

LXXXIX. *The Artificial Disintegration of Light Elements.*

By Sir E. RUTHERFORD, *F.R.S., Cavendish Professor of Experimental Physics*, and J. CHADWICK, *Ph.D., Clerk Maxwell Scholar, University of Cambridge*.*

IN previous papers, one† of us has shown that when swift α particles pass through dry air or nitrogen, a few long-range particles are produced which can be detected by their scintillations on a zinc-sulphide screen. These particles were bent in a magnetic field to about the same extent as swift H atoms of the same range, and it was concluded that some of the nitrogen atoms were disintegrated by the intense collisions with α particles and that a positively charged hydrogen atom (H atom) was liberated at a high speed. No such long-range particles were observed in oxygen or carbon dioxide. In these preliminary experiments, the scintillations due to the H atoms were so few in number and so feeble in intensity, that it was found difficult to decide with certainty whether the maximum range of the H atoms from nitrogen differed from that for the corresponding H atoms set in swift motion by the passage of α particles through hydrogen or other hydrogen material.

Recently the optical arrangements of the microscope have been so improved that the counting of scintillations has become much easier and more certain. By this means, it was at once found that the particles from nitrogen had a greater range of penetration than the corresponding H atoms from hydrogen. For example, using radium C as a source of α rays with a range in air of 7 cm., no H atoms from hydrogen can be detected after passing through absorbing screens of aluminium or mica of stopping-power equivalent to 29 cm. of air. On the other hand, the maximum range of the particles from nitrogen corresponds to 40 cm. of air. This shows at once that the emission of these particles from nitrogen cannot possibly be ascribed to the presence of free hydrogen or hydrogen in combination as a contamination. This observation gave a simple method of testing whether other elements besides nitrogen emitted long-range particles. If the scintillations are counted for absorptions greater than 29 cm. of air, the results are quite independent of the presence of hydrogen as an impurity in the substance under

* Communicated by the Authors.

† Rutherford, *Phil. Mag.* xxxvii., I. II. & III., pp. 538-587 (1919); Bakerian Lecture, *Proc. Roy. Soc. A*, xcvi. p. 374 (1920).

examination. In this way we have obtained definite proof that, in addition to nitrogen, also boron, fluorine, sodium, aluminium, and phosphorus exposed to α rays give rise to particles whose ranges vary between 40 and 90 cm. of air.

In the present paper, a brief account will be given of the general methods employed in examining a number of elements and also a more detailed account of the variation in the number of particles with velocity of the incident α rays for two typical elements, viz., nitrogen and aluminium.

Counting of Scintillations.

With the microscope originally employed, the scintillations due to H atoms were in general weak and difficult to count with accuracy. The brightness of the scintillations can be much increased by the use of special lenses. We have found most suitable for our purpose a holoscopic objective of focal length 16 mm. and aperture $\cdot 45$. With an eyepiece of low magnifying power, this gave a field of view of diameter 3.25 mm. and of area 8.3 sq. mm. The magnification of the system employed was about 40. In these experiments it was essential to include as large an area of screen as possible in order to give a convenient number of scintillations per minute. For this reason, the use of short focus objectives, which can readily be obtained of wide aperture, was quite out of the question. In order to avoid the direct effect on the eyes due to the γ rays from the source of radiation, a special microscope was constructed in which the light from the objective was turned through a right angle by means of a totally reflecting prism. In this way, by use of suitable absorbing screens, the observer could be protected from the direct effect of the powerful sources of γ rays employed in some experiments. This microscope was designed and constructed for the purpose by Mr. Twyman of Hilger and Co., and has proved very satisfactory.

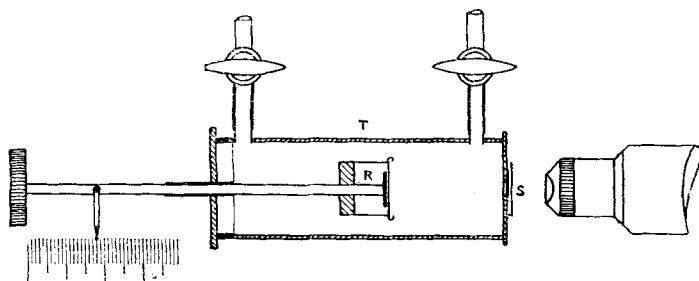
An account of the precautions to be taken in counting weak scintillations has been given in a previous paper, but attention should be drawn to a few additional points. In order to reduce the luminosity of the zinc-sulphide screen due to the γ rays, it is important to employ a thin and finely powdered layer. With the use of a strong magnetic field to turn aside the β rays, we have found it feasible to count the scintillations with a source of radium C of activity equivalent to 20 mgs. Ra only 2.5 cm. away from the zinc-sulphide screen. With the new microscopes we have found the counting results much more concordant than with the old,

and observations taken at six months interval have been found in good agreement. In order to count as many particles as possible during an experiment, two counters were always used who counted alternately for a period of one minute each. An additional observer made the necessary adjustments and recorded the data.

