Contemporary Advances in Physics, XXVII
The Nucleus, Second Part *

By KARL K. DARROW

In this Second Part the major subject is Transmutation: that is to say, the alteration or disintegration of a nucleus, the unique and distinctive part of any atom, by impacts of fast-moving corpuscles. For the last year and a half the pace of progress in this field has been increasingly rapid, and in all likelihood is destined to become yet swifter. This is partly because of the discovery—a discovery due largely to theoretical foresight—that transmutation of some elements is practicable with protons of a relatively modest energy which can be produced in laboratories without any serious difficulty. Partly it is due to the discovery of neutrons and of deutons, particles which apparently possess remarkable ability in effecting certain kinds of transmutation. Partly also it is due to advances and refinements in the methods of working with alpha-particles, the first variety of corpuscle with which disintegration of nuclei was ever achieved. People are already beginning to speak of "nuclear chemistry" as a special branch of science, and this is already almost justified by the number of cases known in which two nuclei interact and produce two others which are recognizable.

BRINGING THE FIRST PART UP TO DATE

STRANGE as it seems to speak of "bringing up to date" something that was published only six months ago, one is sometimes obliged to do so by the rapid march of science; and three of the "elementary particles" of which I spoke in the First Part were and still are so young—or to speak more carefully, our acquaintance with them is still so young—that their rôle and situation in the body of physical knowledge is changing from month to month.

The Positive Electron

Of the positive electron the most striking new thing to be said is, that there is now a new way of generating it: by impacts of alpha-particles against metals. This so far has been applied only by its discoverers, M. and Mme. Joliot; only with alpha-particles from polonium, therefore of energy 5.3 millions of electron-volts; only to five metals, of which beryllium and boron and aluminium yielded positive electrons, while silver and lithium did not. It is as yet the most efficacious way of producing positive electrons, Joliot having evoked last summer as many as 30,000 of these corpuscles per second from aluminium. This of course looks small when compared with the torrents of negative electrons which incandescent metals will pour out,

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* "The Nucleus, First Part" was published in the July 1933 issue of the *Bell Sys. Tech. Jour.*, Vol. XII.

but these are not a proper standard of comparison. Rather should one say that in the autumn of 1932 positive electrons were being observed at the rate of three or four a year, and already by the summer of 1933 this rate had been enhanced to thirty thousand in the second!

The other voluntary way of generating positive electrons—by applying hard gamma-rays to heavy elements—has already been studied enough to yield the data of the following table. Here, in the first column, stand the names of various sources of gamma-rays (the one denoted as "Po + Be" is beryllium exposed to impacts of alpha-particles from polonium); in the second, the energy-values in MEV (I use this symbol hereafter for "millions of electron-volts") of the individual photons of these rays; in the third, the symbols of various metals; in the fourth, the number of positive electrons per hundred negatives, ejected from these metals by these gamma-rays; in the fifth, the authorities:

Po + Be	5	U	40	Joliots
		Pb	30	Joliots
		Pb	35	Chadwick
		Cu	18	Joliots
		Al	5	Joliots
ThC″	2.6	Pb	8	Joliots
		Pb	4	Chadwick
Ra(B + C)	1.0–2.2	Pb	3	Grinberg
Po	0.85	Pb	0	Meitner-Philipp

The percentages in the fourth column give at the moment our best available notion as to the relative plentifulness of positive electrons, produced by the several kinds of rays falling upon the several metals. One would prefer to have the total number of positives per unit intensity of the infalling rays, but that is not available at present—I presume because of the difficulty of measuring these intensities. One must remember that the data usually consist in observations of a few hundred or a few dozen cloud-tracks, so that the accuracy of these percentages cannot be great.[1]

We note that with lead the proportion of positive electrons mounts rapidly with increasing photon-energy, and that with 5 MEV-photons

[1] This perhaps is sufficient to account for a discrepancy between the general trend of the table and a value of 1/3 given by Meitner and Philipp for the ratio of positives to negatives when brass is exposed to (Po + Be). Should the table be extended and supported by a successful theory, it should then be possible to determine the frequency of gamma-rays by the percentage of positives which they produce when falling on a metal. In this connection it is interesting that Anderson's latest data indicate that positive and negative electrons are about equally abundant among the ionizing particles of the cosmic rays, a fact which suggests that if they are due to photons, these must be of a distinctly higher energy than any of those cited in the foregoing table.

the proportion goes up rapidly with the nuclear mass of the bombarded atoms.[2] Both of these rules are in harmony with the remarkable theory to which I alluded in the First Part—the theory that each positive electron (together with a negative companion) springs into being from a transmutation of light into electricity! It is supposed that a photon transmutes itself into a pair of electrons, one of each sign.

