LII. *Collision of α Particles with Light Atoms.* II. *Velocity of the Hydrogen Atom.* *By* Professor Sir E. RUTHERFORD, *F.R.S.*[*]

IN the first paper giving an account of the number of H atoms produced by α particles and their absorption by matter, it has been implicitly assumed that the long-range scintillations observed in hydrogen are due to swift hydrogen atoms set in motion by close collisions with α particles. This is supported by the observations that the range of the atoms is in good accord with the value calculated by Darwin from Bohr's theory of absorption of charged particles.

Taking into account, however, the intense forces developed in such collisions and the possibility of the disruption of the structure of the nuclei involved in the collisions, it was thought desirable to determine experimentally the mass and velocity of these flying atoms, and to compare the values with those deduced from the collision theory. Such a determination was rendered the more necessary by certain apparent anomalies observed in connexion with the brightness and distribution of H atoms, an account of which will be given later in this paper.

To determine the mass and velocity of the H atom, it was necessary to measure the deflexions of a stream of H atoms both in a magnetic and in an electric field. The experiments were somewhat tedious and difficult on account of the small number of H scintillations present under the experimental restrictions.

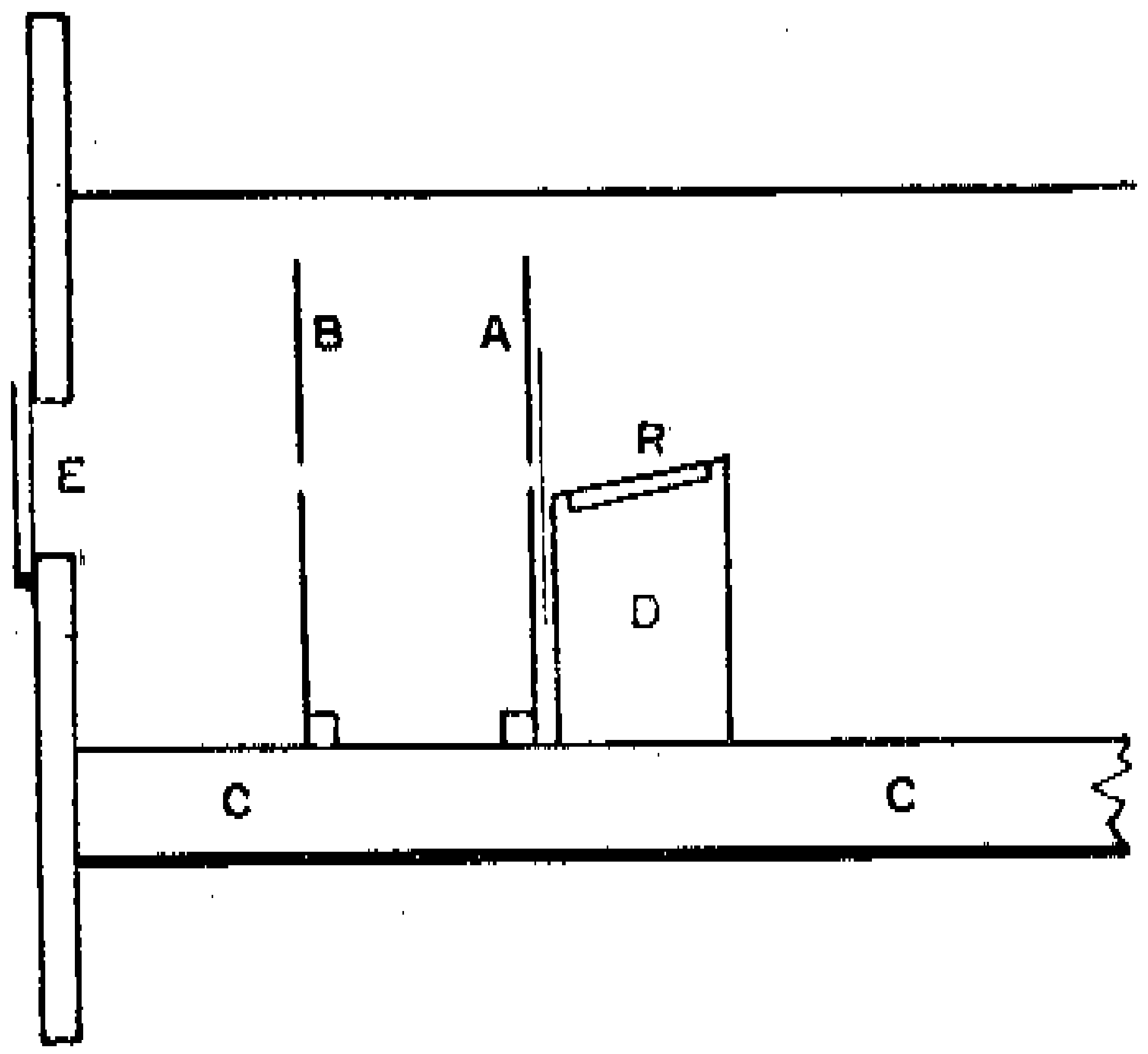
Magnetic deflexion of H *atoms.*

In these experiments it was necessary to produce the H atoms at a definite point, and for this purpose a film of paraffin wax of convenient thickness, exposed to an intense beam of α rays, was used. The method finally adopted was to compare directly the deflexion of a pencil of H atoms produced from the film of paraffin wax, with the deflexion of a pencil of α rays using the same source of α rays in both cases.

The experimental arrangement is shown in fig. 1.

The horizontal slits A and B, about 1 cm. broad and 1 mm. wide, were mounted on a rectangular brass bar C. The source R, consisting of a circular brass disk coated on one side with radium C, was mounted on a vertical block D, close to the slit A and making a small angle with the horizontal. This carrier was then introduced into the rectangular brass vessel shown in fig. 1 of the previous paper, and the whole apparatus was placed between the poles of a strong electromagnet. A vertical slit 1·5 cm. long and 3 mm. wide, cut in

Fig. 1.



the end plate of the box, was covered with a thin sheet of iron E whose stopping-power for α particles corresponded to 4 cm. of air. Close to this was placed the zinc sulphide screen S. The distance between the slits A and B was 2·85 cm., and between B and the iron screen 3·25 cm. On exhausting the apparatus of air a well-defined band of α rays about 2 mm. broad was observed on the screen. The distance measured by the microscope between the centres of the two bands on reversing the field of about 9000 gauss was about 3·9 mm. A film of paraffin wax about 30 μ thick mounted on a frame was then placed close to the slit A between it and the source. This gave a band of H scintillations on the screen, which was of about the same width as the beam of α rays. Aluminium screens were introduced between the iron plate and zinc sulphide screen, so that the total absorption between the source and screen was equivalent to 14·4 cm. of air. Under these conditions the two bands of H scintillations obtained by reversal of the field were carefully determined by the microscope, and the centres of the bands were found to be about 6 mm. apart.

As a result of three concordant determinations, it was found that under the experimental conditions the average deflexion of the pencil of H atoms was 1·45 times the

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[*] Communicated by the Author.

deflexion of the pencil of α rays from radium C. Since the value of $\frac{Mv}{E}$ for α particles from radium C has been accurately determined in other experiments and found to be $3{\cdot}98\times10^5$*, the average value of $\frac{mu}{e}$ for the pencil of H atoms is $2{\cdot}74\times10^5$. Now, on passing the slit A, the maximum range of the H atom is $28-3{\cdot}4=24{\cdot}6$ cm., while the minimum range for H atoms to be observed on the screen is $28-14{\cdot}4=13{\cdot}6$ cm. Since the range of the H atom is proportional to the cube of its velocity, the velocity of the H atoms observed which passed through the magnetic field lies between $\cdot96u_0$ and $\cdot79u_0$, where u_0 is the maximum velocity of the H atom due to an α particle from radium C. Since the relation between number and velocity was approximately linear over this range, the average velocity of the H atoms was $\cdot87u_0$. Consequently the value of $\frac{mu_0}{e}$ for the swiftest H rays produced by α particles from radium C is $1/{\cdot}87\times2{\cdot}74\times10^5=3{\cdot}15\times10^5$. On the collision theory, the velocity u of the H atoms of mass m is given by