Experimental arrangement.

The general arrangement will be clear from fig. 1. The

Fig. 1.



source of α particles R was carried on a rod passing with a sliding fit through a brass stopper. This fitted tightly into the brass tube T of 3 cm. diameter. The end of the vessel was provided with a hole 5 mm. in diameter, which was closed by a silver foil of 6.3 cm. air equivalent. The zinc-sulphide screen S was fixed on the face leaving a slot of 1.3 mm. depth in which absorbing screens could be inserted. The apparatus was placed between the poles of a large electromagnet to reduce the luminosity due to the β rays.

The source R in most experiments was a brass disk of diameter 1 cm. coated with the active deposit of radium. Its initial γ -ray activity was usually equivalent to 25 mgs. Ra. The distance of the source from the screen, generally 3.5 cm., could be varied and the position read off on a scale. In most cases the material to be exposed to α rays was in the form of a powder, generally the oxide of the element. This was heated *in vacuo* and a film prepared by dusting on to a gold foil smeared with alcohol. The average thickness of the film was determined by weighing. The screen thus prepared was placed immediately in front of the source. A stream of dry oxygen, which does not give any particles, was continuously passed through the apparatus to eliminate the effect of the nitrogen in the air which would itself give long-range particles.

In general, absorbing screens of mica were inserted in front of the zinc-sulphide screen so as to make the total absorption in the path of any particles liberated from the bombarded material equivalent to 32 cm. of air. Control experiments were made (1) by placing a sheet of paraffin wax 25μ thick at F, (2) by passing a mixture of CO_2 and H_2 through the apparatus, the source being uncovered. It was found that no H particles could be detected through an absorption of more than 29 cm. of air. Hence the results obtained for the materials under examination were independent of contamination with H or any H compound.

The following table contains in the first column a list of the elements, from lithium to sulphur inclusive, which have been examined in this way; and the second column shows the material actually used in the experiments.

The third column gives the number of scintillations per minute per mgm. activity of the source observed at an absorption of 32 cm. of air under certain conditions. These numbers afford only a rough comparison of the effects given by different elements, for the conditions of experiment, *e. g.* the thickness and distribution of the film of material, varied from element to element. The fourth column gives the approximate maximum range of the particles.

Element.	Material.	No. of particles per min. per mgm.	Maximum range of particles, in cm. of air.
Lithium	Li_2O	—	—
Beryllium	BeO	—	—
Boron	B	15	ca. 45
Carbon	CO_2	—	—
Nitrogen	Air	7	40
Oxygen	O_2	—	—
Fluorine	CaF_2	4	over 40
Sodium	Na_2O	2	ca. 42
Magnesium	MgO	—	—
Aluminium	$\text{Al}, \text{Al}_2\text{O}_3$	1.1	90
Silicon	Si	—	—
Phosphorus	P (red)	7	ca. 65
Sulphur	S, SO_2	—	—

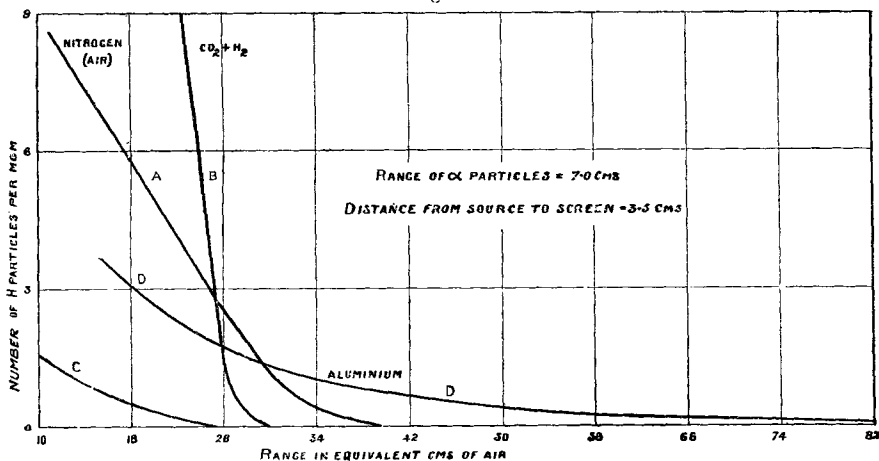
In addition to these, the following elements of higher atomic weight were examined: chlorine as MgCl_2 ; potassium as KCl ; calcium as CaO ; titanium as Ti_2O_3 ; manganese as MnO_2 ; iron, copper, tin, silver, and gold in the form of metal foils. In no case were any particles observed of range greater than 32 cm. of air. The question as to whether any of these elements give particles of range less than 32 cm. has not yet been examined.

