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The Nucleus, Third Part *

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Transmutation, the major subject of the Second Part of this sequence on the nucleus, assumes again a leading role in the present article. Remarkable cases have been discovered since the first of the year, including a great number in which the impact of one nucleus upon another (or of a neutron on a nucleus) provokes an instantaneous transmutation which is followed after seconds, minutes or hours by the spontaneous breaking-apart of one of the resultant nuclei. One may say that these last are the nuclei of new kinds of radioactive elements, and the phenomena are often called "induced radioactivity"; but many of these new unstable elements differ from all radioactive bodies hitherto known in that they emit *positive* electrons. Some additional examples of transmutation are described at the end of this article.

INDUCED RADIOACTIVITY

UP to the end of last year (1933) it was taken for granted that transmutation is practically instantaneous: that when two nuclei collide, the ensuing fusion and disruption (if any there be) are ended within a time inappreciably short. Nowadays, however, many cases are being discovered, in which a disruption occurs a long time—several minutes or even hours, possibly not for days—after the collision. We must suppose that at the moment of the collision something happens, which entails the eventual disruption. In a very few cases we may be reasonably sure that this initial "something" is itself a transmutation, resembling those previously known in that it is instantaneous, but differing from them in that one of the resulting fragments is an unstable nucleus, of which the eventual spontaneous disruption is that which is observed. This may be the course of events in all cases, but it is also conceivable that in the collision one of the original nuclei may be put into an unstable state without the occurrence of an initial transmutation.

The first-to-be-known of these phenomena was discovered by M. and Mme. Joliot at the very start of 1934, when they exposed samples of aluminium (and boron and magnesium) to the bombardment of the 5.3-MEV alpha-particles from polonium, and after a few minutes of exposure removed them from the bombarding beam and placed them

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* In this issue is published the first section of "The Nucleus, Third Part." The paper will be concluded in the October, 1934 issue.

"The Nucleus, First Part" was published in the July, 1933 issue of the *Bell Sys. Tech. Jour.* (**12**, pp. 288–330), and "The Nucleus, Second Part" in the January, 1934 issue (**13**, pp. 102–158).

beside a Geiger-Müller counter.[1] Hundreds of counts per minute disclosed the emergence of fast-flying particles from the samples. The number per minute fell off *exponentially* (Fig. 1) with the lapse of time: a very important feature, for this is the law of radioactivity. The exponential decline implies that the nuclei which were destined to emit these particles were formed at the moments of collisions and existed intact for periods of time—"lifetimes"—not the same for all but distributed in a perfectly random fashion. Such a decline is characterized by a singe constant, the "half-period," or lapse of time during which the rate of emission of particles drops to one-half of its initial value. The half-periods in the three cases examined by the Joliots are different: boron 14′, magnesium 2′ 30″, aluminium 3′ 15″. This is a welcome feature wherever it occurs, as when two substances exhibit different half-periods the effect cannot be ascribed to any contamination common to both.[2]