$$u=\frac{2M}{M+m}\cdot v\cos\theta,$$

and the maximum value

$$u_0=1{\cdot}6v_0.$$

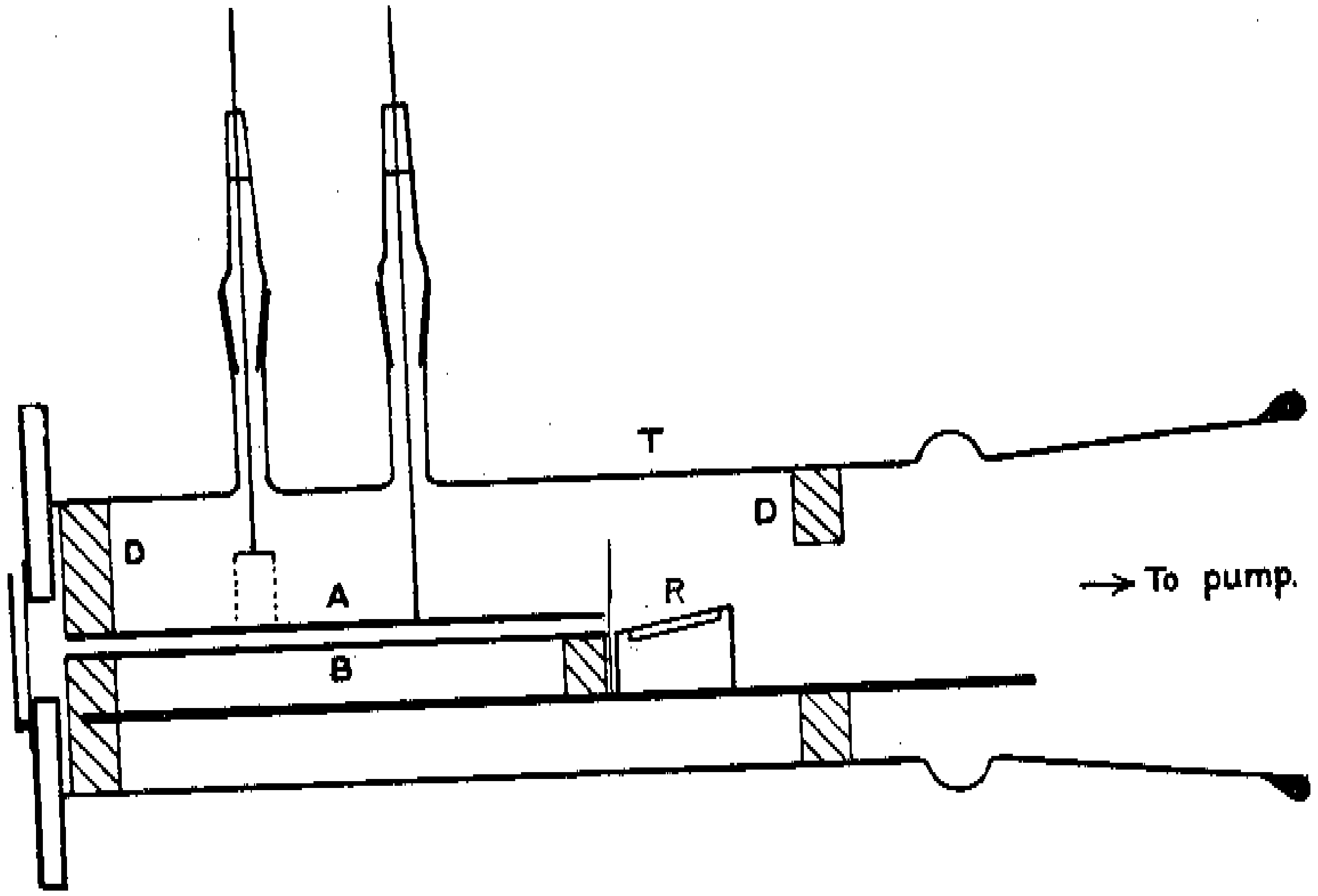
The value of $\frac{mu_0}{e}$ for H atoms carrying unit charge should consequently be $3{\cdot}2\times10^5$. The agreement between theory and experiment is closer than we should expect considering the difficulty of the measurements. In these experiments it was found that all the H atoms carried a positive charge, and no sign of scintillations was observed indicating the presence of negatively charged or neutral atoms.

Electrostatic deflexion of H *atoms.*

The determination of the deflexion of H atoms in an electric field was a much more difficult and lengthy process. The experimental arrangement finally adopted is shown in

fig. 2. The α rays from a slanting source R passed through a film of paraffin wax about 30 μ thick placed at the end of two parallel insulated brass plates A and B, 6·02 cm. long, and 0·155 cm. apart. These were mounted on an ebonite frame DD with circular ebonite ends which slipped into a glass tube T. A brass plate with a slit 1 cm. long and 3 mm. wide covered with a thin silver plate of stopping power 6 cm. of air, was fixed at the end of the tube T. The zinc sulphide screen was mounted outside close to the silver plate. The electric connexions with the plates A and B were made through ground-glass stoppers shown in the figure.

Fig. 2.



As radium C was employed as a source, it was necessary to arrange for rapid exhaustion of the apparatus to stand 5000 volts between the plates after a short interval. After preliminary evacuation by a Fleuss and Gaede mercury-pump a Langmuir pump was used, and the process was so rapid that the necessary vacuum was reached and held within two minutes of introducing the apparatus into the glass tube.

In order to deflect completely the H atoms in passing between the parallel plates, it was calculated that about 30,000 volts would be required. Apart from the difficulty of obtaining rapidly a vacuum sufficient to support and maintain such a voltage, a steady supply of not more than 7000 volts was available in the Laboratory. To overcome this difficulty, it was arranged to compare the deflexions of

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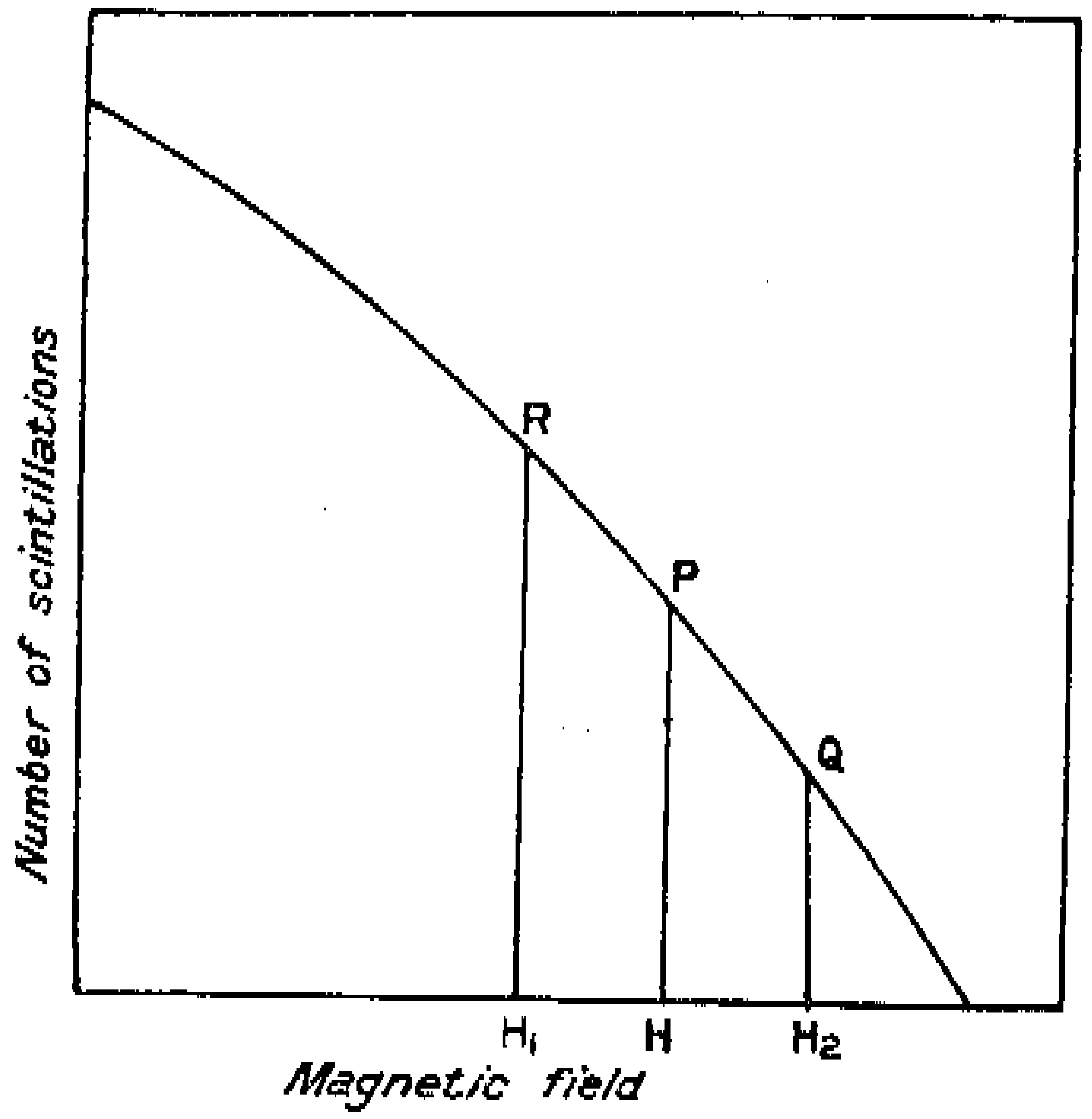
* Rutherford and Robinson, Phil. Mag. xxviii. p. 552 (1914).