Long-range Particles from Nitrogen.

In these experiments the source of α rays was always fixed at 3.5 cm. from the zinc-sulphide screen and a continuous stream of dry air was drawn through the apparatus. The number of particles was counted after passing through mica screens of different stopping power.

(Curve A (fig. 2) is a typical absorption curve of the

Fig. 2.



particles from nitrogen using radium C as a source of α rays. The ordinates represent the number of scintillations observed per minute per milligram of activity of radium C measured by γ rays; the abscissæ, the stopping power of the absorbing screens for α particles expressed in terms of centimetres of air. It is seen that scintillations were observed up to 40 cm. of absorption. Curve B is the corresponding absorption curve when the α rays passed through a mixture of hydrogen and carbon dioxide, about 1 volume of H_2 to 1.5 of CO_2 , which gave the same stopping-power as air for α rays. It is seen that no H atoms were observed beyond 29 cm. of absorption, but the number rose very rapidly with diminishing absorption. The actual number of scintillations from nitrogen for 12 cm. absorption was very much less than the number liberated in the H_2 and CO_2 mixture. Curve C represents the "natural" effect when the nitrogen was replaced by dry oxygen. The scintillations observed in this case are believed to have their origin from a slight hydrogen contamination of the source of α rays. This natural effect is small compared with that shown by nitrogen.

Curve D is an illustration of the effects observed when a

screen of aluminium of stopping-power equivalent to 3.5 cm. of air is placed over the source and the air replaced by oxygen. It is seen that the particles liberated from aluminium are able to penetrate a much greater distance of matter than those from nitrogen. The number of scintillations becomes so small for large absorptions that it is difficult to fix the limiting range with accuracy.

Effect of Velocity of α Particles.

A series of experiments was made to find how the number and range of the particles were affected by change in the velocity of the incident α particles. For this purpose the following sources were employed :—

(1) Deposit of thorium C obtained by immersing one side of a nickel disk in a strong solution of radiothorium*. This source gives complex α rays, viz., $2/3$ of range 8.6 cm. and $1/3$ of range 5.0 cm. The γ -ray activity of this source with thorium C and D in equilibrium was measured in terms of milligrams of radium. Recently some experiments have been made in this laboratory by Professor Schlundt and Mr. Shenstone to compare the number of α particles of long range (8.6 cm.) emitted from Th C and D with the corresponding number from Ra B and C of equal γ -ray activity. Under the conditions of measurement in our experiments, the number of long-range particles per milligram of activity of ThC is taken as 70 per cent. of the corresponding number of α particles of range 7 cm. per milligram of radium C. In order to make the results for thorium C and radium C comparable, it is consequently necessary to multiply the numbers of scintillations found in the ThC experiments by 1.4. This has been done in all direct comparisons.

(2) A source of radium B+C giving α rays of 7 cm., obtained by exposure of a brass disk to the emanation of radium.

(3) Sources of α rays of ranges 6 and 4.9 cm. of air were got by placing silver or gold foil of stopping-power 1 cm. and 2.1 cm. respectively over a source of radium B+C. Previous experiments had shown that neither silver nor gold gave any long-range particles.