Fig. 1—Tracks of an electron-pair (positive and negative) arising in argon exposed to gamma-rays, and probably created near an argon nucleus by transmutation of a photon. (M. et Mme. Joliot)

Conservation of the net charge of the universe is assured in this hypothetical process. Conservation of mass and energy is attainable, for the speeds of the electrons may be such that their energies together are equal to the energy of the vanished photon. I take this occasion to repeat Einstein's principle, which figures so importantly in these articles. The energy E of a material particle moving with speed v (relatively to the observer) is given by the formula:

$$E = m_0(1 - \beta^2)^{-1/2}c^2 = mc^2,$$

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[2] In this connection it should be noted that the source "Po + Be" emits neutrons as well as photons, and while the first-named are certainly not chiefly responsible for the positive electrons, they may produce some of these. Chadwick observed that the rays from a "Po + B" source (boron in place of beryllium), which consist of neutrons plus some photons of about the same energy as the photons of ThC″, evoked from lead a distinctly larger percentage of positive electrons than do the rays of ThC″.

in which c stands for the speed of light in vacuo; β for v/c; and m_0 for a constant. The ratio of E to c^2 is the function of v and m_0 which this equation defines, and is denoted by m and called the mass of the particle: it is in this sense that mass and energy are equivalent. We may (mentally) divide the mass of the moving particle into two terms m_0 and $(m - m_0)$, and the energy into two terms m_0c^2 and $(m - m_0)c^2$. We may further call m_0 the rest-mass and m_0c^2 the energy associated with the rest-mass; and we may call $(m - m_0)c^2$ the kinetic energy and $(m - m_0)$ the mass associated with the kinetic energy or the extra mass due to the motion of the particle. Such will be the terminology used in these articles, although this definition of kinetic energy is only approximately the same as the classical and familiar one.[3]

Returning to the argument about the transmutation of light into electrons, or more precisely, of a photon into an electron-pair: conservation of mass and energy is attainable, for the two electrons may have such speeds—call them β_1c and β_2c—that the sum of $m_0(1 - \beta_1^2)^{-1/2}c^2$ and $m_0(1 - \beta_2^2)^{-1/2}c^2$ is equal to the energy $h\nu$ of the photon. But the demand for conservation of momentum makes apparently serious trouble. If we assume that a photon voyaging through the depths of space suddenly converts itself spontaneously into a pair of electrons, and if then we attempt to impose both conservation of momentum and conservation of energy, the equations lead us straightway into an inescapable muddle, in which the original assumptions contradict each other. We are driven therefore to infer that the imagined process is impossible. But this seeming catastrophe of the theory turns out to be a blessing. What is observed is not after all the transmutation of a photon in the depths of empty space, but a process which occurs in the depths of plates of lead and other heavy elements. If we suppose that such a transmutation occurs near to a massive nucleus, then this may receive some of the energy and some of the momentum of the photon; and the equations show that the momentum which it takes may be quite sufficient to permit the process to occur, while the energy which it takes is so small that for practical purposes we may still pretend that the whole of the energy of the photon is divided between the electrons (though we certainly should not forget about the small fraction which goes to the nucleus). All the principles are thus fulfillable: conservation of charge requires that there should be

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[3] The classical definition of kinetic energy is $(1/2)mv^2$; the present or relativistic definition, viz. $(m - m_0)c^2$, is an infinite series of which the first term is identical with the classical definition. The difference between the two definitions increases as the speed of the particle increases, but so far as I know there has not yet been an actual case in which it is of practical importance.

two electrons of opposite signs; conservation of energy, that they should have appropriate speeds; conservation of momentum, that the process should occur only near a massive nucleus.

This is the most alluring of all theories, for it is the doctrine that the substance of matter and the substance of light are ultimately the same, being interconvertible. It therefore demands, and is surely destined to receive, the sharpest and fullest of testing; the more so because there is a rival in the field, the theory that the positive electron exists beforehand and from all time in the nucleus of the atom, and is ejected from it by the photon. The newest way of producing positive electrons by alpha-particle impact seems to speak in favor of the latter. One could indeed suppose that the kinetic energy of the alpha-particle is transformed into an electron-pair, directly or through the intermediacy of a transiently-existing photon; but this would be an artificial idea unless it were to be supported by a basic theory or by observing that the positive electrons are often paired with negatives (which the Joliots do not say). In favor of the former theory speak the facts that in several scores of cases paired electrons have been observed—*i.e.*, two electrons of opposite signs were seen to spring from the same point (so far as the eye could tell)—when metal plates were bombarded with gamma-rays; and the further fact that the energies of these electron-pairs and of individual positives did not surpass those of the infalling photons, though they approached it often.[4] There are always apparently unpaired positives and many more unpaired negatives; but one may always say that with some of the pairs it happened that one member remained in the metal and the other got away, while many of the negatives are surely electrons which have been expelled from their places by photons acting in the well-known ways. Further, there are more or less forcible indications that some part of the absorption of gamma-rays in heavy metals may be ascribed to the formation of electron-pairs, and some part of the radiation scattered from the metals when gamma-rays fall on them may be attributed to the reunion of two electrons of opposite sign which re-transmute themselves into light; but some of the data are not checked, and the time seems not ripe for reviewing them. In the hands of Oppenheimer and Plesset the transmutation theory has supplied other quantitative