H atoms due to a magnetic field with that due to a combined magnetic and electric field. The glass tube carrying the source and parallel plates was placed between the poles of a strong electromagnet, the plane of the plates being parallel to the direction of the magnetic field. The microscope was fixed in the centre line of the plates A and B so as to count the scintillations emerging from the plates, and the variation of the number with strength of the magnetic field was determined. The reduction of the number with increase of the magnetic field depended on two causes:—(1) the removal of H atoms bent to the sides of the plates, and (2) the bending of the H atoms emerging from the plates in the magnetic field in the short distance between the end of the plates and the zinc sulphide screen. These two effects were difficult to separate, but (2) was made as small as possible by reducing to a minimum the distance between the end of the plates and the screen. The relation between the number of scintillations and strength of field with no electric field acting, is shown diagrammatically in fig. 3. Suppose the magnetic field to be of a strength H corresponding to a poin the curve. If a voltage be now applied so as to bend the H atoms in the same direction as the magnetic field, the number of scintillations on the screen decreases corresponding to a point Q on the curve of field H_2. On reversing the voltage the two fields oppose each other, and the number of scintillations correspond to the point R of field H_1. Suppose

Fig. 3.



for simplicity that the number of H atoms are counted as they emerge from the plates A and B. Let H be the steady magnetic field and X the electric field applied between A and B. Then it is clearly seen that, if u be the velocity of the H atom,

for assisting fields, $$Heu + Xe = H_2eu,$$

for opposing fields, $$Heu - Xe = H_1eu.$$

Subtracting $$2eX = (H_2 - H_1)eu,$$

and $$u = \frac{2X}{H_2 - H_1},$$

so that the velocity of the H atoms can be determined directly. In practice, it was found that the curve PQR over the experimental range was nearly a straight line. The initial field H was varied in different experiments, but was usually about 4000 gauss. The steady voltage employed was about ±4500 volts. The ratio of the number of scintillations observed on reversal of the electric field varied in different experiments according to the magnetic field H and the voltage, but lay between 1·8 and 3 in the various experiments. Each experiment was complete in itself, for not only were the scintillations counted on reversal of the electric field, but also the number for two magnetic fields on either side of the fixed field which give nearly the same ratio of number of scintillations as that obtained by reversal of the electric field.

The paraffin film had a stopping power of 3·2 cm. of air, and the stopping power of the silver plate together with the aluminium screens was 11·4 cm. The range of H atom, which passed between the parallel plates and produced scintillations on the screen, thus lay between $28 - 3{\cdot}2 = 24{\cdot}8$ cm. and $28 - 14{\cdot}6 = 13{\cdot}4$ cm.

The corresponding velocities are $\cdot 96u_0$ and $\cdot 78u_0$ where u_0 is the maximum velocity of an H atom due to an α particle from radium C. As in the experiments on the magnetic deflexion the average velocity was found to be $\cdot 87u_0$. In calculating the relative effect due to a magnetic and electric field, a small correction is necessary to allow for the fact that the electric field was only effective the length of the plates, while the magnetic field acted on the H rays from the slit A to the zinc sulphide screen. Making this correction, estimated to be about 12 per cent., the deflexion due to 1000 volts between the plates was found to correspond in five different experiments to 235, 227, 260, 235, 221 gauss respectively, with an average value of 238 gauss.

Thus,

$$u=\frac{\mathrm{X}}{\mathrm{H}}=\frac{10^{11}}{\cdot 155}\times\frac{1}{238}=2\cdot 71\times 10^{9}\text{ cm. per sec.}$$

The maximum value

$$u_0=\frac{1}{\cdot 87}\times 2\cdot 71\times 10^{9}=3\cdot 12\times 10^{9}\text{ cm. per sec.}$$

The calculated value of $u_0=1\cdot 6\times 1\cdot 92\times 10^{9}$

$$=3\cdot 07\times 10^{9}\text{ cm. per second.}$$

The experimental and calculated values agree well within the probable error of experiments. From the magnetic deflexion we found that

$$\frac{mu_0}{e}=3\cdot 15\times 10^{5},$$

and from the electric deflexion

$$u_0=3\cdot 12\times 10^{9},$$

consequently, $e/m=10^{4}$ e.m. units.

The value of e/m for the hydrogen atom in the electrolysis of water is 9570. The agreement is sufficiently close to show that the long-range scintillations produced by α particles in hydrogen are due to hydrogen atoms carrying a unit positive charge. The agreement between the calculated and observed velocities shows that, within the margin of experimental error, the conservation of momentum and energy hold for close collisions between the atomic nuclei and that there is no sensible loss of energy due to radiation.

Brightness of scintillations.

The maximum energy communicated to an H atom is ·64 of the energy of the colliding α particle. After passing through 12 cm. of air, for example, the energy of the H atom is reduced to ·44 of the energy of the particle. Supposing that the H atoms are produced by α particles of radium C of range 7 cm., the energy of the H atom after passing through 12 cm. of air, corresponds to an α particle of range about 2 cm. In practice, the brightness of the corresponding H scintillations is much less than is to be expected from its energy, and is not greater than that produced by an α particle of range 5 mm. This relative lack of brightness of H scintillations compared with α particles of corresponding energy holds for all velocities of the H atoms. Since we have seen that we can rely on the calculations of the energy of the H atom, it seems clear that the H atom is less effective

in producing light on a zinc sulphide screen than an α particle of equal energy. This may be a consequence of the much weaker ionization along the path of the H atom, for since its range is four times that of the α particle and energy ·64, the energy spent per unit path is only 1/6 of that due to an α particle.

In this connexion it is of interest to note, that nitrogen atoms set in motion by α particles from radium C have a range in air of about 9 cm. Although the energy of the nitrogen atoms after traversing 7 cm. of air is less than that of the H atoms after traversing 12 cm., the nitrogen atom gives a much brighter scintillation than the H atom.

Probability distribution of H *scintillations.*

In the course of counting H scintillations, it was often noted that a number of the scintillations appeared as *instantaneous* doubles, *i. e.* two points of light of about equal brightness appeared in the field of view at the same instant. Some preliminary experiments seemed to show that the number of these doubles was greater than was to be expected from probability considerations. For example, in counting bright scintillations due to the active deposit of thorium, on an average, about 1·5 doubles per minute were counted for an average of 30 scintillations per minute, while for a similar number of H scintillations the number of doubles was about 5. If these "doubles" from hydrogen were instantaneous doubles, it was obviously a matter of great importance, possibly indicating the disruption by collision of one of the nuclei into two parts.

A large number of experiments were made to test this question, using both hydrogen and paraffin wax as a source of H atoms, but very similar results were obtained under all conditions of experiment. The most favourable theoretical conditions were chosen to increase the number of such doubles if they existed. For example, the H atoms were liberated in a thin film of paraffin covering an opening 1 mm. in diameter, placed near the zinc sulphide screen. The distance of the screen from the paraffin film and the nature of the absorber between was adjusted, so that even if two atoms were shot forward nearly in the same direction, the scattering would separate them on an average a convenient distance in the field of view of the microscope, which included a field of view 2 mm. diameter. No apparent advantage as regards the number of doubles was gained by this arrangement.