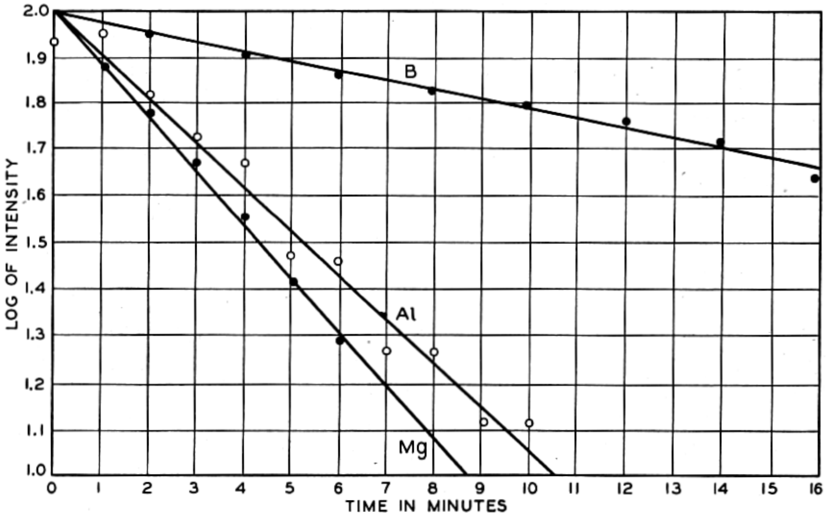

Fig. 1—Exponential decay of the radioactivity induced by boron, aluminium, magnesium with alpha-particles: semi-logarithmic plot. (F. Joliot & I. Curie-Joliot, *Journal de Physique.*)

Since thus there are not only delays between the bombardment and the ultimate disruption, but also (at any rate in the tested cases) a

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[1] "The Nucleus, Second Part," p. 119; the "Geiger-Müller" counter has a thin wire for its inner electrode, while most of those called simply "Geiger counters" have needle-points, though the earliest counters invented by Geiger were of the former type.

[2] Cases are on record in which several different elements have exhibited decay-curves, each the sum of two exponentials, one having a half-period characteristic of the element and the other a half-period common to all samples; the latter is then ascribed to a common admixture.

random distribution of the lengths of these delays, it is customary and proper to refer to these phenomena as "induced radioactivity."

Examples of induced radioactivity have already been provoked with all of the four known agents of transmutation: alpha-particles acting on B, Na, Mg, Al and P,—protons acting on boron and carbon—deutons acting on boron and carbon and a number of others—neutrons acting on a large variety of elements. The half-periods reported when neutrons are the agents have ranged from a few seconds to a couple of days, while in all other cases they are of the order of a few minutes.

The nature of the ejected particles resulting from the ultimate disruption is of course of the greatest importance. The Joliots found them to be positive electrons or orestons [3] in their pioneering experiments, and this was confirmed by Ellis and Henderson at the Cavendish Laboratory; the tests have been made by applying magnetic fields to tracks made visible in the Wilson chamber or to beams of particles on their way to photographic or other detectors, and are doubtless to be regarded as conclusive, though no details have yet been published. Induced radioactivity provoked by α-particles, in the few cases so far known, thus results in the emission of orestons.[4] This seems also to be the rule when it is provoked by deutons or protons, as is shown by splendid Wilson-chamber photographs (Figs. 2, 4) obtained by Anderson when samples of various elements (boron in the form of B_2O_3, carbon, aluminium, beryllium) were first bombarded for several minutes and then put right into the chamber itself. The tracks of the particles springing from the samples have the specific aspect of electron-tracks,[5] and in the imposed magnetic field of 800 gauss they have a curvature of which the sense proves the particles to be positive. On the other hand it is stated by Fermi that the radioactivity induced by impacts of neutrons involves the emission of *negative* electrons, though in his very brief reports there is no intimation as to how this is shown.

For each individual case it is important to inquire whether the half-period is independent of such circumstances as the kinetic energy K_0 of the impinging particles. If so, it is sufficient to postulate a single kind of unstable nucleus resulting from the collisions; otherwise, not. This has been investigated in the cases of radioactivity induced by alpha-particle impact; the Joliots reduced K_0 from 5.3 to 1 MEV, without observing any change in the half-perod.

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[3] As an occasional alternative to "positive electron" I adopt Dingle's beautiful word "oreston" (Orestes, in Greek mythology, was the brother of Electra).

[4] Excepting that the Joliots have lately reported that magnesium emits electrons of both signs, which they attribute to different isotopes.

[5] "The Nucleus, First Part," p. 303.