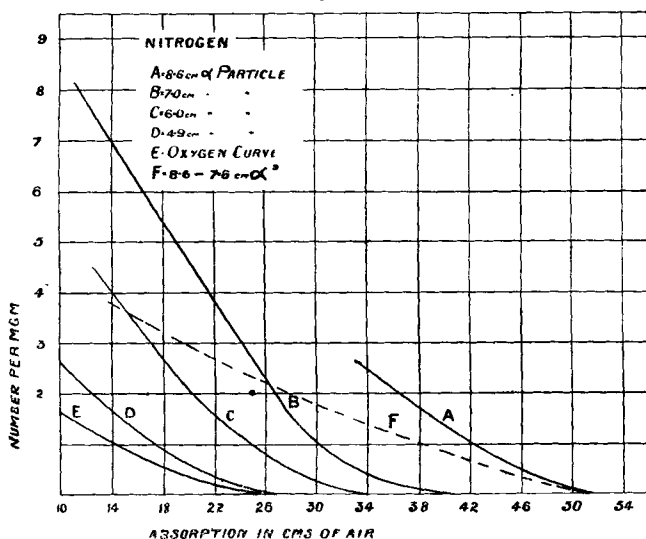
The absorption curves are shown in fig. 3.

* We are very much indebted for the success of these experiments to the generosity of Dr. H. N. McCoy, who kindly presented one of us with a preparation of radiothorium of activity more than 30 mgr. Ra. Under the best conditions, we were able to obtain sources of ThC on a nickel disk corresponding in activity to 20 mgs. Ra.

Curve A is for rays of range 8.6 cm. Only the end part of the curve is given, as the initial portions are complicated by the effects of the α rays of range 5 cm.

Curves B, C, D are for α rays of ranges 7.0, 6.0, and 4.9 cm. respectively. Curve E shows the natural effect when the air is replaced by dry oxygen. It was found that to a first approximation the range of the liberated particles was proportional to the range of the incident α particles. For example, the ranges of the particles were about 50, 40, 34 cm. for α particles of range 8.6, 7.0, and 6.0 respectively.

Fig. 3.



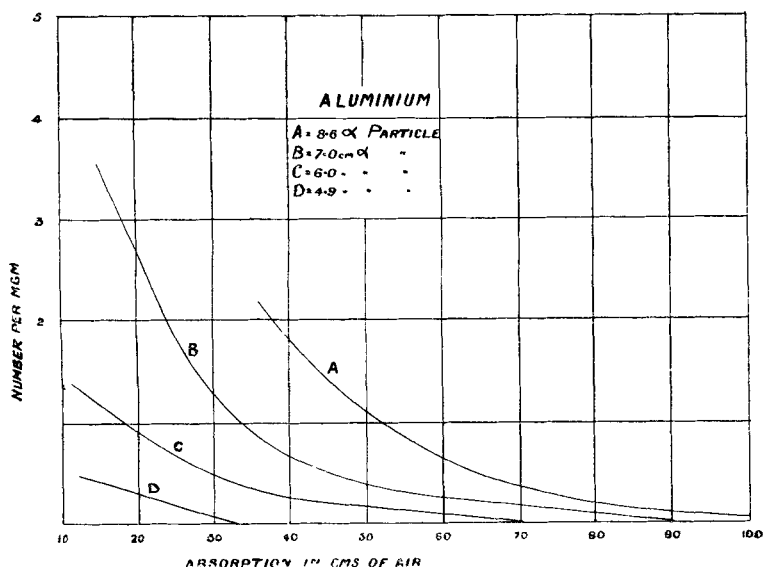
It is seen that the number of particles observed increased rapidly with the velocity of the α particle. Allowing for the natural scintillations given by curve E, the number observed for 12 cm. absorption is 6.5, 3.4, 0.8 per milligram for rays of range 7.0, 6.0, and 4.9 cm. respectively. The corresponding numbers for half the maximum range in each case is 4.3, 2.5, and 0.7. It is to be remembered that the α rays pass through a length of 3.5 cm. of gas, so that in the case of α rays of initial range 7 cm., the gas is acted on by rays varying in range from 7 to 3.5 cm. Without definite information as to the angular distribution of the particles liberated by the collisions, it is difficult to estimate the number of particles provided by each part of the column of gas traversed. It seems clear, however, that the number rises rapidly with increase of velocity of the α rays. This

was shown by the following experiment. A screen of silver of stopping-power 3.7 cm. was placed 1 cm. distant from the source of α rays of range 8.6 cm. We know from experiment that the rays after traversing the silver are ineffective in producing long-range particles. Consequently the swift atoms are produced only in the first centimetre of the air. This absorption curve of the H atoms liberated by α particles of range between 8.6 and 7.6 cm. is shown in curve F (fig. 3). When a source of rays of range 7 cm. was substituted for the 8.6 cm. the effects observed were considerably smaller. The effect due to the α rays of range 5 cm. emitted by ThC was small and easily allowed for.

Experiments with Aluminium.