I was fortunate, in January of this year, to obtain for a short time the skilled assistance of Professor E. Marsden before his return to New Zealand. Systematic observations were undertaken to record electromagnetically the time of appearance of each scintillation on a chronograph tape while the number of doubles was separately recorded. Mr. Marsden and Mr. Kay counted alternately for a minute interval, and the counts of each observer were separately analysed by the former at leisure. On the probability theory, the number of intervals between t_1 and t_2 seconds is given by $Ne^{-\mu(t_1-t_2)}$ where $1/\mu$ is the average interval between each scintillation and N the total number of intervals. Marsden and Barratt* had previously verified the correctness of this theory, which shows that short intervals are more probable than long ones. If the average number of scintillations is 30 per minute, $\mu=1/2$, and if the eye fails to distinguish an interval less than 1/10 of a second, the average number of doubles to be expected is 1·5 per minute. In practice, under favourable conditions, the eye is just able to detect 1/10 second intervals for bright α ray scintillations.

Comparisons were made to test the probability distribution of α particles from polonium, whose range was adjusted to give a scintillation of about the same average brightness as the H atom.

The results of a typical series of counts both for α rays and H atoms are included in the following table. The theoretical and observed number of intervals <1/10, <1/2, and <1 second are given in the table below :—

Observer.	Average number scintillations per min.	Total number of scintillations.	Number of doubles.	Calculated number of intervals. <1/10 sec.	Observed number of intervals. <1/2 sec.	Calculated number of intervals. <1/2 sec.	Observed number of intervals. <1 sec.	Calculated number of intervals. <1 sec.
α particles from polonium.								
M ..	28·0	250	13	12·9	53	60	106	105
K ...	25·4	229	10	9·6	45	45	83	79
Hydrogen atoms.								
M ...	24·3	243	15	9·6	50·5	46	84	81
K ...	22·7	250	25	9·2	58·5	45	92	79
M ...	31·0	216	24	11	60·5	50	95	88
K ...	29·6	148	18	7	33	35	59	58

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* Marsden and Barratt, Proc. Phys. Soc. xxiii. p. 367 (1911); xxiv. p. 50 (1913).

The calculated numbers are the sum of each observation worked out separately.

It will be seen that while there is a very satisfactory agreement between theory and experiment for the α rays from polonium, the agreement is not so good for the H atoms. In the case of the α rays, the number of doubles shows that the eye cannot distinguish an interval less than 1/10 second; while in the case of H atoms the number of doubles is nearly twice the theoretical number calculated on this power of distinction. Whether this difference is apparent or real is difficult to decide, for it must be remembered that counting such weak scintillations and at the same time distinguishing time intervals make a difficult task.

It is clear that under the experimental conditions, only a small fraction of the number of scintillations can be regarded as possible instantaneous doubles, and the effect is too small and uncertain to draw any very definite conclusions. It may be urged that a question of this kind could be settled more definitely by arranging that a small number of scintillations fell on the screen per minute when the probability of short intervals becomes very small. On the other hand, it takes a long time to count a sufficient number to compare theory with experiment, and it is very fatiguing to the eye and unreliable to count for long under such conditions.

I am much indebted to Professor Marsden for his valuable help in obtaining and analysing data for me on this important point.

LIII. *Collision of α Particles with Light Atoms.* III. *Nitrogen and Oxygen Atoms.* *By* Professor Sir E. RUTHERFORD, *F.R.S.*[*]

BOHR[†] has worked out a general theory of the absorption of electrified atoms in passing through matter, and has verified his conclusions by consideration of the absorption of α particles. On this theory, Darwin[‡] has shown that the range of a swift hydrogen atom in hydrogen can be calculated, and the value so found is in good accord with experiment. It is not difficult to deduce by the same method that the range x in hydrogen of an electrified atom of charge e and mass m moving with a speed equal to an

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[*] Communicated by the Author.

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

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

α particle of range R in hydrogen is given by

$$x/\mathrm{R} = \frac{m}{\mathrm{M}} \cdot \frac{\mathrm{E}^2}{e^2}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where M is the mass and E the charge on the α particle.

It is to be expected that this relation would hold approximately for the passage of electrified atoms through light substances like air and aluminium. Since $\mathrm{M}=4$ and $\mathrm{E}=2e$ where e is the unit charge, the range x of a particle carrying a single charge is obviously $x=m\mathrm{R}$. The velocity u acquired by an atom of mass m due to a close collision with an α particle of velocity v is given by

$$u = \frac{2\mathrm{M}}{\mathrm{M}+m} \cdot v \cos\theta,$$

where θ is the angle of deflexion of the atom after the collision. Assuming that the range of electrified atoms in general like the range of α particles varies as the cube of the velocity, the range x after collision of an atom carrying unit charge is given by

$$x = m\mathrm{R}\left(\frac{2\mathrm{M}}{\mathrm{M}+m}\right)^3 \cos^3\theta.$$

Applying this result to H atoms, the maximum velocity should be $(8/5)^3\mathrm{R}=4{\cdot}1\mathrm{R}$, while the observed value is about 4R. As a further test of this relation, consider the range to be expected for the recoil atom of radium B of mass m resulting from the expulsion of an α particle of range 4·75 cm. from radium A. By the principle of momentum $\mathrm{M}v=mu$ and the velocity of recoil $u=\frac{\mathrm{M}}{m}v$ where $m=214$. Consequently the range in air x

$$= 214 \,.\left(\frac{4}{214}\right)^3 \times 4{\cdot}75 = {\cdot}067 \text{ cm}.$$

The value found by Wertenstein* is ·12 mm., but, considering the very wide range of velocity, the agreement is fairly satisfactory. If it be assumed that the range is proportional to the power 2·85 instead of 3, this is a good agreement both for the hydrogen and recoil atoms.

If the atom after collision with an α particle carries a charge of two units, its range from (1) should be only about 1/4 of the same atom carrying a single charge. For example, in a collision of an α particle with the helium nucleus of equal mass, the range of the helium atom should be the same as the α particle before the collision if it carries two charges, but four times this range if it carries one charge.

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* Wertenstein, *C. R.* cl. p. 869 (1910) ; cli. p. 469 (1910).

We have collected in the following table data connected with the collision of α particles with the lighter atoms of matter. The maximum velocity, momentum, and energy of the atom after collision are given as fractions of that of the incident α particle. The range is calculated on the assumption that it is proportional to the power 2·9 of the velocity and that the atom carries unit charge.

For convenience, the data for hypothetical atoms of mass 2 and 3 times that of hydrogen are included.

TABLE I.

Element.	Atomic weight.	Ratio of velocity to that of α particle.	Ratio of momentum to that of α particle.	Ratio of energy to that of α particle.	Ratio of range to that of incident α particle.
Hydrogen	1	1·6	·4	·64	3·91
?	2	1·33	·66	·89	4·6
?	3	1·14	·85	·98	5·05
Helium	4	1·00	1·00	1·00	4·00
Lithium	7	·727	1·27	·925	2·78
Beryllium	9	·615	1·38	·85	2·20
Boron	11	·533	1·46	·78	1·77
Carbon	12	·500	1·50	·75	1·61
Nitrogen	14	·444	1·55	·69	1·33
Oxygen	16	·400	1·60	·64	1·12
Fluorine	19	·348	1·65	·575	·89
Neon	20	·333	1·67	·55	·82
Sodium	23	·296	1·70	·50	·67
Magnesium	24	·286	1·71	·49	·64
Aluminium	27	·258	1·74	·45	·53
Iron	56	·133	1·86	·25	·19
Silver	108	·071	1·92	·136	·05
Gold	197	·040	1·92	·079	·017

It is seen that, on the assumption of unit charge, all the atoms of atomic weight up to oxygen should be detected beyond the range of the α particle. Supposing that α particles of range 7 cm. are used, the maximum range to be expected for unit charge are for He 28·0, Li 19·6, Be 15·4, Bo 12·4, C 11·2, N 9·3, O 7·8 cm.

Some preliminary experiments have been made with helium, using the apparatus similar to that employed for hydrogen and described in paper I. but on a smaller scale.

The results show that if the collisions of α particles with helium atoms give any long-range scintillations of the order of 28 cm. range, their number is very small compared with that produced in hydrogen under similar conditions. We may consequently conclude that the swift helium atoms produced by collision carry a double charge like the α particle.