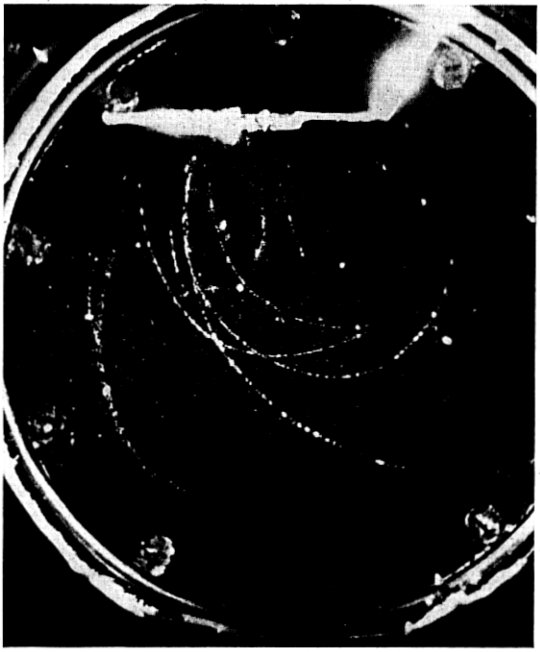

Fig. 2—Induced radioactivity resulting from bombardment of carbon by 0.9-MEV protons: tracks of positive electrons. (C. D. Anderson.)

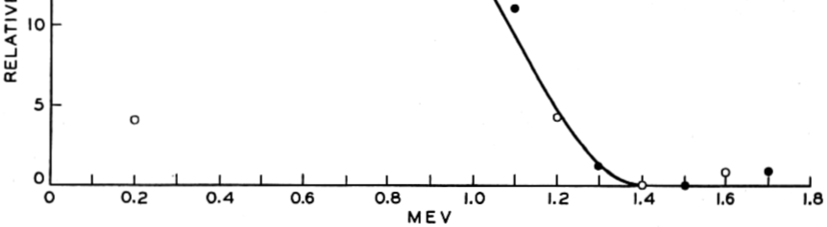

Fig. 3—Distribution-in-energy of positive electrons of the induced radioactivity resulting from bombardment of carbon by 0.9-MEV protons. (Anderson & Neddermeyer, *Physical Review*.)

One next inquires whether all of the orestons resulting from a given type of impact spring off with the same energy. Experience with natural radioactivity shows that while alpha-particles are emitted either with a single definite energy or with one of several definite discrete energies characteristic of the particular process, negative electrons (beta-particles) are always emitted with a very wide and continuous distribution-in-energy. Short as is the time which has elapsed since January last, and weak as are the beams of positive electrons resulting from induced radioactivity, it is already assured that in several cases at least it is the latter rule which is followed and not the former. The best distribution-curves are those derived at Pasadena from a statistical study of oreston-tracks made visible in a Wilson chamber and curved by an imposed magnetic field; they refer to radioactivity provoked by 0.9-MEV protons falling on carbon, and by 0.9-MEV deutons falling on Be, B, C and Al. I reproduce one of these curves as Fig. 3 (another curve obtained with 0.7-MEV protons

Fig. 4—Induced radioactivity resulting from bombardment of boron oxide by 0.9-MEV deutons: tracks of positive electrons, some springing from gas adjoining the target, as though a radioactive gas had diffused out of the boron oxide block. (Anderson.)

falling on carbon is indistinguishable from it). In one of the cases of radioactivity induced by alpha-particle impact, Ellis and Henderson at the Cavendish Laboratory observed a continuous distribution of energies of the positive electrons ranging between 1 and 2.5 MEV.

In all of these cases of delayed transmutation, nothing is observed of the ultimate disruption excepting the emergence of the electron; the other fragments apparently do not receive energy enough to make a track or reach a detector, and our knowledge is thus forcedly incomplete as it is with most other examples of transmutation. In respect to the initial process occurring at the collision, the prospect of attaining complete knowledge seems even dimmer. We are not without some guidance, for when alpha-particles impinge on aluminium or boron, certain particles are expelled with apparently no delay, and these may be fragments resulting from that initial process. There is, however, an *embarras de choix;* both protons and neutrons are expelled in each of these cases; if one is a fragment resulting from the same process of which an unstable nucleus of half-period 3′ 15″ is another fragment, then the other must be due to something entirely different. Actually Ellis and Henderson inferred from their data that in the case of aluminium, the number of protons produced by a given bombardment is fifty times as great as the number of unstable nuclei which eventually eject orestons. This obliges us to assume that the initial process out of which the delayed transmutation arises is either the one which produces the neutrons, or else some other producing no fast-moving particle at all.

