background seen in the microscope. It is important to adjust and keep the luminosity of the screen to the right amount throughout the whole interval of an experiment. This is most simply done by means of a small "pea"-lamp fixed in a metal tube in which the current is varied. While weak scintillations are readily counted on a dark background, it is difficult under such conditions to keep the eye focussed on the microscope image and the eye rapidly becomes fatigued and counting becomes erratic. The microscope employed had a magnification of about 40 and covered a field of 2 mm. diameter. This in practice was found to be a very convenient magnification. In later experiments, special zinc sulphide screens were prepared in which the smaller crystals were sifted through a fine gauze on to a glass plate covered with a thin layer of adhesive material. These fine crystals completely covered the plate several crystals deep. With such a screen,

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* Ratner, Phil. Mag. xxxiv. p. 429 (1917); xxxvi. p. 397 (1918).

the H scintillations appeared larger and more diffuse, probably due to the scattering of the light in passing through the thick layer of crystals, and were more easily counted, while weak scintillations could be counted on a brighter background than with the ordinary screen. At the same time, the layer of crystals was so uniform, that each incident H atom produced a scintillation.

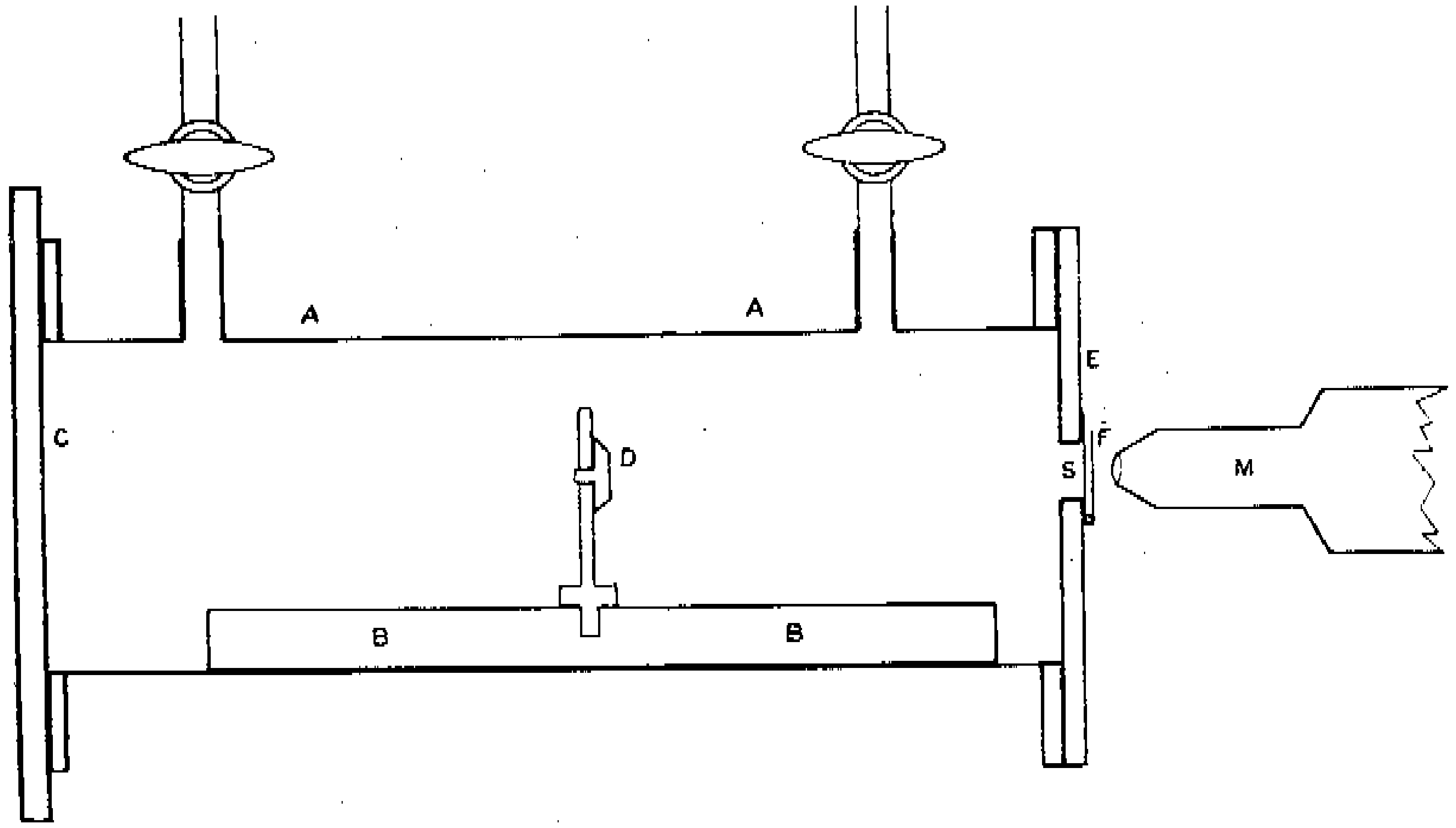
In these experiments, two workers are required, one to remove the source of radiation and to make experimental adjustments, and the other to do the counting. Before beginning to count, the observer rests his eyes for half an hour in a dark room and should not expose his eyes to any but a weak light during the whole time of counting. The experiments were made in a large darkened room with a small dark chamber attached to which the observer retired when it was necessary to turn on the light for experimental adjustments. It was found convenient in practice to count for 1 minute and then rest for an equal interval, the times and data being recorded by the assistant. As a rule, the eye becomes fatigued after an hour's counting and the results become erratic and unreliable. It is not desirable to count for more than 1 hour per day, and preferably only a few times per week.

Under good conditions, counting experiments are quite reliable from day to day. Those obtained by my assistant Mr. W. Kay and myself were always in excellent accord under the most varied conditions. It was usually arranged that the number of scintillations to be counted varied between 15 and 40 per minute.

§ 5. *Experimental arrangement.*

For experiments with hydrogen and other gases, the active disk D (fig. 1) was mounted at a convenient height parallel to the screen on a metal bar B which slid into a rectangular brass box A, 18 cm. long, 6 cm. deep, and 2 cm. wide, with metal flanges at both ends fitting between the rectangular poles of a large electromagnet. One end was closed by a ground glass plate C, and the other by a waxed brass plate E, in the centre of which was cut a rectangular opening 1 cm. long and 3 mm. wide. This opening was covered by a thin plate of metals of silver, aluminium or iron, whose stopping power for α particles lay between 4 and 6 cm. of air. The zinc sulphide screen F was fixed opposite the opening and distant 1 or 2 mm. from the metal covering. By means of two stopcocks, the vessel was filled with the gas to be examined either by exhaustion or displacement. It is a great advantage to have the zinc sulphide screen outside the apparatus, in order to avoid contamination due to volatilized active matter, and for the easy introduction of absorbing material between the end plate and the screen.

Fig. 1.