A few experiments have been made to test whether the atoms of lithium, boron, or beryllium have the range to be expected if they carry a single charge. The salts Li_2CO_3, B_2O_3, BeO were spread in a thin layer over the active source which was inclined at a small angle with the horizontal, and determinations made of the number of scintillations beyond the range of the α particle. The air was exhausted and the α particles absorbed in aluminium and silver foils. No certain evidence was obtained of the presence of appreciable numbers of scintillations at the ranges to be expected if the atoms carry a single charge. Experiments of this kind are not easy on account of the difficulty of obtaining thin uniform films of the salts or metal under examination, and of the necessity of getting rid of all traces of hydrogen and water vapour, which give rise to numerous H atoms. It is intended later to make a systematic examination of these elements to determine the range of the atoms produced by close collisions with α particles.

Experiments in Air and Oxygen.

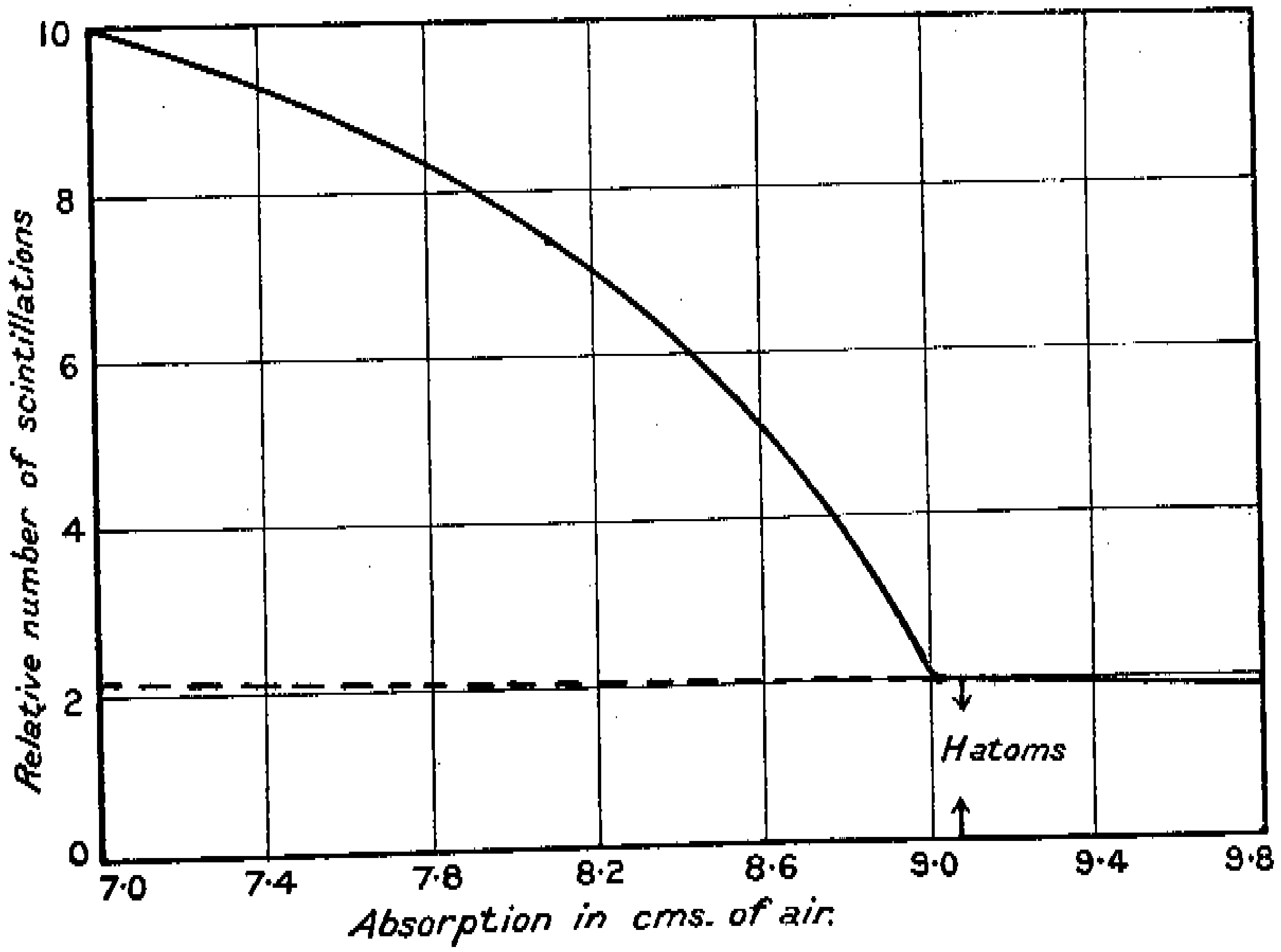
Experiments on the range of swift atoms become much easier and more certain when the elements are in the gaseous state, for there is then no uncertainty with regard to the uniformity of the absorbing column and usually no difficulty in ensuring absence of hydrogen and water vapour. Thin films of rolled metals like aluminium, silver, or gold are usually very irregular in thickness. This irregularity comes out very obviously when intense sources of radiation are employed under conditions when one in a million of the incident particles can be detected. It is not unusual in these cases to find that α particles can be detected at a distance 10 per cent. beyond the average range of the α particles as determined by ordinary methods. Mica films are very uniform and show none of these irregularities, but unfortunately mica contains both hydrogen and oxygen and gives rise to numerous H and O atoms beyond the range of the bombarding α particles.

We have seen that both N and O atoms carrying a single charge should be detected beyond the range of the α particles, and this is borne out by experiment. In the case of air, the active disk coated with radium C of γ-ray activity about 30 mg. Ra, was mounted with its plane vertical at a distance of about 7 cm. from a zinc sulphide screen in the open air. Both the source and screen were placed between the poles of a large electromagnet to deflect the β rays. The vertical convection currents due to the heated electromagnet prevented any contamination of the screen by active matter escaping from the source.

The end of the range of the α particles was sharply defined, but numerous bright scintillations were observed for distances nearly 2 cm. beyond the range of the α particles. There was a steady decrease both in number and brightness up to 9 cm. of air, and beyond that distance the small number of scintillations observed, due to H atoms from the source and from the water vapour in the air, fell off slowly.

The range of these atoms was best determined by placing the screen just outside the range of the α particles (7·1 cm. at 15° C.) and then adding thin screens of aluminium foil close to the zinc sulphide screen. The variation of number with absorption in terms of cms. of air is shown in fig. 1.

Fig. 1.



It will be seen that the scintillations fall off at first slowly with increase of absorption and more rapidly near the end of their range, which was equal to 9·0 cm. of air at normal pressure and 15° C. The scintillations, presumably due to swift N and O atoms, are bright and easily counted for a total absorption corresponding to about 7·5 cm. of air. At this stage they appear equal in brightness to those given by an α particle of range about 1 cm.

In other experiments with air, nitrogen, and oxygen, and carbon dioxide, the screen and source were placed in a rectangular box and a slow current of the dried gas passed through during the experiment. This prevented contamination of the screen by diffusion of active matter from the source, and the range was determined by altering the distance between source and screen.

The scintillations in pure oxygen and carbon dioxide were about the same brightness for corresponding ranges, and had nearly the same equivalent ranges in air as those due presumably to N atoms from the air.

This was rather surprising, as we should expect the O atoms to have considerably less range than the lighter N atom. The calculated ranges (see table above) are 7·8 and 9·3 cm. respectively. This suggested the possibility that the scintillations might be due not to N or O atoms but to actual α particles of range 9 cm. which were expelled from the radioactive source. If this were the case, the total range of the α particles should not be altered by placing an absorbing screen of aluminium or gold of known stopping power close to the source in the path of the α rays. On the other hand, if the scintillations were due to swift N or O atoms from the air, the range should be diminished. For example, if a screen of stopping power equal to 3·5 cm. of air were placed in the path of the α rays of range 7·0 cm., the resulting range of the α particles acting on the gas is 3·5 cm., and the total range of the N or O atoms measured from the source should be $3{\cdot}5+\frac{9}{7}\times 3{\cdot}5=8{\cdot}0$ cm. instead of 9·0 cm. Experiments of this kind were made with an aluminium and a gold screen of stopping powers 3·7 and 4·2 cm. respectively, but were not altogether satisfactory on account of the inequalities of the films already referred to. They showed, however, that no appreciable number of scintillations could be detected beyond 8 cm. The results indicated that the scintillations were due to atoms of N and O and not to α particles from the source. This was further confirmed by experiments with mica screens of stopping power 7·0 cm. The number of bright scintillations which resembled α particles were less than half the number observed in air or oxygen gas under similar conditions, but the presence of numerous H atoms from the mica interfered with an accurate determination. Since mica contains oxygen as well as hydrogen we should obtain swift O atoms, and the number of scintillations observed was about that to be expected from the amount of oxygen present, but was less than the number observed in air. There appears to be no doubt that the scintillations observed in air between the ranges 7 and 9 cm. arise from collision of α particles with N and O atoms. The observation that the range of the swift atoms, produced by α particles in their passage through carbon dioxide, is equivalent to the range of O atoms, indicates that there are no carbon atoms carrying a single charge, for in that case bright scintillations should have been observed for ranges up to 12 cm. of air (see Table I.).