A plate of aluminium of stopping-power 3.5 cm. was placed immediately in front of the source, whose distance from the zinc-sulphide screen could be varied. The aluminium had been carefully heated in a vacuum furnace to drive off occluded hydrogen and water-vapour. Dry oxygen was circulated through the apparatus. By placing absorbing screens of silver and gold between the source and the

Fig. 4.



aluminium plate, the effect of velocity of the α particle on the number and range of the emitted particles could be examined as before. The results are shown in fig. 4, where

curves A, B, C, D represent the effects due to α particles of initial ranges 8.6, 7.0, 6.0, and 4.9 cm. respectively. The ranges of the particles are more than twice as great as for those liberated from nitrogen. It is seen that the variation of the number with velocity is very rapid. There is a marked difference between curves B and C, and it is doubtful whether the rays of range 4.9 cm. give any particles at all, for the numbers include the effect due to the "natural" scintillations from the source.

It was found exceedingly difficult to fix the end of the range of the particles with accuracy on account of the smallness of the numbers of scintillations. To increase the effect, a stronger magnetic field was used to bend away the β rays and the source brought as close to the screen as the luminosity due to γ rays and residual β rays allowed. The results as a whole showed that the ranges of the particles were approximately proportional to the ranges of the incident α rays, but a special series of experiments will be required to fix the ranges with the accuracy desired. It is an important question to decide whether such a proportionality exists, as it may help to throw light on the mechanism involved in the liberation of these swift particles. It seems certain, however, that some of the particles from aluminium due to α rays of range 7 cm. have a range of at least 90 cm. of air. The number of scintillations was too small to follow the absorption further. As it is, the experiments have been carried out to the point of detecting 1 particle per minute for 20 mgs. at the standard distance of 3.5 cm.

Direction of escape of Particles.

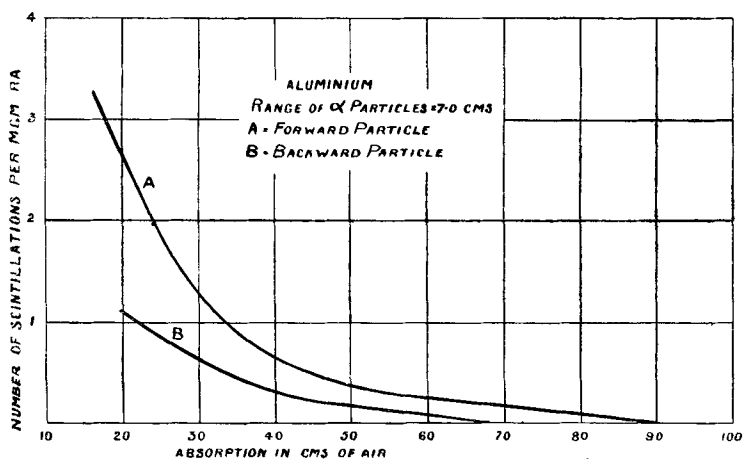
From analogy with the projection of H atoms by α particles from hydrogen, it is to be expected that the great majority of the particles liberated from the elements would be expelled in the direction of the α particles. In the case of aluminium, however, it was found that the direction of escape of the particles was to a large extent independent of the direction of the impinging α particles. Nearly as many were expelled in the backward as in the forward direction. This effect was first observed when an aluminium instead of a brass disk was coated with active deposit, and used as a source of α rays in an atmosphere of oxygen. The aluminium plate in front of the source was removed. The particles which fall on the zinc-sulphide screen can be liberated only by α rays, which are fired into the aluminium disk in a direction away from the zinc screen.

This type of experiment is, however, open to the objection

that some of the active deposit may have penetrated some distance into the aluminium disk and there given rise to particles in the forward direction of the α rays. To avoid this uncertainty, one side only of a silver plate of 3.7 cm. stopping-power was coated with active deposit by fixing it at the end of a tube filled with emanation. This plate was then used as a source with the active side facing away from the zinc sulphide screen. The active face of the silver was covered by an aluminium foil of 3.5 cm. stopping-power.

The number and absorption of the particles which are projected in a backward direction is shown in curve B of fig. 5. The corresponding curve for particles which are shot

Fig. 5.



in the forward direction for an equal thickness of aluminium is shown in curve A. It is seen that the number in the backward direction is of the same order of magnitude as for the forward; but the maximum range in the backward direction for particles of range 7 cm. was smaller—viz., 67 cm. instead of the 90 cm. observed for those shot forward.