Decision between these alternatives is made from a most notable experiment of the Joliots, sufficient indeed by itself to settle the nature of the initial process. To introduce it in the way in which it suggested itself to them, I make the tentative assumption that the initial process is a case of what is called[6] "disintegration by capture with emission of a neutron," and that the residue of this process is the unstable nucleus. Embodying this assumption in equations of "nuclear chemistry" written after the fashion of those in the Second Part with atomic number for a subscript preceding the symbol of each element (so that ${}_0n$ and ${}_1e$ become the proper symbols for a neutron and an oreston) we have for boron and for aluminium:

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\begin{aligned}
{}_2\mathrm{He} + {}_5\mathrm{B} &= {}_7\mathrm{N} + {}_0n, \quad \textit{followed by} \quad {}_7\mathrm{N} = {}_6\mathrm{C} + {}_1e,\\
{}_2\mathrm{He} + {}_{13}\mathrm{Al} &= {}_{15}\mathrm{P} + {}_0n, \quad \textit{followed by} \quad {}_{15}\mathrm{P} = {}_{14}\mathrm{Si} + {}_1e.
\end{aligned}
$$

The unstable nucleus, if it is surrounded by its proper quota of orbital

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[6] "The Nucleus, Second Part," pp. 147–148, 155.

electrons, should then possess the chemical properties of nitrogen in the former case, phosphorus in the latter.

The important experiment of the Joliots consisted in showing that when a sample of boron (or aluminium) is first exposed to alpha-particle bombardment and then to such chemical processes as would remove nitrogen (or phosphorus) commingled with the boron (or aluminium), the induced radioactivity is itself removed and carried away. I quote *verbatim:* "We have irradiated the compound BN. By heating boron nitride with caustic soda, gaseous ammonia is produced. The activity separates from the boron and is carried away with the ammonia. This agrees very well with the hypothesis that the radioactive nucleus is in this case an isotope of nitrogen. When irradiated Al is dissolved in HCl, the activity is carried away with the hydrogen in the gaseous state, and can be collected in a tube. The chemical reaction must be the formation of PH_3 or SiH_4. The precipitation of the activity with zirconium phosphate in acid solution seems to indicate that the radio-element is an isotope of phosphorus."

The assumed equations are thus substantiated in a very striking way. These experiments are in a sense the first chemical identifications of any product of transmutation; I say "in a sense," because while this nitrogen and this phosphorus are identified by virtue of chemical properties, they are detected only by virtue of their radioactivity.[7]

Some striking photographs, taken at Pasadena with an expansion-chamber containing a block of boron oxide previously bombarded by alpha-particles, show many tracks of positive electrons springing from points in the air of the chamber (Fig. 4). It is inferred that the unstable nuclei formed from the boron (not from the oxygen, since bombardment of SiO_2 has no effect) are carbon nuclei which unite with electrons to form carbon atoms and then with oxygen atoms to form molecules of CO or CO_2 having a natural tendency to diffuse out of the solid mass. The radioactivity may be driven completely out of the solid block in short order by heating to 200° C. The radioactive particles are unable to pass through a liquid-air trap.