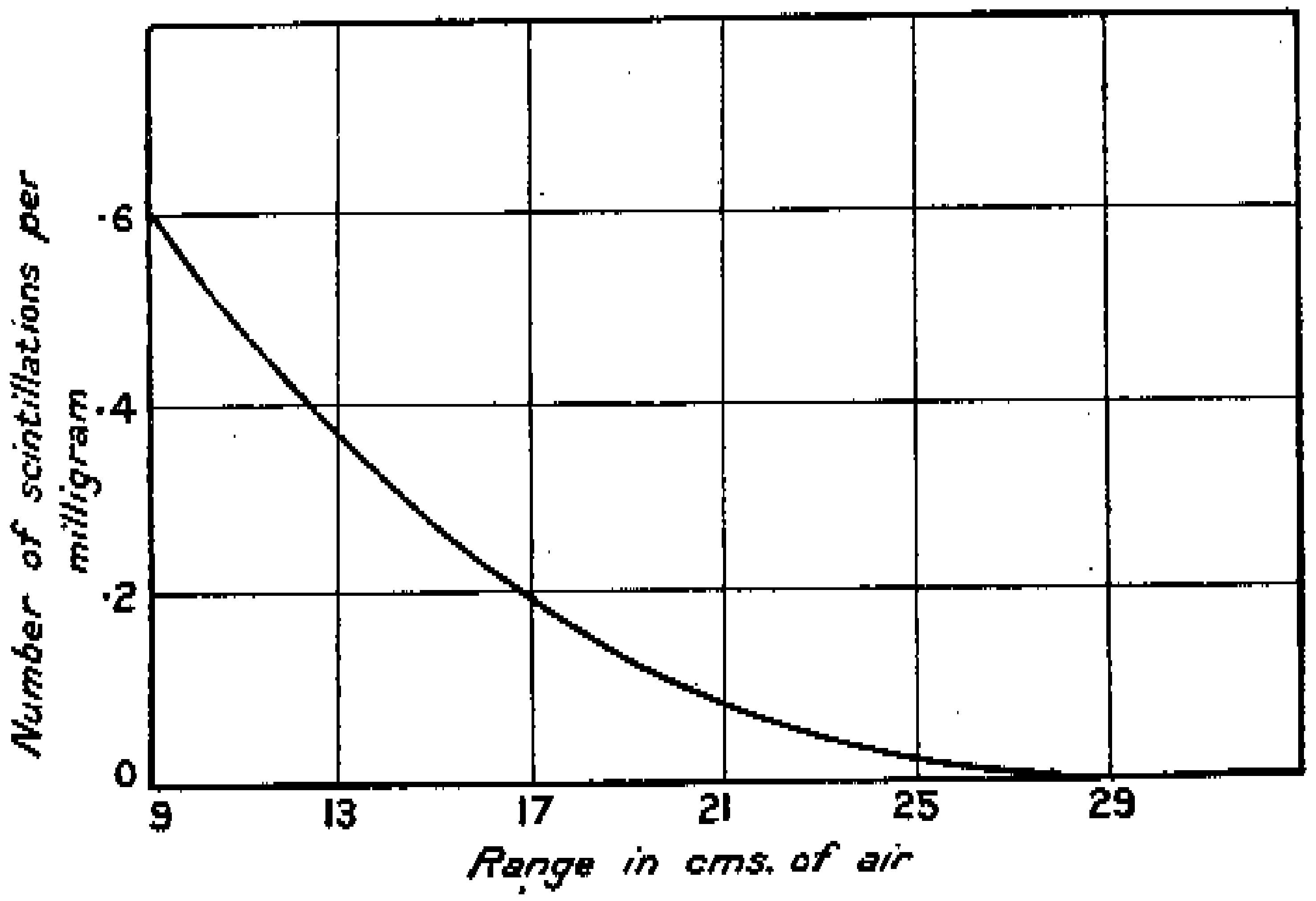
In practice, the source was introduced into the brass vessel at a convenient distance from the screen, and the air exhausted. The α rays after traversing the end plate fell on the screen, and the marked luminosity due to them was a guide in fixing the microscope M in the centre of the opening. The diameter of the field of view (2 mm.) was less than the width of the opening (3 mm.).

Since the number of H atoms observed under ordinary conditions is less than one in a hundred thousand of the number of α particles, H atoms, projected in the direction of the α particles, can only be detected when the α rays are stopped by the absorbing screens. It was not found possible to bring an intense source closer than 3 cm. from the screen on account of the luminosity excited in it by the γ rays and swift β rays, which prevented counting of weak scintillations. A strong magnetic field was necessary to bend away the β rays which caused a very marked luminosity on the screen. A field of 6000 gauss was generally employed for this purpose.

§ 6. *Scintillations due to source and absorbing screens.*

When the containing vessel was exhausted of air, scintillations were always observed on the screen proportional in number to the activity of the source. The number fell off rapidly between 7 and 12 cm. air absorption and then more slowly, but a few could be observed nearly to 28 cm. The variation of number with amount of absorption in terms of cms. of air is shown in fig. 2. This refers to a heated brass source, 3·3 cm. from the screen, with a heated silver plate of stopping power 6 cm. of air just before the screen.

Fig. 2.



These scintillations appear to be due mainly to H atoms excited partly in the source and partly in the absorbing screens. Thin foils of aluminium, for example, placed close to the source increase the number of scintillations. This is due to the occlusion of hydrogen, which can be removed by heating the aluminium in an exhausted furnace just below the melting-point. Similar effects were observed with silver but not with gold. In practice, all screens to be used in the path of the α rays were heated to drive off occluded gases as far as possible. This is very necessary when small numbers of scintillations have to be counted. Usually a silver plate was used to absorb the α rays. Gold was found to be very free from hydrogen, but it could not be used in place of silver close to the screen on account of the marked luminosity set up on the screen well beyond the range of the α particles. This peculiarity of gold had been previously noted by Marsden, but I was surprised to observe the magnitude of the effect with strong sources of radiation. A fuller account of the nature and cause of this luminosity will be postponed till a later paper. In a similar way, mica was found to cause a good deal of luminosity, apparently due to gamma rays. In addition, as is to be expected, mica gives rise to numerous H atoms and swift oxygen atoms. For these reasons, mica is unsuitable for an absorbing screen for α particles in this type of experiment.

§ 7. *Theory of Collision of α particles with light atoms.*

It will be seen later that the number of H atoms and their distribution with velocity differ markedly from the results to be expected theoretically. It is consequently desirable to consider first with some detail the results to be anticipated on simple theoretical grounds, before discussing the experimental results.

The effect of collision of swift α particles with light atoms has been worked out by C. Darwin *.

α particle : M mass, E charge, v initial velocity, ϕ angle of scattering from original direction.
Light atom : m mass, e charge, u velocity after impact, θ angle of deflexion from original direction of α particle.

From considerations of simple impact, it follows that

$$u = 2v\frac{M}{M+m}\cdot\cos\theta, \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\tan\phi = \frac{m\sin 2\theta}{M-m\cos 2\theta}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If there is no loss of energy in the impact we should consequently expect $u = \frac{8}{5}v\cos\theta$ for the hydrogen atom, quite independently of any assumption as to the nature and magnitude of the forces involved in the impact. In order, however, to calculate the number of H atoms scattered within a given angle θ, it is necessary to make special assumptions as to the magnitude and direction of the forces. Assuming that the forces arise from the charges carried by the atomic nuclei which are to be regarded as points, and that the forces vary as the inverse square, Darwin has shown that

$$p = \mu\tan\theta, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where p is the perpendicular distance from the atom on the initial direction of motion of the α particle and $\mu = \frac{Ee}{v^2}\left(\frac{1}{m}+\frac{1}{M}\right)$.

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* C. Darwin, Phil. Mag. (*loc. cit.*).