As previously pointed out, it is very difficult to fix the exact ranges in these cases on account of the smallness of the observed effects. A few experiments were made to test whether the particles from nitrogen showed a similar effect. The arrangement was the same as for aluminium, but the α particles were fired backwards into air instead of into the aluminium plate. The number projected in a backward direction, if there are any at all, is very small compared

with the number in a forward direction. For an absorption of 18 cm., the number was certainly less than 1/50 of the corresponding number in the forward direction.

We have not so far been able to make similar experiments with the particles from boron, fluorine, sodium, or phosphorus.

Discussion of Results.

Experimental evidence shows that the long-range particles expelled from nitrogen are swift H atoms carrying a unit positive charge. While we have not yet been able to test the nature of these long-range particles liberated from other elements, it seems very probable that the particles are in all cases H atoms, which are released at different maximum speeds depending on the nature of the element and on the velocity of the incident α particle. Under the conditions of the experiments, such H atoms can only arise from a disintegration of the nucleus brought about by a close collision with an α particle.

It is of interest to note that of the elements so far examined only those whose atomic mass is given by $4n+2$ or $4n+3$, where n is a whole number, give rise to H atoms. Elements of mass $4n$ like carbon, oxygen, sulphur, show no effect. This result is clearly seen from the following table of elements which give H atoms:—

<i>Element.</i>	<i>Mass.</i>	$4n+a.$
Boron	11	$2 \times 4 + 3$
Nitrogen	14	$3 \times 4 + 2$
Fluorine	19	$4 \times 4 + 3$
Sodium	23	$5 \times 4 + 3$
Aluminium	27	$6 \times 4 + 3$
Phosphorus	31	$7 \times 4 + 3$

This result receives a simple explanation on the assumption that the nuclei of these elements are built up of helium nuclei of mass 4 and of hydrogen nuclei. The importance of the helium nucleus as a unit of atomic structure in heavy elements is clearly brought out by the study of the radioactive transformations.

In order to account for the liberation of an H atom at high speed, it is natural to suppose that the H nuclei are satellites of the main nucleus. In a close collision, the α particle is able to give sufficient energy to the satellite to cause its escape at high speed from the central nucleus.

Since probably the forces holding the H satellites in equilibrium increase with the nuclear charge of the element, it is to be anticipated that the H satellites are closer to the nucleus for aluminium than for nitrogen. The velocity of escape of the H atom, however, does not seem to be very simply connected with the nuclear charge of the disintegrated elements. For example, the range of the H atoms from boron (charge 5) is greater than that for nitrogen (7); while the range of the H atom from aluminium (13) is greater than that expelled from phosphorus (14).

An α particle in a direct collision with a free H nucleus at rest communicates to it $\cdot 4$ of its momentum and $\cdot 64$ of its energy. In order to communicate greater energy and momentum, the nucleus must be in motion in the opposite direction to that of the α particle. The momentum communicated to an H satellite will thus depend on two factors: (1) the velocity of the H satellite in its orbit or, in more general terms, the closeness of its binding to the central nucleus; (2) the nearness of the satellite to the central nucleus.

In order that the colliding α particle may communicate much of its momentum to the satellite, the latter must be held by strong forces to the nucleus. If, however, the H satellite is very close to the nucleus, the α particle may have to communicate a considerable fraction of its momentum to the central nucleus, and the velocity of escape of the H satellite is correspondingly reduced. This, for example, may be the explanation why the H atoms from aluminium are faster than those from phosphorus of higher nuclear charge. In phosphorus, the H satellites may move so close to the nucleus, that the α particle is able to give a smaller share of its momentum to the H satellite than in the case of the more distant satellite of aluminium.

The failure of the α particle to release H atoms from elements of mass greater than phosphorus may be due to the fact that the H atoms either move very close to the nucleus or are incorporated in its structure.

It should be borne in mind that the chance of ejecting an H satellite at great speed from a nucleus is much smaller than for setting a free H atom in correspondingly rapid motion. The number of swift H atoms released from the nucleus is, as we have seen, very dependent on the velocity of the α particle and also on the structure of the nucleus, but on an average is not more than $1/20$ of the corresponding number of swift H atoms which are set in motion by collision of the α particles with free hydrogen nuclei. This shows

that the presence of the central nucleus greatly diminishes the chance of such a direct collision with the H satellite as will give it sufficient velocity to escape from the system. It may be that it is only within certain prescribed limits of velocity of the satellite and position with regard to the central nucleus that a liberation of the satellite at a high speed by an α particle is possible.