[7] Inserting mass-numbers into the equations, one finds that since Al has but the one known isotope 27, the value 30 is indicated for the mass-number of "radio-phosphorus," as Joliot calls it; while since boron has two isotopes 10 and 11, the two values 13 and 14 are indicated for radio-nitrogen, with no certain evidence to dictate a choice between them. Ordinary stable phosphorus has no known isotope 30, and ordinary stable nitrogen has no known isotope 13, but the vast majority of its atoms are of mass-number 14. It seems natural that a very unstable isotope should have a different mass-number from any of the known and stable ones, and this may be a valid argument for inferring that it is B^{10} rather than B^{11} which is concerned in the induced radioactivity of boron; but there is nothing to prohibit us from supposing that there may be an unstable isotope of nitrogen agreeing in mass-number with the one which is durable.

The result of bombarding carbon with deutons might be expected to be the same as that of bombarding boron with alpha-particles, it being natural to assume the reactions:

$${}_1H^2 + {}_6C^{12} = {}_7N^{13} + {}_0n^1, \quad \textit{followed by} \quad {}_7N^{13} = {}_6C^{13} + {}_1e.$$

The half-period of the delayed disruption has been determined at Pasadena as 10.3 minutes. This does not agree with that observed by the Joliots when alpha-particles are projected against boron. The disagreement is not so welcome as agreement would have been, but does not in the least invalidate the foregoing equations, since it is perfectly conceivable that two different unstable nuclei with different half-periods might both have the atomic number 7 and the mass-number 13. Bombardment of carbon with protons leads to delayed disruptions with the same half-period of about ten minutes, and this is not so easy to understand as it may seem, since the obvious notion that the proton and the C^{12} nucleus simply merge into a nucleus N^{13} which later on explodes leads into difficulties with the principles of conservation of energy and conservation of momentum.

As to the way in which the number of observed disruptions varies with the kinetic energy K_0 of the impinging particles, there are data relating to the bombardment of aluminium by alpha-particles. The Joliots varied K_0 from 5.3 MEV downwards; they report that the number of positive electrons diminishes with falling K_0, becoming imperceptible for boron at about 3 MEV, for Mg and Al at 4 to 4.5 MEV. Ellis and Henderson varied K_0 from 5.5 upward to 8.3 MEV, by using alpha-particles emitted from other radioactive bodies than polonium; they found the number of orestons steadily increasing with rising K_0, rising in the ratio 15 : 1 as K_0 was raised from 5.5 to 7 MEV, and showing signs of approaching a maximum not far beyond $K_0 = 8.3$ MEV.

The positive electrons emitted in induced radioactivity are frequently—perhaps generally—accompanied by high-frequency photons, of which energy-measurements may hereafter show that they are due to the coalescence of positive with negative electrons to form light.

I close this section by listing the elements which have been observed to display induced radioactivity after bombardment by one or other of the four agents of transmutation, and add those which have been tested without positive results, in order to show the scope of the experiments. In certain cases positive results have been obtained by some observers and not by others, but this may signify simply a weaker bombarding stream or a less sensitive detector in the apparatus of the latter.

Bombardment by alpha-particles: B, Mg, Al (Joliots, Ellis & Henderson); Na, P (Frisch); negative results with H, Li, Be, C, N, O, F, Na, Ca, Ni, Ag (Joliots).

Bombardment by deutons: Li, Be, B, N, C, O, F, Na, Mg, Al, Si, P, Cl, Ca (Henderson, Livingston & Lawrence, with 3-MEV deutons); Li, Be, B, C, Mg, Al (Crane & Lauritsen, with 0.9-MEV deutons).

Bombardment by protons: B, C (Crane & Lauritsen); C (Cockcroft, Gilbert & Walton with 0.6-MEV protons); C (?) (Henderson *et al.*, with 1.5-MEV protons). Negative results by Henderson *et al.* with 1.5-MEV protons on all but C among the elements listed above before their names.

Bombardment by neutrons: F, Na, Mg, Al, Si, P, Cl, Ti, V, Cr, Fe, Cu, Zn, As, Se, Br, Zr, Ag, Sb, Te, I, Ba, La, U (Fermi); F, Mg, Al (Dunning and Pegram).