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[4] See First Part of this article, pp. 304–305, *B.S.T.J.*, July 1933. The ***kinetic*** energies of electron-pairs and *a fortiori* of positive electrons should not come within one million electron-volts of the energy-value of the photons, for the rest-mass of two electrons amounts approximately to a million of these units. This rule has lately been strengthened by evidence from Anderson and his colleagues, who in a couple of hundred of additional cases find no violation of it; the distribution-in-energy curves for pairs and for (apparently) isolated positives extend up to the predicted upper limit, and there they fall to the horizontal axis. More evidence of this kind has been accumulated by Blackett (loc. cit. footnote 5).

predictions meet for testing, and it is likely that in six months more a great deal will be learned.[5]

The Deuton

The newly-discovered isotope of hydrogen of mass-number 2—H^2, "heavy hydrogen," or, to adopt Urey's name for it, "deuterium"—has suddenly become the most popular and the most eagerly sought-after of all chemical substances. This is because of the notable chemical and physical differences between it and its compounds on the one hand, H^1 and the corresponding compounds of H^1 on the other. So great are these differences that by the usage of twenty years ago H^2 would probably have been called a new element, and indeed it deserves all the prestige that would accrue to it from being so denoted; but to violate the present and most wisely-based of usages, whereby an element is characterized by atomic number rather than by the ensemble of its properties, would be mistaken.[6]

Deuterium is so rare by comparison with H^1 (Urey's "protium") that it would still be very unfamiliar, but for the unexpected and remarkable efficacy of the electrolytic method of separating water molecules comprising H^2 atoms from water molecules comprising none but H^1 atoms. It turns out that if an aqueous solution is electrolyzed until only a very tiny fraction of the original liquid remains, the proportion of the former kind of molecule in that tiny residue is anomalously large. Washburn seems to have been the first to suspect that this might happen; he procured samples of the residues from electrolytic cells which had been operated continuously in commercial plants for two and three years, and sent them to Urey, who performed a spectrum-analysis and observed "a very definite increase in the abundance of H^2 relative to H^1." Shortly afterwards the method was put into operation on a grand scale by G. N. Lewis and his collaborators, with spectacular results. In one experiment, for instance, they started out with twenty liters of water, electrolyzed it until there remained but half a cc. of liquid, and found that in this residue deuterium atoms made up two-thirds of all the hydrogen atoms which were left. For months thereafter, nearly every paper on deuterium and on the deuton which was published began with an acknowledgment to Lewis for a small amount of water rich in heavy hydrogen which the fortunate author had received from him.

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[5] For a fuller account of the situation as it now stands, see an article of mine in the *Scientific Monthly*, January 1934; also one by P. M. S. Blackett, *Nature* **132**, pp. 917–919 (Dec. 16, 1933), which incidentally contains some further data.

[6] I should think that the case of deuterium by itself would make it necessary henceforth to define the concept "element" altogether from the concept "atomic number," forsaking all the earlier definitions.

Interesting as are the chemical and physical properties of deuterium and its compounds, we are here concerned only with the nucleus of the H^2 atom, the deuton (all the other suggested names seem to be fading out). The accepted value for its mass is that given by Bainbridge, 2.0131 on the standard scale in which the mass of the O^{16} atom is 16 exactly. Of its spin I shall speak in a later article. Its powers of transmutation are remarkable, and quite unlike those of H^1; if first a beam of H^1 nuclei (protons) and then an equal beam of deutons be directed against targets of various elements, the number of fragments observed per unit time is greater for some elements and less for others, and their ranges in general are different. In some cases it seems possible that the deutons themselves are being split into protons and neutrons, a result of great importance if it can be established beyond question. We shall consider the data at length.

The neutron

Most of what has newly been learned about the neutron will find appropriate places elsewhere in this article. There should be a separate section about the deflections suffered by neutrons when they impinge on or pass close to nuclei without transmuting them—the topic known as "scattering," "interception," or (badly) "absorption" of neutrons. This topic however is scarcely ripe for description in such an article as this, the experiments being difficult and the inferences from the data being highly controversial. I therefore postpone it to some future occasion, remarking only that it seems established that a neutron may pass within a very short distance indeed from a nucleus—only a very few times 10^{-13} cm from the centre thereof—without interacting with that nucleus in any perceptible way.

MASSES OF THE LIGHTER ATOMS

There are now thirteen of the lighter atoms of which the masses—in terms of the mass of the O^{16} atom taken as 16 exactly—have been determined to four and even to five significant figures. Most of these values were mentioned in the First Part, but it will be convenient to have them all tabulated here. They are the masses of complete atoms, nuclei accompanied by their full quotas of orbital electrons. The uncertainties quoted are the "probable errors"; where Aston originally gave the maximum possible uncertainty, this has been divided by 3 (see First Part, footnote 10). Values marked with an asterisk are from Bainbridge, the others from Aston; the value for H^1 has been obtained by both.