It will be remembered that in the beautiful photographs of Mr. C. T. R. Wilson * showing the trails of α particles, an example is given where the α particle in air shows a sudden deflexion of 43°, and there is clear evidence of a well-marked spur presumably showing the trail of the N or O recoil atom. It is of interest to compare the length of this spur with the range to be expected for a collision with an O atom. If ϕ be angle of deflexion of the α particle and θ the deflexion of the O atom,

$$\tan\phi=\frac{m\sin 2\theta}{\mathrm{M}-m\cos 2\theta},$$

where m = mass of O atom and M = mass of α particle.

Putting $\mathrm{M}=4$, $m=16$, $\phi=43°$, then $\theta=63°{\cdot}55$.

If v = velocity of the α particle before the collision, the velocity of the O atom

$$=\frac{2\mathrm{M}}{\mathrm{M}+m}\cdot v\cos\theta={\cdot}178\,v,$$

while the velocity of the α particle after the collision is $\cdot 934\,v$.

$$\frac{\text{Range of recoil O atom}}{\text{Range of }\alpha\text{ particle after collision}}=16\times\left(\frac{\cdot 178}{\cdot 934}\right)^{2\cdot 9}={\cdot}13.$$

This is based on the calculation that the maximum range of O atoms due to α particles from radium C is 7·8 cm., while the observed range is 9·0 cm. Making this correction, the value ·13 becomes ·15.

It is possible to compare only roughly the ranges of the α particle and recoil atom in the photograph, but the results are in fair accord with the calculation.

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* C. T. R. Wilson, Proc. Roy. Soc. A. lxxxvii. p. 277 (1912).

In the same photograph the α particle shows another sudden bend of 10°·5. In this case, the range of the recoil O atom should be only about 1/800 of the α particle and could not be distinguished on the photograph.

Number of N *atoms.*

In a previous paper we have calculated the number and distribution of H atoms produced by α particles on the assumption that the nuclei may be regarded as point centres of force repelling according to the law of the inverse square. When these calculations are applied to the collision of α particles with nitrogen or oxygen nuclei, the distribution with velocity of the N and O atoms is very similar to that for H atoms. We should consequently expect on the simple theory that the number of N and O atoms should fall off very rapidly between 7 and 9 cm., and that the number of short-range atoms should greatly preponderate. Quite the contrary is observed in the experiments (fig. 1), where it is seen that the number of scintillations fall off quite gradually with range.

There seems to be no doubt that the effects produced by the collision of α particles with N and O atoms are very similar to those observed in hydrogen. The observations only receive an explanation on the assumption that the N and O atoms like the H atoms are thrown forward mainly in the direction of the α particles and, at any rate for swift α particles, the velocities of the recoil atoms are nearly uniform for a given velocity of the α particles. It should be pointed out that the experiments with air and oxygen differ in one respect from those with hydrogen. In the case of air the α particles are completely absorbed in the column of gas, while in the case of hydrogen the stopping power was usually equivalent to less than 1 cm. of air. Consequently in the air experiments, the scintillations observed are due to N and O atoms which are produced by α particles of all ranges between 7 and 0 cm., and thus have a wide range of velocities.

A number of experiments were made by the use of absorbing-screens of aluminium and gold in order to determine the number of N and O atoms produced by α particles of different range. The result as a whole showed that, for example, the number produced in the first 3·5 cm. of the range of the α particle from radium C was greater than in the last 3·5 cm., but accurate deductions were vitiated by the lack of uniformity in thickness of the metal films.

A number of concordant measurements were made to fix the total number of scintillations observed in air for a known activity of the source. The number of scintillations per minute due to N and O atoms at a distance of 7·5 cm. in air at 15° C. was 2·2 on an area of the zinc sulphide screen equal to 3·14 sq. mm. Referring to curve 1, it is seen that the number corresponding to an absorption of 7 cm. should be 2·6 and the number for 8 cm. absorption 1·5.

All those atoms of range equal to or greater than 8 cm. must be produced in the first 3·5 cm. of the path of the α rays; for the O atoms produced by α particles of range 3·5 cm. cannot travel further than 8 cm. from the source, and probably only a small fraction reach this distance owing to scattering and straggling.

For the purpose of calculation, suppose that the production of swift atoms is uniform over the first 3·5 cm. of the range and that ρ is the ratio of the number of swift atoms produced per cm. of path to the number of α particles passing through the gas.

The number Q of recoil atoms falling per second on the screen of area A after passing through l cm. of gas is given by

$$Q=\rho\cdot\frac{AlN}{4\pi r^2},$$

where N is the total number of α particles emitted by the source per second ($3{\cdot}7\times10^7$ per second per mg. Ra of activity) and r is the distance of the source from the screen.

Putting

$$Q=\frac{1{\cdot}5}{60},\quad A={\cdot}0314 \text{ sq. cm.},\quad l=3{\cdot}5 \text{ cm.},\quad r=7{\cdot}5 \text{ cm.},$$

then the average value of $\rho=4{\cdot}3/10^6$.

When we take into consideration the well-known way in which the α particles fall off near the end of the range in consequence of scattering, it is obvious that the true value of ρ is considerably greater than the above and is probably about $7/10^6$.

In the experiments with hydrogen, it was shown that $\rho=1/10^5$ about—a value not very different from that observed in these experiments. We may consequently conclude that about the same number of swift atoms are produced per centimetre of path by the passage of α particles through air, oxygen, and hydrogen. As in the case of hydrogen, it can be shown that all α particles, shot within a perpendicular distance $p=2{\cdot}4\times10^{-13}$ cm. of the atomic nucleus, give rise to swift atoms of nitrogen and oxygen.

It is clear from these results that the nuclei under consideration can no longer be regarded as point charges for distances of approach of the order of the diameter of the electron. As far as experiment has so far gone, it is difficult to fix with certainty the distance at which the forces between the nuclei become abnormal, but a rough estimate can be made. Regarding the nuclei as point charges, the closest distance of approach in a collision is $1\cdot9 \times 10^{-13}$ cm. in the case of a hydrogen atom and $3\cdot8 \times 10^{-13}$ cm. in the case of the oxygen atom. Taking into account the close similarity of the effects produced by α particles in hydrogen and oxygen and the greater repulsive forces between the nuclei in the latter case, it seems probable that the abnormal forces in the case of oxygen manifest themselves at about twice the distance observed in the case of hydrogen. This would mean that the rapid variation in the magnitude and direction of the forces between the nuclei which lead to the recoil of swift atoms mainly in the direction of the α particle should begin at a distance about 7×10^{-13} cm. Such a result is to be anticipated on general grounds, for presumably the oxygen nucleus is more complex and has larger dimensions than that of helium.

In a paper published three years ago Mr. A. B. Wood and the writer * described experiments which showed that the active deposit of thorium gave rise to a few α particles of range 11·3 cm. in addition to the main group of ranges 5·0 and 8·6 cm. In these experiments, the α rays of range 8·6 cm. were absorbed in mica. In the light of the present experiments, the oxygen present in the mica should give rise to scintillations like α particles of range

$$8\cdot6 \times \frac{9\cdot0}{7\cdot0} = 11\cdot1 \text{ cm.}$$

This range is nearly the same as that observed in the thorium experiment, and raises the question whether these long range α particles are not in reality due to collision of α particles with the oxygen atoms in the mica. A fraction of the scintillations must undoubtedly have been due to this cause, but on the other hand the number of scintillations observed, about 1/10000 of the number of α particles, is considerably greater than is to be expected from the experiments with radium C. Further experiments to clear up this important point have been undertaken by Professor Marsden in New Zealand.

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* Rutherford and Wood, Phil. Mag. xxxi. p. 379 (1916).