If Q α particles pass normally through a layer of gas thickness dx, which contains N atoms per c.c. at N.T.P., then the number dn of H atoms projected between the angles 0 and θ is given by

$$\begin{aligned} dn &= \mathrm{QN}\pi p^2 dx \\ &= \pi\mathrm{NQ}\mu^2 \tan^2\theta \, . \, dx. \end{aligned}$$

Since the reduction of velocity of the α particle in passing through 1 cm. of hydrogen is small, the number n of H atoms produced per cm. of path is given by

$$n/\mathrm{Q} = \pi\mathrm{N}\mu^2 \tan^2\theta. \quad . \quad . \quad . \quad . \quad . \quad . \qquad (4)$$

In this case n/Q is the fraction of α particles which give rise to an H atom between 0 and θ.

Taking $e = \frac{1}{2}\mathrm{E} = 4{\cdot}77 \times 10^{-10}$ e.s. unit, $v = 1{\cdot}922 \times 10^9$ cm. per sec., $\mathrm{N} = 5{\cdot}41 \times 10^{19}$, and $e/m = 9570$ for hydrogen,

$$\text{then} \qquad \mu = 9{\cdot}27 \times 10^{-14}$$

$$\text{and} \qquad n/\mathrm{Q} = 1{\cdot}46 \times 10^{-6} \tan^2\theta. \quad . \quad . \quad . \quad . \qquad (5)$$

It was found experimentally that the swiftest H atoms due to an α particle from radium C had a range corresponding to 28 cm. of air or four times the range of the α particle. Generally it was found that the maximum range of the H atom was four times the range of the α particle producing it. Since the range of α particles varies as the cube of their velocity, it follows that the range of H atoms is proportional, at any rate approximately, to the cube of their velocity. Since the velocity of an H atom projected at an angle θ with the α particle is $u_0 \cos\theta$ where u_0 is the maximum velocity of the H atom, the range R of an H atom projected at angle θ is given by $\mathrm{R}/\mathrm{R}_0 = \cos^3\theta$ where R_0 is the maximum range. Since, however, the α particles fall nearly normally on the screen, the H atoms deflected at an angle θ travel a distance $\mathrm{R}\sec\theta$. Consequently the range R in the direction of the α particles is given by $\mathrm{R}/\mathrm{R}_0 = \cos^4\theta$. Substituting the value of θ in equation (5),

$$n/\mathrm{Q} = 1{\cdot}46 \times 10^{-6}\left(\sqrt{\frac{\mathrm{R}_0}{\mathrm{R}}} - 1\right).$$

This equation only applies to α particles of velocity v_0 emitted by radium C. Since $p \propto 1/v^2$, it is seen that the number of H atoms varies as $1/v^4$. Remembering that the range of the α particle varies as v^3, it is easily seen that for α particles of range r

$$n/\mathrm{Q} = 1{\cdot}46 \times 10^{-6}(r_0/r)^{\frac{4}{3}}\left(\sqrt{\frac{\mathrm{R}_{\mathrm{max.}}}{\mathrm{R}}} - 1\right),$$

where r_0 is range of α particle from radium C, viz. 7·0 cm., and $\mathrm{R}_{\mathrm{max.}}$ is the maximum range of the H atom for a range r, viz. $4r$.

The values of n/Q for different values of R are given in Table I. for α particles of range 7, 5, and 3 cm. in air respectively. It should be noted that Q/n represents the number of α particles required to produce on the average in traversing one centimetre of the gas one H atom, which has a range equal to or greater than R cms. of air.

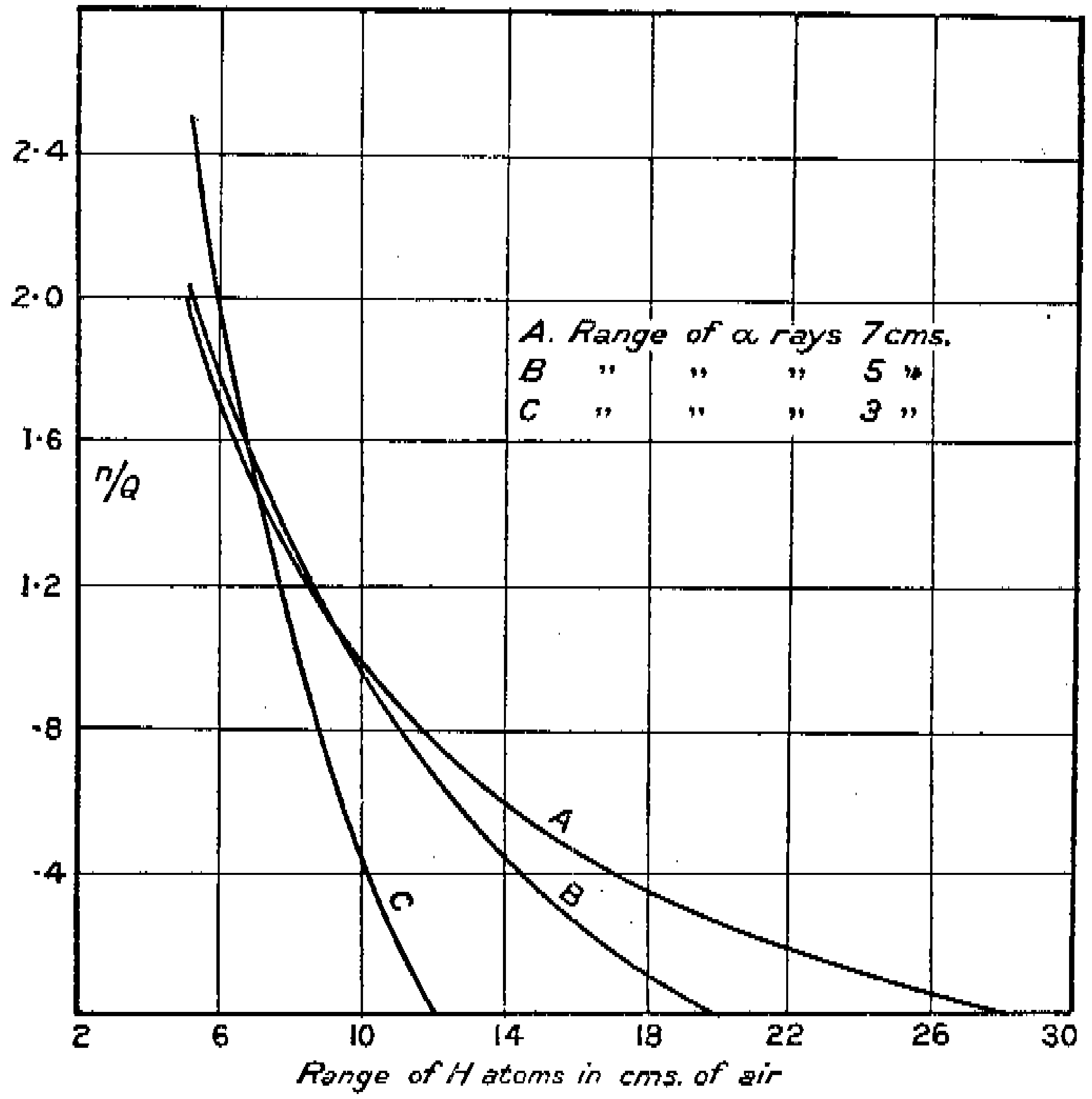
Table I.