In discussing the possible mechanism of release of an H atom from a nucleus by the close collision with an α particle, two important experimental facts should be borne in mind—viz. (1) the maximum velocity of escape of an H atom for a given element is, at any rate to a first approximation, proportional to the velocity of the colliding α particle; (2) in the case of aluminium and possibly of the other elements, the H atoms escape in all directions, but the velocity is less in the backward than in the forward direction. The data in the case of aluminium and nitrogen are collected in the following table. Since the velocities of the H atoms are nearly proportional to the velocity V of the colliding α particle, the velocity, momentum, and energy of the H atom are expressed in terms of the incident α particle.

	Velocity. V	Momentum. 4V	Kinetic energy. $2V^2$
Incident α particle	V	4V	$2V^2$
H atoms from aluminium :			
(1) in forward direction ...	2.37V	2.37V	$2.81V^2$
(2) in backward direction ...	2.13V	2.13V	$2.27V^2$
H atoms from nitrogen :			
(1) in forward direction	1.80V	1.80V	$1.62V^2$

The velocities are calculated on the assumption that the maximum velocity of a free H atom is 1.6V and that the corresponding range is 28 cm. of air for an α particle of 7 cm. range. It is assumed from analogy with α particles that the velocity of an H atom is proportional to the cube root of its range. The general evidence indicates that this relation holds, at any rate, approximately. It is seen that the energy of the H atom escaping from aluminium is 1.40 times the energy of the incident α particle, and even in the backward direction the energy is 13 per cent. greater. This additional energy must come from the atom in consequence of its disintegration.

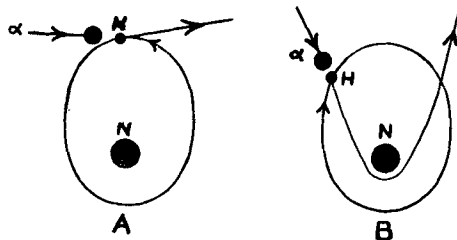
Mechanism of Disintegration.

It is of interest to consider whether any further information can be obtained which will throw light on the

ultimate distribution of kinetic energy between the three bodies involved in a collision—viz., the α particle, the H satellite, and the central nucleus. It is also necessary to account for the surprising fact that the H atoms from aluminium are shot out in all directions. The latter fact suggests at once the possibility of an atomic explosion in which the energy of the α particle plays the part of a detonator, and the escaping H particle gains most of its energy from the nucleus. Such a general conclusion, however, is not supported by the observed result that the energy of escape appears to be nearly proportional to the energy of the incident α particle. On account of the difficulty of determining the ranges in these experiments, too much stress must not be laid on this point.

The escape of the H atoms in all directions may be explained in a simple way, which is illustrated in fig. 6.

Fig. 6.



The H atom is supposed to be moving in an orbit round the central nucleus N. If the collision occurs, as in A, the H atom is driven in the forward direction of the α particle and away from the nucleus; if, as in B, the H atom is driven towards the nucleus, it describes an orbit close to the nucleus and escapes in the backward direction. The difference of velocity of the H atoms in the forward and backward directions is probably due to the fact that the nucleus has been set in motion in the direction of the α particle before the close collision with the H satellite occurs. On this view, the relative velocity of the H atom and residual nucleus is the same whether the H atom escapes in the backward or forward direction, but the actual velocity in the backward direction is less.

It is clear that in the case of aluminium, the law of conservation of energy does not hold, unless we take into

account the energy derived from the disintegration of the nucleus. If we suppose, however, that the law of conservation of momentum is valid in this problem, we can, on certain assumptions, calculate the final distribution of energy between the three bodies involved in the collision.

We shall suppose that, in addition to the conservation of momentum, the resultant kinetic energy of the three bodies involved is the same whether the H atom is liberated in the forward or backward direction, and in particular that the final energy of escape of the α particle is not sensibly different in the two cases. Both of these assumptions seem not unreasonable.

Let M , m , μ be the masses of the α particle, H atom, and residual nucleus respectively; V , V' the initial and final velocities of the α particle; v_1 , v_2 the maximum velocities of the H atoms in the forwards and backwards direction; u_1 , u_2 the corresponding velocities of the residual nucleus. The velocities are all measured in the direction of the α particle.