OTHER CASES OF TRANSMUTATION

It is not altogether safe to separate cases of "induced radioactivity" from "other cases of transmutation," inasmuch as most of the latter class have been observed under conditions where it was impossible to tell whether or not there was a delay between collision and disruption, and perhaps some of them belong in the former class. Of certain transmutations one may say that if there is such a delay, the law of conservation of momentum must be suspended for the duration thereof, resuming its sway only at the moment of the disruption. Nevertheless I should not wish to affirm that for the processes mentioned in this section or in the Second Part the delay is always literally zero.

Early in this year was first achieved, at the Cavendish Laboratory by Oliphant, Shire and Crowther, what had been the aim of many physicists for over a decade: the separation of a metal, normally consisting of more than a single isotope, into films each comprising atoms of practically a single isotope only, and thick enough for physical experiments. This was performed with lithium, and when protons and alternatively deutons were projected against films of Li^6 and alternatively Li^7, the four resulting sets of observations settled the attributions of the various groups of fragments previously observed when ordinary blocks of lithium had been bombarded. The origin of the two long-range groups of paired alpha-particles described in the Second Part was precisely as had been suspected: they proceed from the interactions:

$$_1H^1 + {}_3Li^7 = 2\,{}_2He^4 + (T_1 - T_0); \quad {}_1H^2 + {}_3Li^6 = 2\,{}_2He^4 + (T_1 - T_0),$$

where $(T_1 - T_0)$ stands for the amount of energy transformed in each reaction from energy-of-rest-mass to kinetic energy, equal to about 17 MEV in the first case and to about 23 MEV in the second. The continuous distribution of alpha-particles up to range 7.8 cm (Fig. 9 in the Second Part) is due to impacts of deutons against Li^7, and thus may still be attributed to a transmutation in which three nuclei,—a neutron and two alpha-particles—spring from the merger of a deuton with a Li^7 nucleus. Of the other attributions I shall presently speak.

The transmutations arising from the impact of deutons on deuterium are in some ways unique. They are the first to be known in which the two colliding particles are identical, both being H^2 nuclei; one of them appears to be much the most abundant yet observed, in the sense that a given number of bombarding particles produces an unprecedentedly great number of detectable fragments; each of them results in the formation of a nucleus long sought but never certainly detected till 1934.

The better-known of these reactions is described by the equation,

$$ {}_1H^2 + {}_1H^2 = {}_1H^3 + {}_1H^1 + (T_1 - T_0). \tag{1} $$

It is both somewhat amusing and somewhat annoying to realize that this is not a transmutation at all in the formerly-proper sense of the word, since there is no change of one element into another! the hydrogen isotope of mass-number 2 is changed into hydrogen isotopes of mass-numbers 1 and 3 respectively; it will be desirable to enlarge the scope of the term "transmutation" to cover cases like this one. The H^1 nuclei resulting from this reaction were vividly demonstrated by Tuve and Hafstad when they projected deutons into divers gases in an ionization-chamber—air, carbon dioxide, ordinary hydrogen, and deuterium successively; there were no emerging protons (of range superior to 3.5 cm, the minimum observable) from any of the three first named, but from the last there was the "very large yield" of one proton per several thousand impinging deutons. Another estimate of yield has been supplied from the Cavendish school, by Oliphant Harteck and Rutherford; theirs refers to impacts by deutons of energy 0.1 MEV, a value considerably smaller than those of Tuve's research; they find that the number of protons coming forth from a thick layer of deuterium is of the order of a millionth of the number of such deutons entering the layer. The estimates do not seem incompatible, especially as the Cambridge people find the number of fragments to be mounting very rapidly as the deuton-energy T_0 increases;[8] and they show that any possibility of a slight admixture

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[8] The "thick layers" are films of certain compounds of hydrogen in which a large proportion of the usual H^1 atoms have been replaced by H^2 atoms. The curve

of deuterium with any other substance must be very carefully considered and assessed, whenever that other substance is bombarded with a beam containing deutons and it is observed that protons are produced.