Range of α particles $=7$ cms.		Range of α particles $=5$ cms.		Range of α particles $=3$ cms.	
Range R of H atoms.	n/Q.	**Range R of H atoms.**	n/Q.	**Range R of H atoms.**	n/Q.
1 cm.	$6{\cdot}3 \times 10^{-6}$	1 cm.	$7{\cdot}9 \times 10^{-6}$	1 cm.	$11{\cdot}1 \times 10^{-6}$
2 „	4·0 „	2 „	4·9 „	2 „	6·5 „
4 „	2·8 „	4 „	2·8 „	3 „	4·5 „
7 „	1·46 „	7 „	1·53 „	4 „	3·3 „
10 „	·98 „	10 „	·95 „	5 „	2·5 „
14 „	·60 „	14 „	·45 „	6 „	1·9 „
18 „	·34 „	16 „	·27 „	8 „	1·0 „
22 „	·19 „	18 „	·12 „	10 „	·4 „
24 „	·12 „	20 „	0 „	12 „	0 „
26 „	·05 „				
28 „	0 „				

These results are shown graphically in fig. 3, curves A, B, and C respectively, for ranges of the H atoms from 5 to 28 cm. It is seen that the curve A is approximately exponential between 8 and 18 cm., falling to half value in about 5·3 cm. This holds equally for curves B and C over corresponding ranges. These curves give the theoretical variation in number of the H atoms with range such as would be observed if the numbers of H atoms were counted for different thicknesses of absorber.

As the value of n/Q is less than 1/100000, it is not feasible with the present arrangement to detect H atoms within the range of the much more numerous α particles. For this reason, it is not possible to compare theory with experiment in the region of short ranges for which some of the values are calculated. It is seen that while the number of H atoms for short ranges increases rapidly with the reduction of range of the α particle, the three curves show approximately the same ordinates for 6·5 cm. range of the H atoms.

Fig. 3.

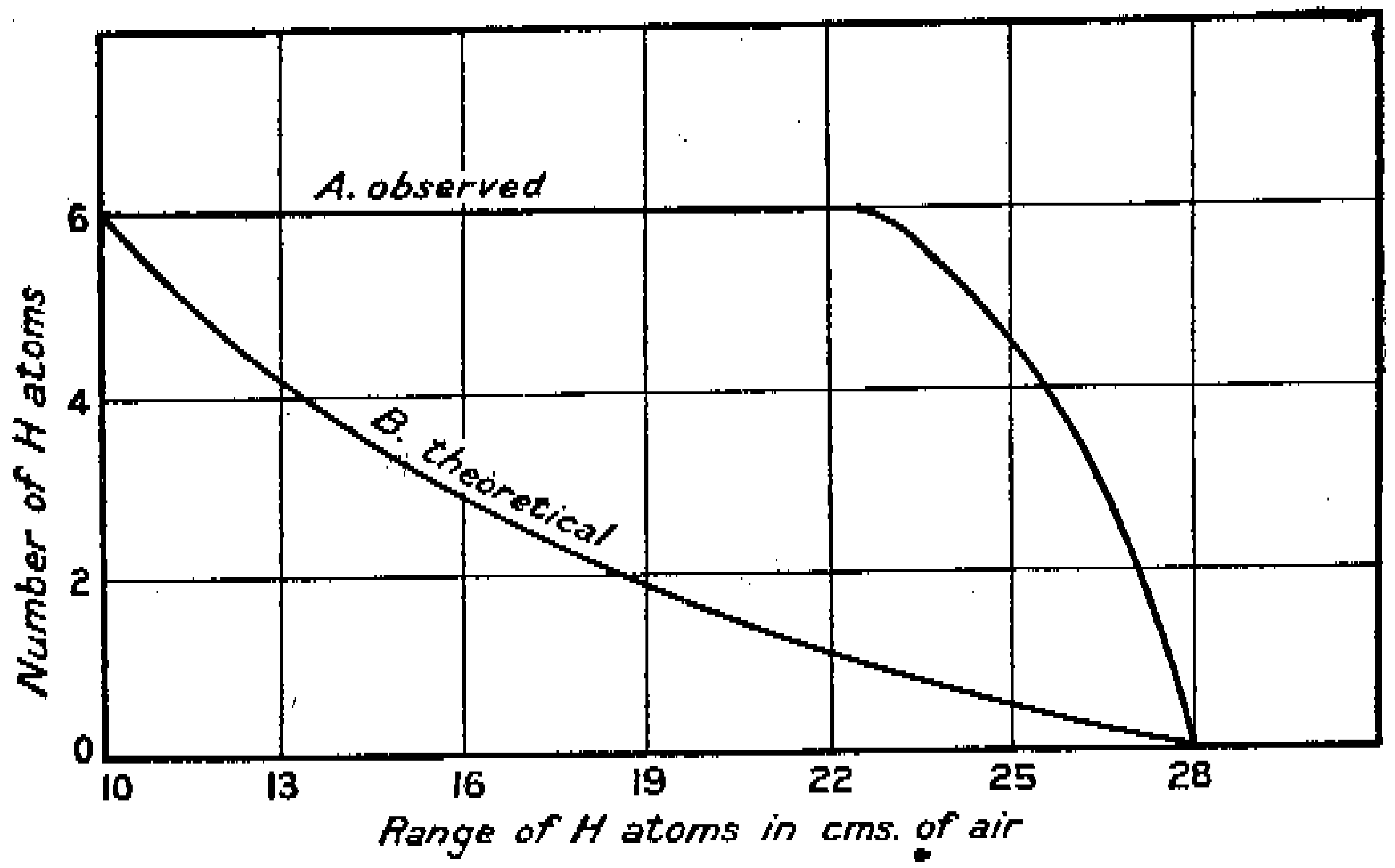


§ 8. *Absorption of* H *atoms.*

The source of α rays was a brass disk coated with radium C only in the central part, in order to reduce the area emitting α rays. The initial γ-ray activity of the disk was equivalent to about 10 mg. Ra. The zinc sulphide screen was mounted parallel to the disk in the apparatus shown in fig. 1 at 3·3 cm. distance from the source. An opening in the end of the box was covered with a heated silver plate, whose absorption for α particles was equivalent to 5·8 cm. of air, and the whole apparatus was filled by exhaustion with dry hydrogen, at atmospheric pressure. Suitable absorbing screens of aluminium foil were interposed between the silver plate and the screen, and the scintillations counted.

The results obtained are shown in fig. 4, curve A, where the ordinates represent number on an arbitrary scale and the abscissæ the thickness of absorbing material measured in terms of cms. of air for α particles. The equivalent absorption in the silver plate and in the hydrogen is included. The latter was taken as equivalent to 8 mm. of air or one quarter the length of the path of the α particles in hydrogen. The correction due to the natural scintillations from the source and silver plate was small.

Fig. 4.



It is seen that there is no diminution in the number of scintillations for absorptions between 9 and 19 cm. of air*. After 19 cm., there was a slow decrease followed by a rapid fall near the end of the curve. No scintillations were observed beyond 28 cm., *i. e.* for a range four times that of the α particles from radium C.

The shape of the absorption curve is entirely different from that to be expected theoretically. The latter is shown in curve B, calculated from the data given in § 7, the same ordinate being taken for an absorption of 10 cm. Between 9 and 19 cm. absorption, the number of scintillations according to theory should fall from 100 to 28.