LIV. *Collision of α Particles with Light Atoms.* IV. *An Anomalous Effect in Nitrogen.* *By* Professor Sir E. RUTHERFORD, *F.R.S.**

It has been shown in paper I. that a metal source, coated with a deposit of radium C, always gives rise to a number of scintillations on a zinc sulphide screen far beyond the range of the α particles. The swift atoms causing these scintillations carry a positive charge and are deflected by a magnetic field, and have about the same range and energy as the swift H atoms produced by the passage of α particles through hydrogen. These "natural" scintillations are believed to be due mainly to swift H atoms from the radioactive source, but it is difficult to decide whether they are expelled from the radioactive source itself or are due to the action of α particles on occluded hydrogen.

The apparatus employed to study these "natural" scintillations is the same as that described in paper I. The intense source of radium C was placed inside a metal box about 3 cm. from the end, and an opening in the end of the box was covered with a silver plate of stopping power equal to about 6 cm. of air. The zinc sulphide screen was mounted outside, about 1 mm. distant from the silver plate, to admit of the introduction of absorbing foils between them. The whole apparatus was placed in a strong magnetic field to deflect the β rays. The variation in the number of these "natural" scintillations with absorption in terms of cms. of air is shown in fig. 1, curve A. In this case, the air in the box was exhausted and absorbing foils of aluminium were used. When dried oxygen or carbon dioxide was admitted into the vessel, the number of scintillations diminished to about the amount to be expected from the stopping power of the column of gas.

A surprising effect was noticed, however, when dried air was introduced. Instead of diminishing, the number of scintillations was increased, and for an absorption corresponding to about 19 cm. of air the number was about twice that observed when the air was exhausted. It was clear from this experiment that the α particles in their passage through air gave rise to long-range scintillations which appeared to the eye to be about equal in brightness to H scintillations. A systematic series of observations was undertaken to account for the origin of these scintillations. In the first place we have seen that the passage of α particles through nitrogen and

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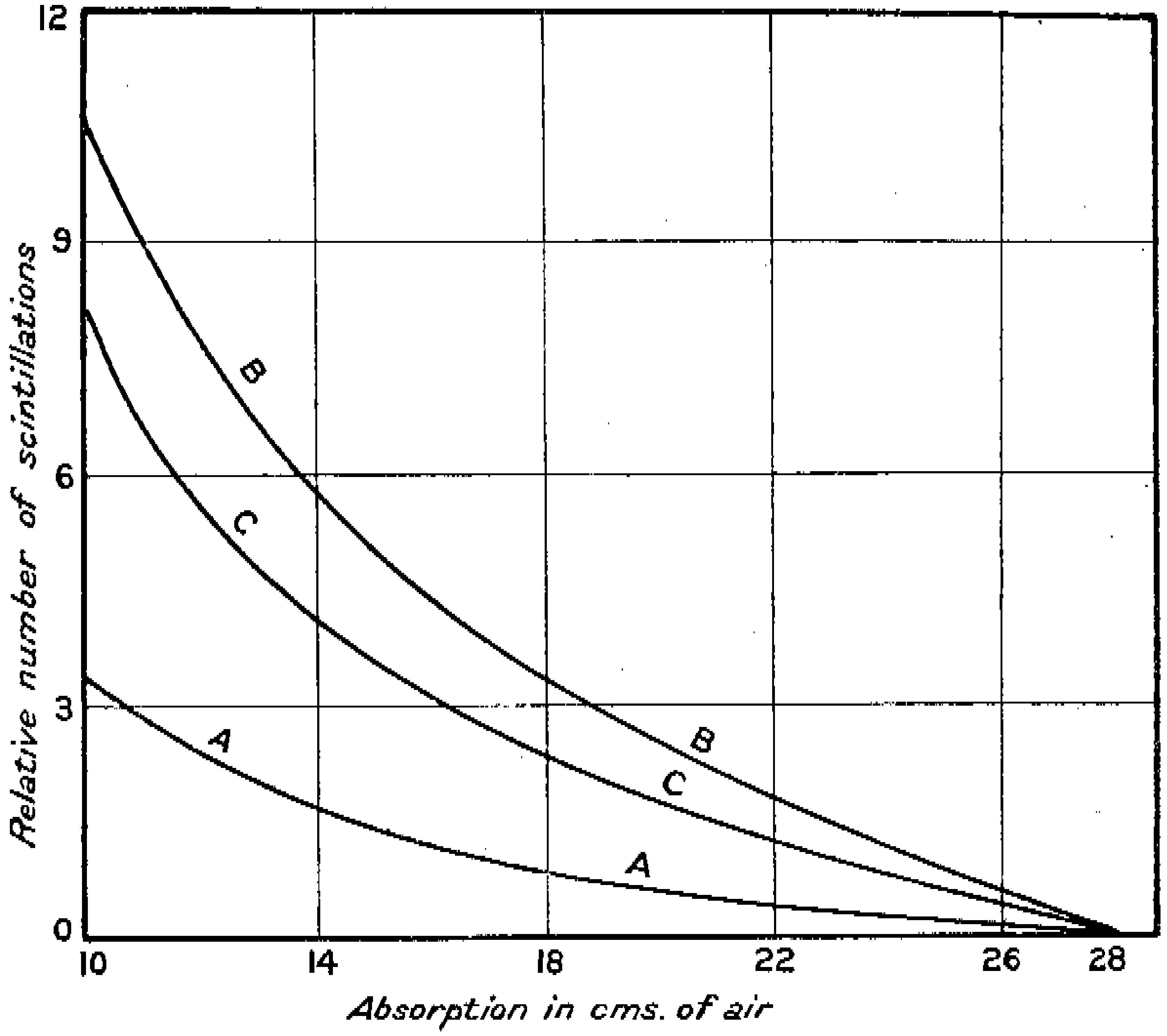
* Communicated by the Author.

oxygen gives rise to numerous bright scintillations which have a range of about 9 cm. in air. These scintillations have about the range to be expected if they are due to swift N or O atoms, carrying unit charge, produced by collision with α particles.

Fig. 1.



All experiments have consequently been made with an absorption greater than 9 cm. of air, so that these atoms are completely stopped before reaching the zinc sulphide screen.

It was found that these long-range scintillations could not be due to the presence of water vapour in the air; for the number was only slightly reduced by thoroughly drying the air. This is to be expected, since on the average the number of the additional scintillations due to air was equivalent to the number of H atoms produced by the mixture of hydrogen at 6 cm. pressure with oxygen. Since on the average the vapour pressure of water in air was not more than 1 cm., the effects of complete drying would not reduce the number by more than one sixth. Even when oxygen and carbon dioxide saturated with water vapour at 20° C. were introduced in place of dry air, the number of scintillations was much less than with dry air.

It is well known that the amount of hydrogen or gases containing hydrogen is normally very small in atmospheric air. No difference was observed whether the air was taken directly from the room or from outside the laboratory or was stored for some days over water.

There was the possibility that the effect in air might be due to liberation of H atoms from the dust nuclei in the air. No appreciable difference, however, was observed when the dried air was filtered through long plugs of cotton-wool, or by storage over water for some days to remove dust nuclei.

Since the anomalous effect was observed in air, but not in oxygen, or carbon dioxide, it must be due either to nitrogen or to one of the other gases present in atmospheric air. The latter possibility was excluded by comparing the effects produced in air and in chemically prepared nitrogen. The nitrogen was obtained by the well-known method of adding ammonium chloride to sodium nitrite, and stored over water. It was carefully dried before admission to the apparatus. With pure nitrogen, the number of long-range scintillations under similar conditions was greater than in air. As a result of careful experiments, the ratio was found to be 1·25, the value to be expected if the scintillations are due to nitrogen.

The results so far obtained show that the long-range scintillations obtained from air must be ascribed to nitrogen, but it is important, in addition, to show that they are due to collision of α particles with atoms of nitrogen through the volume of the gas. In the first place, it was found that the number of the scintillations varied with the pressure of the air in the way to be expected if they resulted from collision of α particles along the column of gas. In addition, when an absorbing screen of gold or aluminium was placed close to the source, the range of the scintillations was found to be reduced by the amount to be expected if the range of the expelled atom was proportional to the range of the colliding α particles. These results show that the scintillations arise from the volume of the gas and are not due to some surface effect in the radioactive source.