H^1	1.007775 ± .000035	C^{12}	12.0036 ± .0004
* H^2	2.01363 ± .00008	N^{14}	14.008 ± .001
He^4	4.00216 ± .00013	O^{16}	16.0000 (standard)
* Li^6	6.0145 ± .0003	F^{19}	19.000 ± .002
* Li^7	7.0146 ± .0006	* Ne^{20}	19.9967 ± .0009
* Be^9	9.0155 ± .0006	* Ne^{22}	21.99473 ± .00088
B^{10}	10.0135 ± .0005	* Cl^{35}	34.9796 ± .0012
B^{11}	11.0110 ± .0005	* Cl^{37}	36.9777 ± .0019

The table of the chemical atomic weights reproduced in the First Part has suffered two alterations: a very slight change in the given value for K, from 39.10 to 39.096; and an important change in the chemical atomic weight of carbon, which rises from 12.00 to 12.011, and now permits of an abundance of C^{13} easier to reconcile with the observed intensities of the spectrum-lines of this substance than was the abundance, or rather the scarcity, implied by the former value.[7]

The list of isotopes detected by Aston's mass-spectrograph has been enlarged by the following examples,[8] which the reader may enter upon Fig. 6 of Part I: neodymium, $Z = 60$, $A–Z = 83$; samarium, $Z = 62$, $A–Z = 85, 86, 87, 90, 92$; europium, $Z = 63$, $A–Z = 88, 90$; gadolinium, $Z = 64$, $A–Z = 91, 92, 93, 94, 96$; terbium, $Z = 65$, $A–Z = 94$.

NEW DEVELOPMENTS IN TRANSMUTATION: THE APPARATUS

In the two years and a quarter which are all that have elapsed since I published in this *Journal* an article on transmutation,[9] the situation in this field has vastly changed, and the prospects for the future have been amplified immensely. So lately as the early spring of 1932, disintegration of a nucleus had not yet been demonstrably achieved except by alpha-particles possessing energy not smaller than three millions of electron-volts. Schemes for producing five- and ten-million-volt ions were already under way, being ardently pushed onward because it was supposed that transmutation would never be effected by any agency much feebler. But in the course of 1930, Cockcroft and Walton of the Cavendish Laboratory had been emboldened by a theory (I will describe it later) to imagine that protons of only a few hundred thousand electron-volts might be able to transmute, and to risk their time and labors in the task of developing powerful streams of such particles. After two years of work they

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[7] See an item in *Nature*, **132**, 790–791 (Nov. 18, 1933). In the table of masses on p. 303 of the First Part, change 1.0078 to 1.0072 and 4.002 to 4.001 (the former values refer to complete atoms, not bare nuclei).

[8] F. W. Aston, *Nature* **132**, 930–931 (Dec. 16, 1933).

[9] "Contemporary Advances in Physics XXII," *Bell System Technical Journal*, **10**, 628–665 (October 1931). I refer to this article hereinafter as *Transmutation*.

were justified in the event; for they detected fragments proceeding from targets of lithium bombarded by their protons, with energy-values anywhere from half-a-million down to only seventy thousand electron-volts.

It would be hard to overstate the joyful surprise of this announcement. Transmutation, of some elements at least, was easier by far than had been thought! It would not after all be necessary to fare forth into the unknown, and face at once the problems of applying voltages without precedent; successes which had seemed doubtful at best and assuredly distant were after all to be had by a relatively slight extension of a known technique. All over Europe and America people began making plans for applying these voltages, so much less formidable than those which had previously been thought indispensable. Nevertheless the first who confirmed and extended the work of Cockcroft and Walton were those who had aimed from the start at the higher and harder goal: Lawrence and his colleagues at Berkeley. Their work had not been wasted, for they instantly found themselves able to measure the disintegration of lithium by protons all the way up to 710,000 electron-volts; and within four months they had carried the upper limit onward to 1,125,000, and as I write these lines they have just announced that the limit has soared to three millions! From Pasadena also comes word of transmutation achieved by protons, and deutons, and helium nuclei, endowed with energy by voltages ranging downward from nine hundred thousands.

These are not the only novel results of the last two years and a quarter. The neutron has disclosed itself not only as a product, but as an agent of transmutation, able to alter nuclei which have thus far resisted both the alpha-particles and the protons which have been showered upon them in laboratories. The disintegrations effected by alpha-particles have been studied with ever-increasing minuteness and detail, and are beginning to show that nuclei are structures capable of existing in various normal states and excited states, characterized by distinctive energy-values. The emission of alpha-particles from radioactive nuclei has been studied with a new precision, and leads to the same conclusion. The astonishing feats achieved with bombarding particles of lesser energy have not lessened the hope of achieving startling things with particles of greater.