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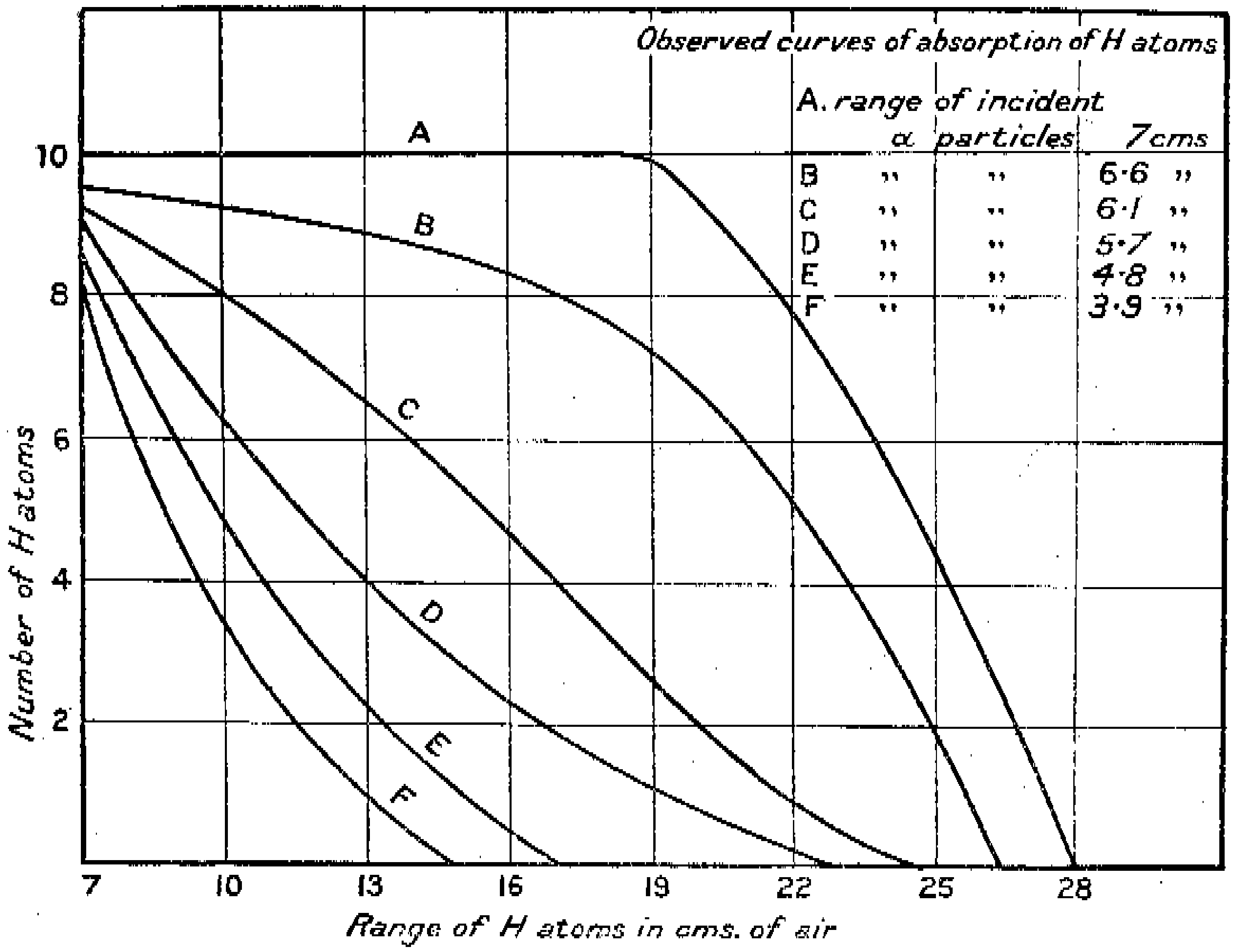
[*] It should be remarked that, for the distances employed, the width of the testing vessel (fig. 1) was sufficient to give the correct average distributions of H atoms with velocity, corresponding to a source at the centre of a sphere.

This peculiarity of the absorption curve is only marked for long-range α particles. In fig. 5 the absorption curves for initial ranges of the α particles 7 cm., 6·6, 6·1, 5·7, 4·8, 3·9 cm. are shown. The range was reduced by interposing gold or aluminium screens of known stopping power for the α particles close to the source. Even when the range of the α particles is reduced from 7 to 6 cm., the absorption curve already shows an evident decrease of number with thickness of absorber, and this decrease becomes much more marked for decreasing ranges between 6 and 3 cm.

Fig. 5.