In fig. 1 curve A the results of a typical experiment are given showing the variation in the number of natural scintillations with the amount of absorbing matter in their path measured in terms of centimetres of air for α particles. In these experiments carbon dioxide was introduced at a pressure calculated to give the same absorption of the α rays as ordinary air. In curve B the corresponding curve is given when air at N.T.P. is introduced in place of carbon dioxide. The difference curve C shows the corresponding variation of the number of scintillations arising from the nitrogen in the air. It was generally observed that the ratio of the nitrogen effect to the natural effect was somewhat greater for 19 cm. than for 12 cm. absorption.

In order to estimate the magnitude of the effect, the space between the source and screen was filled with carbon dioxide at diminished pressure and a known pressure of hydrogen was added. The pressure of the carbon dioxide and of hydrogen were adjusted so that the total absorption of α particles in the mixed gas should be equal to that of the air. In this way it was found that the curve of absorption of H atoms produced under these conditions was somewhat steeper than curve C of fig. 1. As a consequence, the amount of hydrogen mixed with carbon dioxide required to produce a number of scintillations equal to that of air, increased with the increase of absorption. For example, the effect in air was equal to about 4 cm. of hydrogen at 12 cm. absorption, and about 8 cm. at 19 cm. absorption. For a mean value of the absorption, the effect was equal to about 6 cm. of hydrogen. This increased absorption of H atoms under similar conditions indicated either that (1) the swift atoms from air had a somewhat greater range than the H atoms, or (2) that the atoms from air were projected more in the line of flight of the α particles.

While the maximum range of the scintillations from air using radium C as a source of α rays appeared to be about the same, viz. 28 cm., as for H atoms produced from hydrogen, it was difficult to fix the end of the range with certainty on account of the smallness of the number and the weakness of the scintillations. Some special experiments were made to test whether, under favourable conditions, any scintillations due to nitrogen could be observed beyond 28 cm. of air absorption. For this purpose a strong source (about 60 mg. Ra activity) was brought within 2·5 cm. of the zinc sulphide screen, the space between containing dry air. On still further reducing the distance, the screen became too bright to detect very feeble scintillations. No certain evidence of scintillations was found beyond a range of 28 cm. It would therefore appear that (2) above is the more probable explanation.

In a previous paper (III.) we have seen that the number of swift atoms of nitrogen or oxygen produced per unit path by collision with α particles is about the same as the corresponding number of H atoms in hydrogen. Since the number of long-range scintillations in air is equivalent to that produced under similar conditions in a column of hydrogen at 6 cm. pressure, we may consequently conclude that only one long-range atom is produced for every 12 close collisions giving rise to a swift nitrogen atom of maximum range 9 cm.

It is of interest to give data showing the number of long-range scintillations produced in nitrogen at atmospheric pressure under definite conditions. For a column of nitrogen 3·3 cm. long, and for a total absorption of 19 cm. of air from the source, the number due to nitrogen per milligram of activity is ·6 per minute on a screen of 3·14 sq. mm. area.

Both as regards range and brightness of scintillations, the long-range atoms from nitrogen closely resemble H atoms, and in all probability are hydrogen atoms. In order, however, to settle this important point definitely, it is necessary to determine the deflexion of these atoms in a magnetic field. Some preliminary experiments have been made by a method similar to that employed in measuring the velocity of the H atom (see paper II.). The main difficulty is to obtain a sufficiently large deflexion of the stream of atoms and yet have a sufficient number of scintillations per minute for counting. The α rays from a strong source passed through dry air between two parallel horizontal plates 3 cm. long and 1·6 mm. apart, and the number of scintillations on the screen placed near the end of the plates was observed for different strengths of the magnetic field. Under these conditions, when the scintillations arise from the whole length of the column of air between the plates, the strongest magnetic field available reduced the number of scintillations by only 30 per cent. When the air was replaced by a mixture of carbon dioxide and hydrogen of the same stopping power for α rays, about an equal reduction was noted. As far as the experiment goes, this is an indication that the scintillations are due to H atoms; but the actual number of scintillations and the amount of reduction was too small to place much reliance on the result. In order to settle this question definitely, it will probably prove necessary to employ a solid nitrogen compound, free from hydrogen, as a source, and to use much stronger sources of α rays. In such experiments, it will be of importance to discriminate between the deflexions due to H atoms and possible atoms of atomic weight 2. From the calculations given in paper III., it is seen that a collision of an α particle with a free atom of mass 2 should give rise to an atom of range about 32 cm. in air, and of initial energy about ·89 of that of the H atom produced under similar conditions. The deflexion of the pencil of these rays in a magnetic field should be about ·6 of that shown by a corresponding pencil of H atoms.

Discussion of results.

From the results so far obtained it is difficult to avoid the conclusion that the long-range atoms arising from collision of α particles with nitrogen are not nitrogen atoms but probably atoms of hydrogen, or atoms of mass 2. If this be the case, we must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α particle, and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus. We have drawn attention in paper III. to the rather surprising observation that the range of the nitrogen atoms in air is about the same as the oxygen atoms, although we should expect a difference of about 19 per cent. If in collisions which give rise to swift nitrogen atoms, the hydrogen is at the same time disrupted, such a difference might be accounted for, for the energy is then shared between two systems.

It is of interest to note, that while the majority of the light atoms, as is well known, have atomic weights represented by $4n$ or $4n+3$ where n is a whole number, nitrogen is the only atom which is expressed by $4n+2$. We should anticipate from radioactive data that the nitrogen nucleus consists of three helium nuclei each of atomic mass 4 and either two hydrogen nuclei or one of mass 2. If the H nuclei were outriders of the main system of mass 12, the number of close collisions with the bound H nuclei would be less than if the latter were free, for the α particle in a collision comes under the combined field of the H nucleus and of the central mass. Under such conditions, it is to be expected that the α particle would only occasionally approach close enough to the H nucleus to give it the maximum velocity, although in many cases it may give it sufficient energy to break its bond with the central mass. Such a point of view would explain why the number of swift H atoms from nitrogen is less than the corresponding number in free hydrogen and less also than the number of swift nitrogen atoms. The general results indicate that the H nuclei, which are released, are distant about twice the diameter of the electron (7×10^{-13} cm.) from the centre of the main atom. Without a knowledge of the laws of force at such small distances, it is difficult to estimate the energy required to free the H nucleus or to calculate the maximum velocity that can be given to the escaping H atom. It is not to be expected, *a priori*, that the velocity or range of the H atom released from the nitrogen atom should be identical with that due to a collision in free hydrogen.

Taking into account the great energy of motion of the α particle expelled from radium C, the close collision of such

an α particle with a light atom seems to be the most likely agency to promote the disruption of the latter; for the forces on the nuclei arising from such collisions appear to be greater than can be produced by any other agency at present available. Considering the enormous intensity of the forces brought into play, it is not so much a matter of surprise that the nitrogen atom should suffer disintegration as that the α particle itself escapes disruption into its constituents. The results as a whole suggest that, if α particles—or similar projectiles—of still greater energy were available for experiment, we might expect to break down the nucleus structure of many of the lighter atoms.

I desire to express my thanks to Mr. William Kay for his invaluable assistance in counting scintillations.

University of Manchester,
April 1919.

LV. *The Rotational Oscillation of a Cylinder in a Viscous Liquid.* By D. Coster *.

THIS problem has been dealt with by Stokes † for the purpose of numerical calculations to determine the viscosity of the air. Still, I think it interesting to publish another solution of the problem which gives more opportunity of discussing the different cases, though it is perhaps less adapted to precise calculations.

The method to be followed will be in the main the same as that used by Prof. Verschaffelt in the analogous case of the sphere ‡. We consider the rotational swings about its axis of an infinitely long cylinder which executes a forced vibration. Our object will be to ascertain the motion in the liquid which will establish itself after an infinite time (in practice after a relatively short time §) in order to compute the frictional moment of forces exerted on the cylinder by the liquid. The calculations will be referred to a height of 1 cm.

The motion of the cylinder may be represented by $\alpha = a\cos pt$ where α is the angle of rotation. An obvious assumption to be made is that the liquid will be set in motion in coaxial cylindrical shells each of which will execute its oscillations as a whole. On this assumption it is not difficult

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* Communicated by Prof. G. N. Watson, M.A., D.Sc. First published in the Amsterdam Proc. May 1918, vol. xxi. p. 193.

† Math. Papers, vol. v. p. 207.

‡ *Cf.* Amst. Proc. vol. xviii. p. 840; Comm. Leiden, 148 C.

§ *Cf.* Comm. Leiden, p. 22, footnote.