Cockcroft and Walton, inspired by theory, had built an apparatus for producing half-million-volt protons, and had proved them able to transmute. The proton-streams had not, however, been greater than five microamperes (one microampere or $\mu a = 6.28 \cdot 10^{12}$ protons per second). Next Oliphant and Rutherford, inspired by that result, proceeded to build an apparatus in which the maximum voltage should not go above a quarter of a million, but in recompense the stream of protons should be raised to a hundred microamperes. Another alteration: previously the stream had been a mixture of protons with heavier ions and neutral particles—now Oliphant and Rutherford introduced a magnetic field, adjustable and strong enough to bring either the protons or the more massive ions separately against the target. The magnetic field also assures that all the particles striking the target shall have nearly the same speed, something not completely guaranteed by the constancy of the voltage.

The scheme of this device is sketched in Fig. 2, where the course of the proton-stream is traced (rather too pictorially, I fear!) in a sweeping arc from its origin in the discharge-tube *R*, to the target *T* where the element to be transmuted awaits the impacts. In the discharge-tube all the parts are of steel, and the block *C* and cylinder *B* conjointly form the cathode, while the oil-cooled block *D* and cylinder *A* conjointly form the anode. This unusual material and structure are required partly to minimize cathode-sputtering, and partly to take care of the great amount of heat which is steadily developed in the tube, inasmuch as for the best supply of protons a voltage of 20,000 and a current of many milliamperes are demanded. Something like a twentieth of the current in the discharge is borne through the hole in the cathode by protons (and other positive ions of greater mass, if such there be); and in the space between *C* and *E* these particles receive from an electric field most of the kinetic energy with which they strike the target. In this space and in the region where the magnetic field comes into play, the density of the gas must be kept extremely low, despite the fact that there is an open passage into these spaces from the discharge-tube where the density must always be great enough to sustain the discharge and the supply of protons. This is a task for powerful pumps, which must be kept continuously at work pumping away from the lower chambers the gas which is steadily draining out of the discharge-tube through the hole and must as steadily be replenished by feeding fresh hydrogen in from above. It is no small part of the difficulty of the experiment, that the discharge-tube and the source of its power and the source of its hydrogen must all be maintained at scores or hundreds of thousands of volts above the potential of the ground, in order that the observing-apparatus may itself be at ground-potential. The transmutations are observed by detecting the fragments which issue through the very thin mica pane of the window *W*.

Until the building of this apparatus proton streams had been so scanty, that to bring about disintegrations in measurable number it had been needful to project the protons against thick layers of dense matter. In going through these layers they were slowed down and stopped, and there was no direct way of telling whether the observed transmutations were achieved by protons of full speed, or by those which had already lost some energy, or both. Moreover if the energy of the bombarding particles was raised, the number of disintegrations infallibly went up, but a part of this increase (and sometimes the

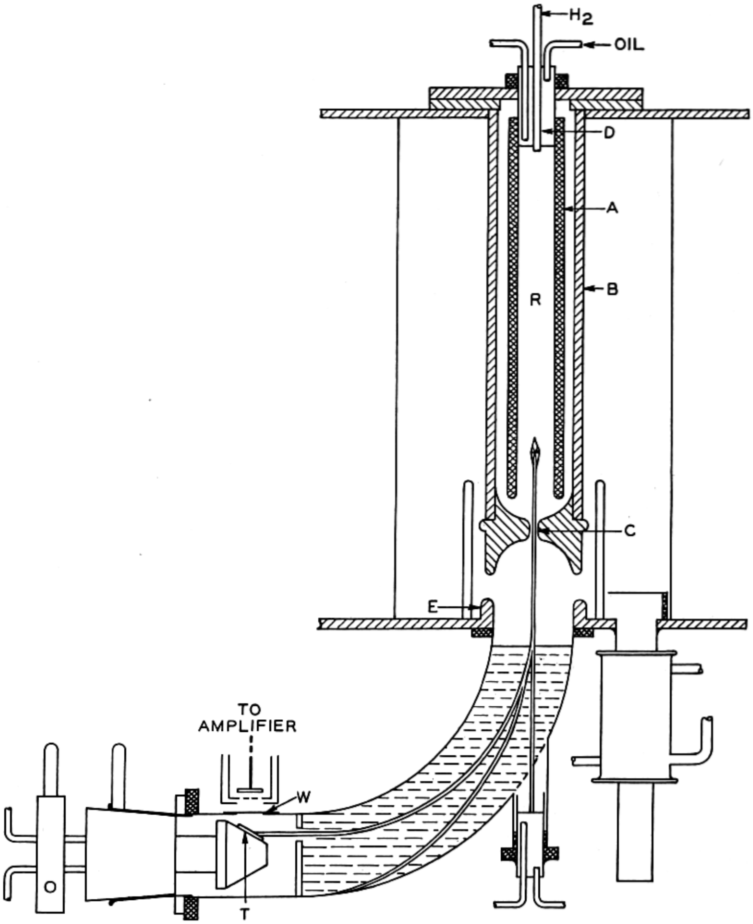

Fig. 2—Apparatus of Oliphant and Rutherford for producing transmutation by intense streams of protons. (*Proceedings of the Royal Society*)

whole of it) was certainly due to the fact that the faster particles went farther into the layer and struck more nuclei. There is no need to labor the point: it is obviously desirable to do the experiments with a film so thin that each oncoming proton either strikes a nucleus with its full and unabated initial energy, or else goes through the film and away without any impact at all. This ideal was closely approached by Oliphant and Rutherford, when they got countable numbers of fragments from films of lithium and boron (deposited on blocks of steel or iron) which were so thin as to be invisible, and of which the latter was known to consist of only seven-tenths as many atoms as would suffice to cover the iron surface with a single monatomic layer. (The curves of Fig. 16 were obtained with these films.)