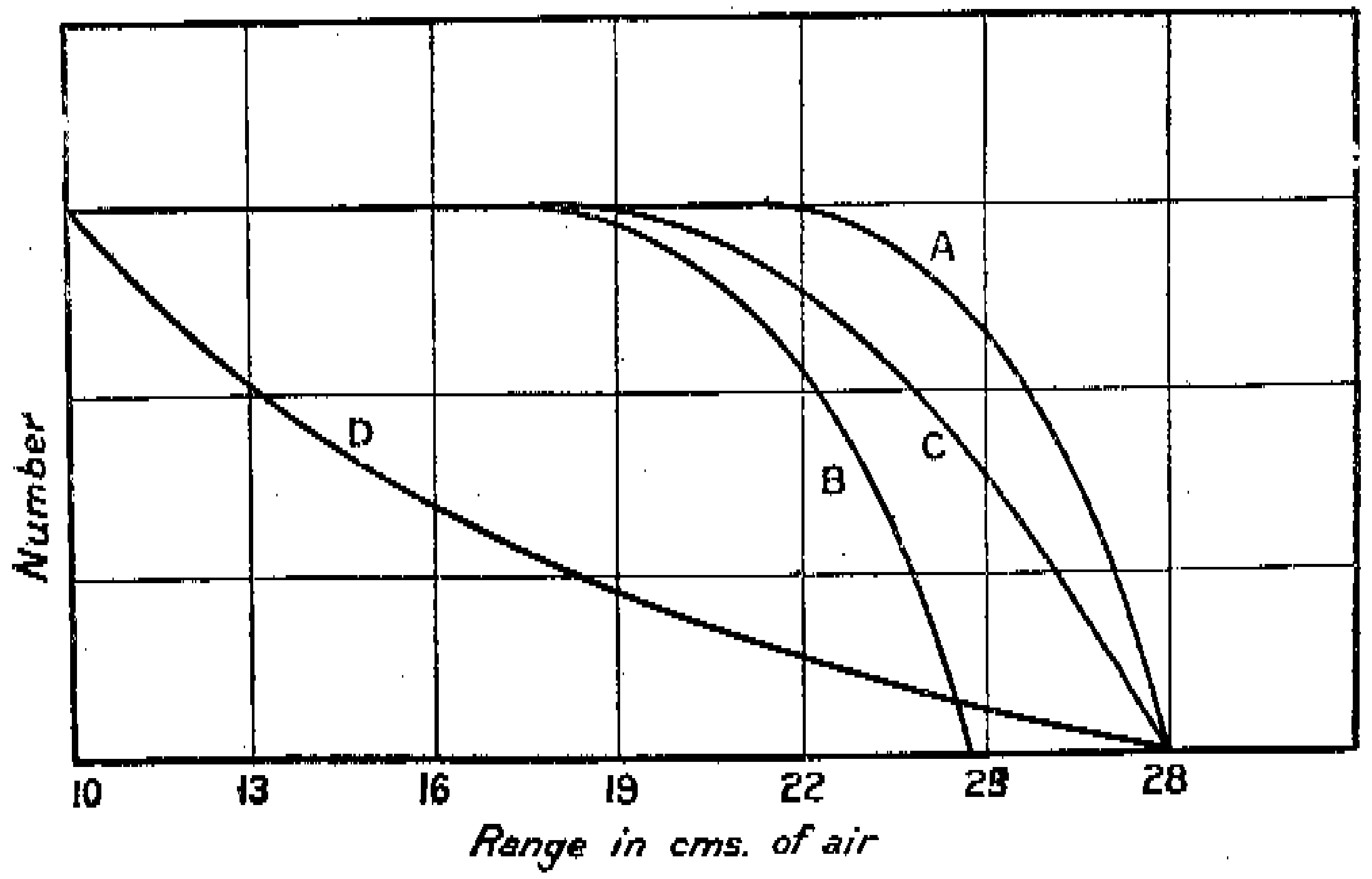


The absorption curves for ranges between 5·7 and 3·9 cm. are very similar in shape to the theoretical curves. For example, in curve F for an initial range of α particles of 3·9 cm. the number of H particles is reduced to $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$ for increase of absorption of 2·4, 4·0, 5·5 cm. respectively. The numbers are in good agreement with the calculated values, viz. 2·8, 5·0, 6·4 cm. respectively. The numbers are in still closer agreement if we take the *average* range of the α particles acting on the hydrogen column, viz. $3·9 - ·4 = 3·5$ cm. The corresponding numbers are then 2·3, 4·2, 5·0 cm. respectively.

We shall now consider the interpretation of the anomalous absorption curve for a range of 7 cm. shown in curve A. The curve is very similar to that to be expected if the hydrogen atoms were thrown forward mainly in the direction of the α particles, and all with the same velocity; in fact, the absorption curve for a pencil of H atoms is very similar in shape to that for a pencil of homogeneous α rays from radium C.

It is well known that the number of α particles counted by the scintillation method in a homogeneous pencil of α rays from radium C remains constant from 0 to 6 cm. of the range, and then rapidly falls to zero in the last centimetre of the range. This end effect is usually ascribed to the scattering of the α particles in their passage through the absorbing material. Now if the H particles consist of H atoms carrying unit positive charge e and projected with a velocity $u = 1·6\,v$, where v is the velocity of the α particle, the average angular scattering per cm. should be proportional to e/mu^2 and should thus be ·78 of that suffered by the α particle for an equal range. Since the H atom has four times the range of the α particle, the average angular scattering of the H atoms before absorption should be approximately $2 \times ·78 = 1·56$ that of the α particle. It follows, therefore, that the decrease in the number for a homogeneous beam of H atoms should begin about 6 cm. from the end of the maximum range 28 cm.

Fig. 6.



This theoretical curve is shown in fig. 6, curve A. Remembering that the stopping power of the hydrogen column for α rays corresponds to 8 mm. of air, the absorption curve of H atoms due to α particles of range 6·2 cm. has a maximum range 24·8 cm. The corresponding absorption curve is given in curve B. The intermediate curve C shows the distribution to be expected for the hydrogen column, supposing the H atoms are all projected in the direction of the α particles with a velocity proportional to the velocity of the α particle at each point of the hydrogen column.

This theoretical curve C is very similar in all respects to the experimental curve (fig. 4, curve A), showing that the H atoms produced in a thin film of hydrogen are nearly homogeneous in velocity and are thrown forward in the direction of the colliding α particles.

It does not follow that the direction of the H atom coincides with the direction of the α particles, but the average deflexion cannot be much more than 10° or 15°. For an angle of deflexion of θ, the range of the H atom in the direction of the α particles is $R_{\text{max.}} \times \cos^4 \theta$. The value of $\cos^4 \theta$ is 0·94 for 10°, 0·87 for 15°, and 0·78 for 20°. An average value of θ of 20° would make the decrease in the number begin about 13 cm. instead of 19 cm.

It is to be anticipated that the average angle of deflexion should increase rapidly with decrease of the velocity of the α particle. The rapid changes in shape of absorption curve with change of velocity of α particle are at any rate partly due to this cause.

It is difficult to determine directly the actual average angle of deflexion of H atoms, since the H atoms are scattered considerably in passing through the minimum 7 cm. of air or other absorbing material required to stop the α particles.

There seems to be little doubt that if a film of hydrogen were exposed to α particles of greater initial velocity than those from radium C, a nearly homogeneous beam of H rays would be obtained, all of which would travel nearly in the direction of the α particles.

§ 9. *Variation of number of* H *particles with velocity of α particles.*

In order to reduce the velocity of the α particles, the vertical column in the apparatus shown in fig. 1 was completely covered with different thicknesses of gold foil whose stopping power in terms of air was accurately determined. The distance between the source and screen was 3·3 cm., and the apparatus filled with hydrogen at atmospheric pressure. The gold foils were pressed tightly against the source to prevent production of H atoms between the source and foils. The number of H particles was determined after passing through absorbers of known stopping power. The results are given in the table below.

Absorption of gold foil in terms of cms. of air.	Issuing range of α rays in cms. of air	Absorption in terms of air between source and screen including the hydrogen.	Observed number of H atoms.	Calculated number of H atoms.
0 cm.	7·0 cm.	8·3 cm.	100	100
1·7 „	5·3 „	8·3 „	77	103
2·5 „	4·5 „	7·5 „	51	119
3·3 „	3·7 „	6·6 „	25	139
4·0 „	3·0 „	6·6 „	5	128

In the last column are given the relative numbers of H atoms to be expected on the simple theory given in § 7, when account is taken of the maximum range of the H atoms and the thickness of absorber traversed. Since the number of H atoms for corresponding ranges varies as the inverse fourth power of the velocity of the α particles, *i. e.*, as the inverse four thirds power of the effective range of the α particles, the number of H atoms should increase with lowering of the velocity of the incident α particles. The observed numbers, however, instead of increasing with reduction of velocity of α particles, fall off slowly at first and then very rapidly for ranges between 3·5 and 3 cm.

In these experiments, the intensity of the H radiation was reduced by this passage through absorbing material equal to 6·6 cm. of air. In order to reduce this absorption, another series of experiments was made in which the silver plate of stopping power 5·8 cm. was replaced by an aluminium plate of stopping power 3·7 cm. The velocity of the α particles was reduced by aluminium foil instead of gold foil, placed close to the source. The aluminium foils used in these experiments were freed as far as possible from hydrogen by heating in a vacuum, and the results obtained with aluminium as absorber were similar to those with gold. The presence of numerous H atoms was observed for α particles of range 2·5 cm., but the number was small and just measurable with certainty for α particles of range 2·0 cm. The actual number in the latter case was small compared with that observed for α particles of range 3 cm. The experiments at low ranges are rendered somewhat difficult by the necessity of taking into account the H scintillations which arise from the absorbing material and source. These are always present, and in number comparable with those produced by the admission of hydrogen. While the general results show that, under the experimental conditions, the number of H atoms becomes relatively small for ranges of α particles between 2 and 3 cm., it is not possible to say with certainty whether the number falls to zero for still smaller velocities of the incident α particles. We are unable to continue observations with this experimental arrangement for absorptions less than 7 cm. of air, so that no information is available of the number of H atoms of range less than 7 cm.

In § 8, the absorption curves for H atoms produced by α particles of different velocities have already been given.

§ 10. *Number of* H *atoms.*

We have already mentioned that the number of H atoms is considerably greater than that to be expected on the simple theory. It is important to determine the number as accurately as possible, as it gives us important information on the nature of the collision. The apparatus of fig. 1 was employed. A thick copper plate with a hole 1·02 mm. diameter was placed over the end silver plate of stopping power about 6 cm., and the zinc sulphide screen placed about 1 mm. away. Even allowing for possible scattering, all the H atoms passing through the opening were counted by the microscope, which had a field of view of diameter 2·0 mm. The source was part of a small hemisphere whose outer surface was active, placed 2·85 cm. from the end of the vessel. The space between was filled with hydrogen at atmospheric pressure. The initial γ-ray activity of the source was about 10 mg. Ra.