The range of the protons due to the foregoing reaction is about 14 cm when T_0 is low—0.1 MEV or thereabouts—and rises with T_0. Translate its minimum value into the corresponding kinetic energy (obtaining about 3 MEV); compute the momentum of the proton—this, save for a minor correction due to the relatively small momentum of the impinging deuton, should be opposite in direction and equal in magnitude to the momentum of the other fragment of the transmutation, the nucleus H^3. Thence compute the kinetic energy of this other fragment, and estimate thence its presumable range; owing to our lack of experience with such particles the estimate may not be very exact; Oliphant, Harteck and Rutherford arrive at the figure 1.74 cm. Now, the protons of 14-cm range of which I have been speaking are not the only fragments to be observed when deutons impinge on deuterium. There are also particles of a much less range; these are equally numerous with the 14-cm protons, and expansion-chamber photographs by Dee have shown that a track of the one variety is likely to be paired with a track of the other, after the fashion of the paired tracks due to the transmutations $H + Li = 2He$ (Figs. 14 and 15, Second Part); and their range of about 1.6 cm. is taken by the Cavendish people as being in substantial agreement with the estimate aforesaid. It is this interlocking of concordant observations which speaks so strongly for the rightness of this description of the reaction, and therefore for the existence of the hitherto-unknown isotope H^3 of hydrogen.

Meanwhile it has been discovered at Princeton that the new isotope can be generated by maintaining a self-sustaining discharge in gaseous deuterium: a way of achieving transmutation several times attempted in past years, but never (so far as I know) with proved success. Out from the discharge tube (where the voltage is 50,000 to 80,000) some of the ionized atoms and molecules shoot through a hole in the cathode into another and very large chamber filled with deuterium in which they disperse themselves, thus having opportunities for transmutation in both this chamber and the tube. A sample of the gas is afterwards

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of number-of-fragments *vs.* T_0 shows the peculiar shape common to such curves when obtained with thick layers, which suggests that as T_0 is raised the increase in the number of transmutations is at first partly due to an increase in the probability of transmutation at an impact, but later entirely due to the fact that the faster particles enter farther into the layer and have more opportunities of striking nuclei before their energy is gone than do the slower (The Nucleus, Second Part, p. 141). The theory of such curves has, however, never been worked out.

extracted and is ionized in a separate chamber; the charge-to-mass ratios of its ions are determined by an especial type of deflection-apparatus. Search is made for ions having the charge-to-mass ratio of a singly-ionized molecule of mass about 5, such as could be a molecule H^2H^3. Such ions occur. To discover them, however, is not the same thing as to prove the existence of H^3, since so far as anyone can tell from their charge-to-mass ratios (as measured with the accuracy attainable in these experiments) these ions might have the constitution $H^2H^2H^1$—there being some of the isotope H^1 in the gas. How to make such discriminations is one of the major problems in the analysis of the ions found in gases. In this case it happens to be known that in ordinary hydrogen, the ratio of the number of triatomic to that of diatomic molecular ions is proportional to the density of the gas. Now in these experiments, the ratio of the number of mass-5 ions to the number of mass-4 ions is the sum of two terms, one proportional to the gas-density and the other independent of it. The latter term is taken as the measure of the amount of H^2H^3, therefore of H^3, in the gas. A like study made with deuterium none of which had been exposed to the discharge indicated a very small amount of H^3, about one atom in two hundred thousand of H^2; the discharge enhanced this ratio fortyfold in an hour.