This is a success which proves it possible to investigate films consisting each of only a single isotope of the element in question; for feeble as are the ways of separating isotopes in all but a few very favorable cases, they yet are powerful enough to produce pure monatomic layers. This article will amply show how valuable will be the privilege of getting data from a single isotope, of lithium or boron for example; already there are several cases of important antagonistic theories, the decisions between which will be given once and for all by such data.

The apparatus devised by E. O. Lawrence and developed in his school at Berkeley is of a singular ingenuity, inasmuch as in it ions are accelerated until their energies are such as would be derived from an unimpeded fall through a potential-difference of literally millions of volts, and yet the greatest voltage-difference at any moment between any two points of the apparatus is only a few thousands. It owes its elegant compactness to the lucky fact that when a charged particle is moving in a plane at right angles to a constant magnetic field, and consequently is describing a succession of circles, the time which it takes to describe a single circle is the same whatever its speed. One sees this readily by writing down the familiar equation,

$$mv^2/\rho = Hev/c,$$

in which e, m, v stand for the charge (in electrostatic units), mass, and speed of the ion and ρ for the radius of curvature of the circle, and on the right we have the force exerted by the magnetic field H upon the ion and on the left the so-called "centrifugal force" to which it is equal. The radius ρ varies directly as v, but the time $T = 2\pi\rho/v$ which the ion takes to describe a circle is independent of v. This is no longer true if the ion is moving so fast that the foregoing classical equation must be replaced by its relativistic analogue, but fortunately the desired results are attained without forcing the speed to such heights.

Suppose now that while the ion is describing its consecutive circles each in a time T, its speed is suddenly increased; it continues to make circles, of a larger radius but with the same duration. Suppose that the increase occurs twice in each cycle, at intervals $T/2$; the path is a succession of semicircles each broader than the one preceding but all described in equal time. Now we arrive at Lawrence's device. The ions circulate in a round flat metal box, sliced in two along one of its diameters (Figs. 3, 4); and every time that one of them passes from within half-box B to within half-box A it is accelerated by a voltage-difference existing between B and A, and every time that it passes from within A to within B it is again accelerated by a voltage-difference between B and A. Of course if this voltage-difference remained the same, the ion would lose at the latter passage just the energy which it gained at the former; but here is precisely the distinctive feature of the method: *the potential-difference between the two half-boxes is reversed in sign between each two consecutive passages.* So rapidly do the successive passages follow on one another, that if the intervals between them were unequal it would probably be impossible to devise any mechanism that would perform the potential-reversals at the proper

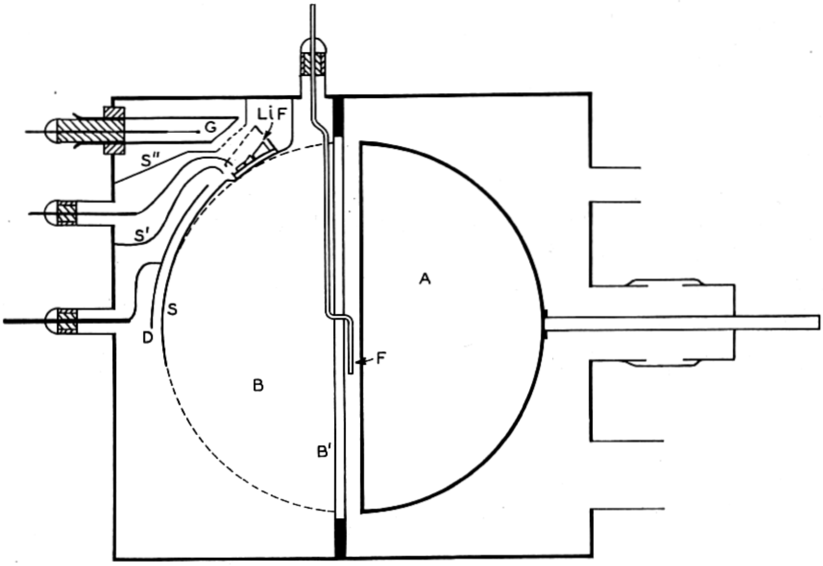

Fig. 3—Diagram of the Lawrence apparatus for cumulative accelerations of protons and other ions with auxiliary magnetic field. (After Henderson)

moments, but the felicitous law of the equality of the intervals makes all easy—all that is needed is to connect an oscillator of the proper frequency (determined by the strength of the magnetic field and the charge and mass of the ions) across the pair of half-boxes.[10]