The zinc sulphide screen was specially made for the purpose and was estimated to have about 90 per cent. efficiency in giving scintillations. As a result of three separate concordant determinations, it was found that the number of H atoms for hydrogen at N.T.P. falling on the screen corresponded to 5·1 per minute per milligram of activity, including an allowance of 10 per cent. for inefficiency of the screen.

If l = length in cms. of path of α particles in hydrogen,
A = area of opening in sq. cms.,
n = number of α particles emitted per second by one milligram of radium,
ρ = fraction of α particles which produce an H atom per centimetre of path in hydrogen at N.T.P.

Then obviously

number of H atoms per second on area $A = \frac{5\cdot1}{60} = \frac{\rho A l n}{4\pi l^2}$.

Taking $l = 2\cdot85$ cm., $A = 0\cdot84$ sq. mm., $n = 3\cdot72 \times 10^7$,
then $\rho = 9\cdot7 \times 10^{-6}$,
or in round numbers $\rho = 10^{-5}$.

This number was obtained for a total absorption in path of H atom corresponding to about 15 cm. of air, but we have already seen that the number under conditions of experiment does not vary sensibly between 9 and 19 cm. absorption. We have seen in § 7 that the number of H atoms to be expected on the simple theory is $\cdot98 \times 10^{-6}$ for 10 cm. absorption and $\cdot31 \times 10^{-6}$ for 19 cm. We thus see that for an absorption of 10 cm., the observed number of H atoms is 10 times the theoretical value and for 19 cm. 31 times.

Using the observed result that 1 in 10^5 of the α particles produces one H atom per centimetre of path of hydrogen, it is easy to calculate the maximum distance of the direction of flight of the α particles from the centre of the hydrogen atom in order to produce a high speed atom.

If p = this perpendicular distance,
N = number of atoms of H per c.c. at N.T.P.
Then $\pi p^2 N = 10^{-5}$.
Taking $N = 2 \times 2\cdot705 \times 10^{19}$,
then $p = 2\cdot4 \times 10^{-13}$ cm.,

or, on an average, each α particle of radium C of range 7 cm. produces an H atom when the perpendicular distance of its path from the centre of the H atom is equal or less than $2\cdot4 \times 10^{-13}$ cm. It should be remembered that this calculation deals with the α particles of range 7 cm. when the H atoms are projected mainly in the direction of the incident α particles and with a range not less than 19 cm. of air, *i. e.*, with a velocity comparable with the maximum velocity of the H atom. As already shown, the distribution of velocity is very different for α particles of shorter range, although the actual number in all cases exceeds considerably the value calculated on the simple theory.

§ 11. *Closeness of approach of α particles to* H *nucleus.*

The experimental results considered show that the number and distribution of H particles are very different from those calculated on the assumption that the α particle and H atom are to be regarded as point nuclei carrying charges $+2e$ and $+e$ respectively, and indicate that the forces involved in a close collision differ considerably in magnitude and probably in direction from those to be expected on the simple theory.

In order to throw light on the magnitudes involved, consider the following case. Assume that for distances greater than D between the centres of the colliding atoms, the forces are given by the simple theory but for decreasing distances the forces between the nuclei augment rapidly according to other laws, and that all the collisions of closer approach than D result in the production of a high-speed H atom which for α particles of range about 7 cm. tends to be projected approximately in the line of flight of the α particles.

Darwin (*loc. cit.*) has shown that the apsidal distance D between an α particle and H atom is given on the simple theory by

$$\mathrm{D}=\frac{\mu {v_0}^2}{v^2}(1+\sec\theta),$$

where $\mu=\frac{\mathrm{E}e}{{v_0}^2}\left(\frac{1}{m}+\frac{1}{\mathrm{M}}\right)=9{\cdot}27\times10^{-14}$ for α particles of maximum range 7 cm., where θ is the angle of deflexion of H atom and v_0 the velocity of α particles from radium C. In the same notation (§ 7)

$$p=\mu\frac{{v_0}^2}{v^2}\tan\theta.$$

Eliminating θ from these two equations, $p^2=\mathrm{D}\left(\mathrm{D}-2\mu\frac{{v_0}^2}{v^2}\right)$.

We have seen (§ 9) that for α particles of range about 7 cm. the value of $p=2{\cdot}4\times10^{-13}$. Substituting this value of p and putting $v=v_0$ we find the corresponding value of $\mathrm{D}=3{\cdot}5\times10^{-13}$ cm. It will be seen later that all collisions for which D on the simple theory is greater than this value, should give rise to H atoms of velocity too small for detection. We may consequently conclude that all collisions for which D is equal or less than $3{\cdot}5\times10^{-13}$ cm. give rise to a high-speed H atom.

It is of interest to consider, on these assumptions, how the number of H atoms should vary with the velocity of the incident α particles. From the above equation, it is seen that $p=0$ when $\mathrm{D}=2\mu\frac{{v_0}^2}{v^2}$. Substituting the value $\mathrm{D}=3{\cdot}5\times10^{-13}$, $\mu=9{\cdot}27\times10^{-14}$, we find $v_0/v=1{\cdot}89$. The range of α particles of this velocity v is 2·7 cm. This result means that α particles of range less than 2·7 cm., acted on by the forces given by the simple theory, are unable to approach within the critical distance D of the nucleus of the hydrogen atom.

Since the number of H atoms produced is proportional to the value of p^2 given in equation

$$\frac{\text{Number of H atoms of velocity } v}{\text{,, ,, ,, ,, } v_0}=\frac{\mathrm{D}-2\mu\frac{{v_0}^2}{v^2}}{\mathrm{D}-2\mu}.$$

Substituting the values of D, μ, v_0/v, the relative number of H atoms to be expected for different values of v are given below :—

Range of incident α particles in cms.	7	6	5	4	3·5	3·0	2·7
Relative number of H atoms	100	88	72	50	35	15	0

It has been previously pointed out that the observed number of H atoms shows a rapid decrease for ranges between 3 and 2 cm., a result in general accord with these calculations. It is, however, not to be expected that there would be any close agreement between theory and experiment, for the theory supposes that there is an abrupt variation in the magnitude and direction of the forces for an apsidal distance D, a condition which is physically improbable. We may, however, conclude that the variations of number of H atoms with velocity is not inconsistent with the view that the forces between colliding atoms augment rapidly for values of $\mathrm{D}<3{\cdot}5\times10^{-13}$ cm.

From the known values of D and μ, we are able to calculate the value of θ, *i. e.*, the angle of deflexion of the H atom for a collision of apsidal distance $\mathrm{D}=3{\cdot}5\times10^{-13}$ cm. For α rays of range 7 cm., $\theta=69°$; the corresponding effective range of the H atom is $28\cos^4\theta$ or 4·6 mm. It is thus clear that, on the assumptions made, no atoms for which $\mathrm{D}>3{\cdot}5\times10^{-13}$ should be detected under the experimental conditions.

The general results are consistent with the view that the field of force between the α particle and 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.