Then

$$\begin{aligned} M(V - V') &= mv_1 + \mu u_1 \\ &= mv_2 + \mu u_2, \end{aligned}$$

while the equivalence of energy in the two cases gives

$$mv_1^2 + \mu u_1^2 = mv_2^2 + \mu u_2^2.$$

From these three equations we can determine the three unknowns—viz., V' , u_1 , and u_2 .

In the case of aluminium,

$$m = 1, \quad \mu = 26, \quad v_1 = 2.37V, \quad v_2 = 2.13V.$$

It can be calculated that in this case

$$\begin{aligned} V' &= .19V, \\ \mu u_1 &= .87V, \\ \mu u_2 &= 5.37V. \end{aligned}$$

It is thus seen that the α particle escapes with .19 of its initial velocity, and so gives 96.4 per cent. of its energy to the system. The residual nucleus is shot forward in the direction of the α particle, but with slower velocity in the case of the escape of a forward particle.

The relative energies in terms of the initial energy of the

α particle are 1.404, .007, .036 for the H atom, nucleus, and α particle respectively after a collision in which the H atom is shot forward. The corresponding numbers when the H atom is shot backward are 1.13, .24, .036 respectively.

The total gain of energy of the parts after the collision is .45 the energy of the incident α particle.

These deductions, which apply only to the case of an α particle of range 7 cm., are of the order of magnitude to be expected. Possibly the excess energy may be ascribed to a rearrangement of the nucleus which accompanies the disintegration. Unfortunately, the number of H atoms, if any, emitted backwards from nitrogen is too small for accurate determination of their maximum velocity. From similar calculations to those given above, it can be shown that the system neither gains nor loses energy if the H atoms have a range of 19.2 cm. backwards when the forward range is 40 cm. If the backward range is relatively greater, there would be a gain of energy by the disintegration.

General considerations.

The chance that an α particle is able to liberate a swift H atom from a nucleus is exceedingly small. In the case of aluminium, for example, the number of scintillations observed on a screen of 8.3 sq. mm. area for an absorption of 30 cm. is about one per minute per milligram for a bombarded plate of aluminium of 3.5 cm. stopping-power, 3.5 cm. distant from the screen, and for α rays of initial range 7 cm. Taking the efficiency of the screen as .75, it follows that only two α particles in one million are able to liberate a swift H atom. Knowing that the α particles from one gram of radium produce only 168 cubic mass of helium per year, it is easily seen that the volume of hydrogen per year liberated from nitrogen or aluminium under practical conditions would be exceedingly small.

The observations on the disintegration of the light elements have been interpreted by supposing that the H atoms are satellites of the central nucleus. This implicitly assumes that positively charged bodies attract one another at the very small distances involved. Such attractive forces must exist in order to hold the ordinary composite nucleus in equilibrium, and it seems likely that these attractive forces will extend some distance from the nucleus. If this view be correct, the forces on the α particle are initially repulsive, but change sign very near the nucleus. As the law of force very near such nuclei is unknown, it is difficult to form any

definite idea of the distance of the satellites from the central nucleus, or of its orbital velocity.

It is of interest in this connexion to note that H atoms do not appear to be released from aluminium by α particles of range less than 5 cm. The number liberated increases rapidly as the speed of the α particle is increased. This shows that the "disruption" potential of the nucleus by an α particle, *i. e.* the potential difference required to communicate the same energy to an electron as is possessed by the α particle, is of the order of 6 million volts for aluminium; but the experimental effects are so small that it is difficult to estimate this disruption potential with any accuracy. It is of interest to note that the corresponding potential to liberate an electron from the K or inner ring of electrons is about 2200 volts for aluminium. This question will be discussed later in more detail when the critical velocity for disruption is determined for the other elements.

If our view is correct that the H nuclei are satellites of the central nucleus, the mass of the H satellite should not be very different from that of the free H nucleus. If it be supposed that the nitrogen nucleus is derived from that of carbon by the addition of two H satellites and one electron, it is to be anticipated that the mass of the nitrogen atom should be 14.016 nearly, assuming $C=12.00$, $H=1.008$ in terms of $O=16$.

By accurate experiment with positive rays by Aston's method, it should be possible to decide whether the atomic mass of nitrogen is nearer this calculated value than the whole number 14. Similar considerations should be applicable to the other elements from which H atoms can be liberated.

We are much indebted to Mr. E. S. Bieler and Mr. C. D. Ellis for their help in counting scintillations, and to Mr. Crowe for preparing the radioactive sources.

Cavendish Laboratory,
Aug. 11, 1921.