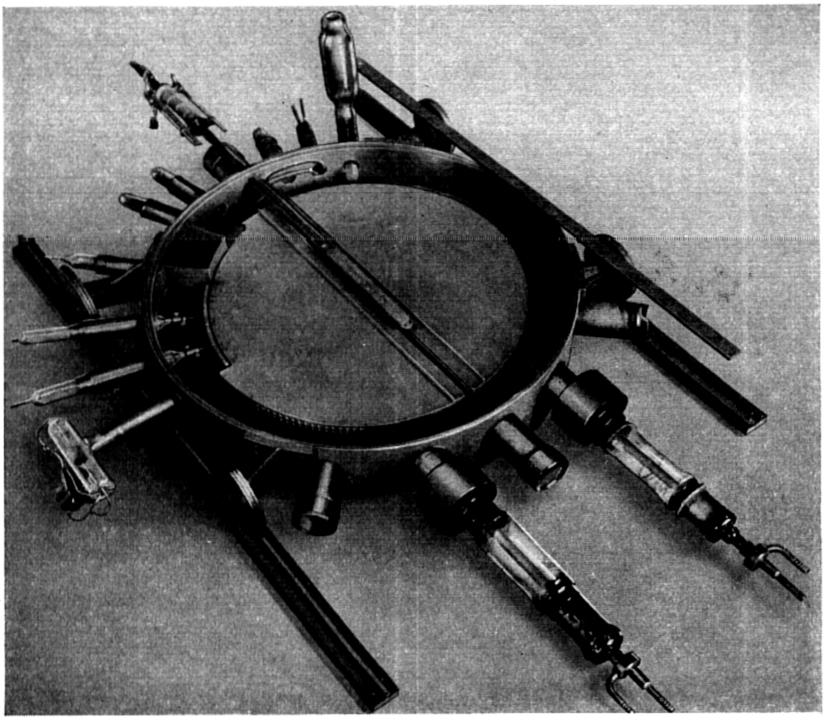

Fig. 4—Photograph of the apparatus sketched in Fig. 3. (E. O. Lawrence)

The sketch of Fig. 3 is of the apparatus wherewith Henderson observed the transmutation of lithium by protons (pp. 140–142). It is filled with hydrogen of a low density, so that electrons proceeding from the hot filament *F* at the center ionize the gas and produce a sufficient number of protons. These are whirled around and around in ever-widening semicircles, till after a number of circuits which may be as high as one hundred and fifty they arrive at the boundary of the

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[10] One may do without the magnetic field, arranging to have the ions proceed along a straight line and to accelerate them at definite points along that line, by voltages produced in rhythm by an oscillator; the points of application of the voltages must be spaced according to a particular way, and the apparatus is inconveniently long, being longer the lighter the ion; it has been successfully employed with mercury ions by Lawrence and some of his colleagues.

half-box *B* opposite the charged electrode *D*, which deflects them enough to bring them into the cup-shaped receptacle at the far end of which the crystals of lithium fluoride are spread. The fragments of lithium nuclei which are observed are those which escape to the left in such directions as to enter the Geiger counter *G*. In this apparatus the radius of the outermost circle was 11.5 cm., the magnetic field 14,000 gauss; the potential-difference between the half-boxes never attained as much as 5000 volts, but it was reversed 4.2 millions of times in a second, so that after three hundred reversals the protons had arrived at the limit of the box and were ready to strike the lithium nuclei with an energy of 1.23 MEV. By using a bigger pair of half-boxes in a more extensive magnetic field, this energy could be augmented; and by viewing the size of the magnet in Fig. 5 one sees what an augmentation is now imminent. The currents were inferior to those achieved by the apparatus of the Cavendish school, being mostly of the order of a few millimicroamperes (one millimicroampere or $m\mu a = 10^{-3}\ \mu a$).