§ 12. *Summary.*

1. The production of high-speed hydrogen atoms due to close collisions between α particles and atoms of hydrogen has been studied using the α particles from radium C as a homogeneous source of radiation. In such close collisions, where the nuclei approach within a distance of about 3×10^{-13} cm., the number and distribution of the H atoms are entirely different from those calculated on the assumption that the nuclei are to be regarded as point charges repelling each other according to the law of inverse squares.

2. The H atoms produced by swift α particles of range 7 cm. are shot forward mainly in the direction of the α particles and are nearly uniform in velocity.

3. The distribution with velocity of H atoms becomes more and more heterogeneous with decrease of velocity of the α particles. For α particles of range less than 4 cm. of air, the distribution and absorption of H atoms are in fair accord with the simple theory although the observed numbers are greater than those calculated on the theory.

4. The number of swift H atoms produced by α particles of range 7 cm. is 30 times greater than the theoretical number. The number falls off rapidly for ranges of α particles between 3 and 2 cm. On an average 10^5 α particles give rise to one swift hydrogen atom in traversing one centimetre of hydrogen.

5. It has been calculated that all α particles of range 7 cm. projected within a perpendicular distance $p = 2{\cdot}4 \times 10^{-13}$ cm. of the centre of the hydrogen nucleus give rise to swift H atoms. The corresponding apsidal distance is about $3{\cdot}5 \times 10^{-13}$ cm.

6. As observed by Marsden, hydrogen atoms are emitted by the radioactive source. The number observed is small, and it is difficult to decide whether these H atoms arise from the radioactive transformation or from occluded hydrogen in the source.

Discussion of results.

On the nucleus theory of the atom, the charged nucleus is supposed to be of such small dimensions that it may be regarded as a point charge for distances of the order of 10^{-11} cm. The correctness of this point of view in the case of hydrogen is strongly supported by the remarkable success of Bohr and those who have followed him in explaining by its aid the finer points of the hydrogen

spectrum. The experiments of Geiger and Marsden * on the large angle scattering of heavy atoms like those of gold showed that the nucleus of the gold atom could be regarded as a point charge for distances of the order of 3×10^{-12} cm., and that the law of inverse squares held up to that distance within the limits of experimental error. In the present experiments on the collision of particles with hydrogen atoms, the atomic nuclei approach still closer, viz. to a distance of the order of 3×10^{-13} cm. It is to be anticipated that for such small distances of the order of the diameter of the electron, the structure of the helium nucleus can no longer be regarded as a point, and this is borne out by experiment. Such a conclusion in no way invalidates the nucleus theory as ordinarily understood; but a study of the forces close to the nucleus is of great importance in throwing light on its actual dimensions.

It is clear from the results given in this paper that a close collision between an α particle and a hydrogen nucleus is an exceedingly rare occurrence. Only 1 in 100000 of the α particles passing through 1 cm. of hydrogen at normal pressure and temperature gives rise to a high-speed H atom, while in the same distance each α particle on an average passes through the sphere of action of about 10000 hydrogen molecules. Thus for every 10^9 collisions with the molecules, in only one case does the α particle pass close enough to the nucleus to give rise to a swift H atom. No doubt a much greater number of H atoms are set into comparatively swift motion by less direct collisions, but these do not give rise to H atoms which can be detected beyond the range of the α particle.

It is clear that for such close collisions, each hydrogen atom in any complex molecule acts as an independent unit, so that swift H atoms should be liberated by α particles from every substance containing free or combined hydrogen. This is fully borne out by experiment.

In seeking for an explanation of these anomalous results, there are two salient facts to bear in mind, viz., that (1) the H atoms produced by α particles of range greater than 6 cm. are projected mainly in the direction of the α particles and over a narrow range of velocity, and (2) the number of such swift H atoms is far in excess of the number on the simple theory of point charges.

If we consider the nuclei of the atoms in collision to act

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* Geiger and Marsden, Phil. Mag. xxv. p. 604 (1913).

as point charges, no advantage in explanation is gained by supposing that the free charges carried by the nuclei are greater than those usually supposed; for while such an assumption gives an increased number of H atoms of all velocities, it fails to account for (1) above.

If we suppose the central forces fall off more rapidly than the inverse square law, the proportion of swift atoms increases relatively. This can be deduced from consideration of the calculations given by Darwin * for the case of the inverse cube law, and it is not difficult to see that this relative increase of high speed particles becomes more marked the more rapid the law of variation of the central force. In all cases, however, the pencil of H atoms should be widely heterogeneous for all velocities of the colliding α particle. It thus seems clear that no theory of single central forces can account for the experimental facts.

This is not unexpected, for we have every reason to believe that the α particle has a complex structure consisting probably of four hydrogen nuclei and two negative electrons †. If we assume, for simplicity, that the hydrogen nucleus acts as a point charge for the distances under consideration, we still have a complicated system of forces near the nucleus of the α particle.

Now we have seen that the anomalous effects in hydrogen manifest themselves when the two nuclei approach within about 3×10^{-13} cm. of each other. Geiger and Marsden have shown that the scattering of α particles in passing through atoms of a heavy element like gold, is consistent within experimental error with an inverse square law of repulsion, and in the case of a head-on collision, the closest distance of approach is about 3×10^{-12} cm. or about 10 times the distance in the case of a close collision between the α particle and the hydrogen atom. It appears significant that, in the latter case, the closest distance of approach is about the same as the accepted value of the diameter of the negative electron, viz. $3{\cdot}6 \times 10^{-13}$ cm. The observed effects are similar to those to be expected if the helium nucleus, for example, consisted of a charged disk of radius about 3×10^{-13} cm. with its plane perpendicular to the direction of motion, and it seems clear that the helium nucleus must have dimensions of this order of magnitude.

If the helium nucleus is composed of two electrons and four hydrogen nuclei, we should expect a complicated field of force round the nucleus and rapid variations in direction and magnitude of the forces for distances of the order of the diameter of the electron. In our ignorance of the detailed structure of the nucleus, we can only speculate as to the magnitude and direction of the forces close to it. Considering, however, the enormous repulsive force between two positive nuclei in collision at a distance of 3×10^{-13} cm.—about five kilograms weight on the inverse square law,—it is to be anticipated that not only the structure of the complex helium nucleus should be much deformed, but that the electron itself may suffer strong deformation under the intense electric forces. If such deformation of the electron be possible, it is not difficult to see in a general way that the forces between the nuclei in collision may vary exceedingly rapidly close to the nucleus, and may even change rapidly from one of repulsion to one of attraction. It may be possible in this way to explain the experimental effects observed, including both the projection in the direction of the α particle and the increase over the number to be expected on the simple theory.

It is of course possible to suppose that the actual law of force, apart from deformation, does not follow the inverse square for very small distances; but since the inverse square law appears to hold at any rate approximately for positive charges up to a distance 3×10^{-12} cm., it seems simpler to suppose that the rapid alteration in magnitude and direction of the force close to the nucleus is due rather to a deformation of its structure and of its constituent parts. Taking into account the intense forces brought into play in such collisions, it would not be surprising if the helium nucleus were to break up. No evidence of such a disintegration, however, has been observed, indicating that the helium nucleus must be a very stable structure.

It will be shown in a later paper that the anomalous effects observed in hydrogen are shown also by collision of swift α particles with nitrogen and oxygen atoms and for about the same distance between the nuclei.

My thanks are due to Mr. W. Kay for his assistance in counting and in all the experimental work.

University of Manchester,
April, 1919.

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* Darwin (*loc. cit.*).

† Rutherford, Phil. Mag. xxvii. p. 488 (1914).