To return to the work at the Cavendish Laboratory: the lesser-known of the two reactions which may occur when deutons meet is probably described by the equation,

$$ {}_1H^2 + {}_1H^2 = {}_2He^3 + {}_0n^1 + (T_1 - T_0) \tag{2} $$

and is a transmutation in the strictest sense of the word, helium as well as neutrons [9] appearing out of hydrogen. I refer to it as lesser-known, because although the neutrons have been observed the helium nuclei have not been. This lack of evidence withholds a desirable support from the equation, but does not contradict it; for on measuring the momentum of the neutron, equating it to that of the hypothetical He^3 nucleus and estimating the range of the latter, this range turns out to be so small as to make detection difficult. We are not, however, without other evidence for He^3; when protons are projected against lithium, particles of ranges 1.15 cm. and 0.68 cm. appear,[10] and the observations made with monisotopic films show that Li^6 is involved in their origin: if we suppose

$$ {}_1H^1 + {}_3Li^6 = {}_2He^4 + {}_2He^3 + (T_1 - T_0) \tag{3} $$

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[9] Harkins has suggested the name "neuton" for the element of which neutrons are the ultimate particles.

[10] Kirchner has lately observed an 0.9-cm. group.

the equation is supported by the facts that the ranges of the two groups stand to one another in the ratio computed by assuming equality of momenta, that particles of one are found to be paired with particles of the other, and that they ionize about as much as alpha-particles of equal range.

The rest-masses of the two new nuclei are estimated by putting, in equations (1), (2) and (3), the best available values for T_0 (the kinetic energy of the impinging deuton, that of the other H^2 nucleus being negligible) and T_1 (the sum of the kinetic energies of both fragments resulting from the reaction). The results are: for the rest-mass of H^3, 3.0151 from (1); for the rest-mass of He^3, 3.0166 from (3). To derive the latter from (2) is not so precise, the energy of neutrons being harder to evaluate than that of charge-bearing particles; Oliphant, Harteck and Rutherford prefer to say merely that the result is not incompatible with that from (3).[11]

These are the fourth and fifth of the nuclei (counting the neutron as one) in order of increasing mass. The departures of their masses from the adjacent integer are abnormally great for light nuclei, and their packing-fractions (First Part, p. 318) are the greatest yet known excepting that for H^2, and fall neatly by the upper branch of the curve of packing-fraction *vs.* mass-number (Fig. 8 of the First Part). The contrast between the packing-fractions 55 of He^3 and 5 of He^4 is especially striking. The new nuclei are the first isobars to be discovered of mass-number less than 40, and the first pair to be discovered of which the masses are distinguishable.

Cockcroft and Walton have studied at length the fragments emerging from lithium, boron and carbon bombarded by deutons. Lithium supplies a group and boron a group of protons which may result from the transformation of the lighter into the heavier isotope according to the schemes,

$$ {}_1H^2 + {}_3Li^6 = {}_3Li^7 + {}_1H^1 + (T_1 - T_0), \tag{4} $$

$$ {}_1H^2 + {}_5B^{10} = {}_5B^{11} + {}_1H^1 + (T_1 - T_0), \tag{5} $$

but the two members of each equation (in which all the rest-masses are known by deflection-experiments) do not agree very well. Carbon supplies a group and boron two more groups of protons which cannot be made to fit into such a scheme without postulating emission of gamma-rays to achieve the balancing of masses—an emission for which,

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[11] These results are computed by assuming that the values of the rest-masses of H^1, H^2, He^4, Li^6, Li^7 and n^1 given by Aston, Bainbridge and Chadwick are exact, and that no additional fragment (such as a gamma-ray photon) of appreciable energy is emitted at the transmutation.

it is true, independent evidence exists in the case of carbon. Boron supplies a group of alpha-particles which may be due to the reaction,

$$_1H^2 + {}_5B^{10} = 3{}_2He^4 \tag{6}$$

and which comprises the most energetic subatomic particles yet known, those of the cosmic rays excepted (12.3 MEV, range 15 cm.). Blocks of various heavier elements emit both alpha-particles and protons, of which the amounts both relative and absolute vary tremendously with heat-treatment, degassing, and other circumstances, so that evidently they cannot altogether proceed from the element constituting most of the block, and their origins furnish a severe problem for research.