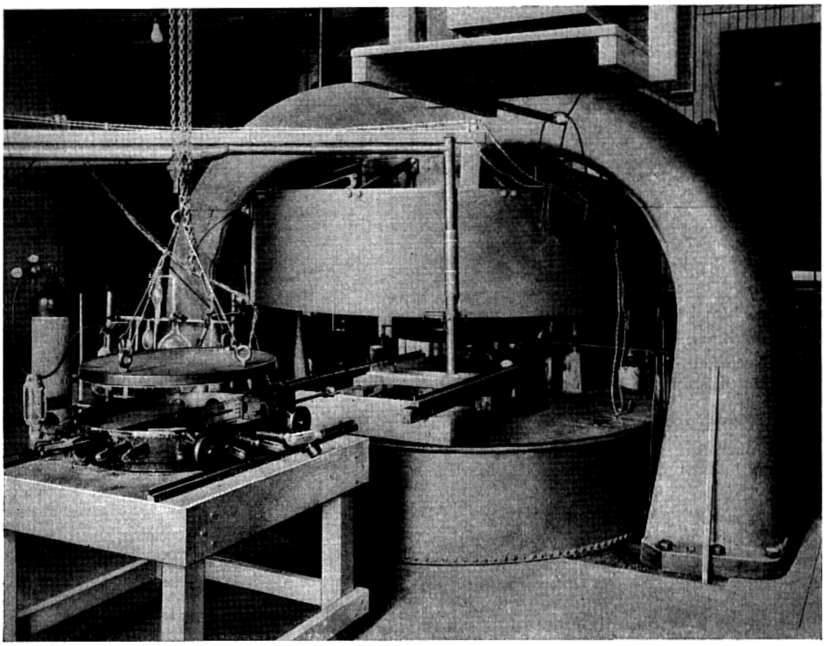

Fig. 5—The Lawrence apparatus for cumulative acceleration, beside the colossal magnet between the poles of which it is placed. (Lawrence)

DETECTION AND MEASUREMENT OF TRANSMUTATION

While thus the scope of transmutation has been so vastly extended in the past eighteen months, there is one limit which has not yet been passed. *No product of transmutation has yet been detected by any chemical means.* Many a plate of metal has been bombarded with protons or with alpha-particles, but no man has seen it change into a plate of another metal, nor alter in any of its chemical properties; many a tubeful of gas has been bombarded, but no man has observed the qualities or the spectrum-lines of another gas appearing in the content of the tube. All that is ever observed is an outpouring of material particles from the piece of bombarded matter; particles of such a nature, that they must come from the nuclei of the atoms. One expects this statement to go out of date from one morning to the next; but at the moment of this writing it is still as true as it was in 1919 when Rutherford first disintegrated nuclei, and broader in one respect only. From 1919 until 1932, one would have said "charged particles"; but since the winter of 1932, it is known that either charged particles or uncharged may be driven out of nuclei, by the appropriate impacts.

Thus there are two great experimental problems, and not one only; beside the problem of producing the streams of bombarding corpuscles, there is that of detecting and of recognizing the particles which fly forth from the bombarded nuclei—the "fragments," I will say. There is a grave objection to this term, and to the common name "disintegration" for the process. Both suggest a picture of the nucleus as a structure of pre-existing pieces which the impact breaks apart and scatters. This picture is surely incorrect, for there are cases in which the fragments contain the susbtance of the impinging corpuscles. In fact, if we define "fragment"—as we should—to include the part which in most of the experiments does not escape from the target bulk, we may say that this kind of case is frequent, and perhaps indeed that there is no other kind! Nevertheless we seem to be unable to get along without the words "disintegration" and "fragment."

For detecting protons and more massive fragments which are charged, there are three methods.

The *first method* (A) is that of observing the scintillations, which fast charged particles produce when they impinge on fluorescent screens. This is the classic and historic method, by which were made the earliest proofs of transmutation by impact of alpha-particles (which I described at length in the earlier article) and also the earliest proof of transmutation by protons. Of late years this method has been largely displaced by the others. Few people outside of the Cavendish

Laboratory and the Institut für Radiumforschung in Vienna have ever submitted themselves to the long, tedious and nerve-racking process of counting thousands of dim flashes for periods of hours in darkened rooms with dark-adapted eyes; and if two disagreed as to what was observed, there was no objective way of deciding between them. The newer methods abolish this strain; they can readily be so shaped as to leave a permanent record, which anyone may consult and analyze for himself; and they are capable of measuring the ionizing power of the fragments. Nevertheless the eldest method still retains the unique advantage that no barrier whatever, not even a gas, need intervene between the detecting screen and the source of the fragments; and also it is often employed by those accustomed to scintillations as a check upon the others.

The *second method* (B) is that of the expansion-chamber or cloud-chamber of C. T. R. Wilson, whereby the tracks of ionizing particles across a gas are made visible by droplets of water which condense upon the ions. This is the splendid invention which is the joy of all who write or lecture on atomic physics, since it enables them to decorate their exposition with pictures which make real the things of which they speak. It has virtue for the investigator also, especially since it may show in a single vivid photograph how many fragments there are formed in a single process, what are the directions in which they fly away, and how far they are able to travel through the gas. The curvature of the track in an applied magnetic field supplies the value of the momentum of the particle which made the track, if the nature of the particle be known; and this last may often be guessed from the aspect of the track, or assured by independent data. The major disadvantage of the method is, that the apparatus records only the particles which fly off during about a hundredth of a second, and then lies idle for several seconds or even minutes while it is being prepared for its next brief interval of effectiveness.

The *third method* (C)—or group of methods rather, for the variants are legion—is the detection by purely electrical methods of the ions which the fragments produce as they shoot across the gas of an ionization-chamber. A fast-flying charged particle loses on the average 30 to 35 electron-volts for every ion, or rather every ion-pair, which it produces.[11] To see the utility of this theorem, turn it around; the number of ion-pairs produced by a fast charged particle going through a gas is about a thirtieth of the number of electron volts which it loses in its transit. A fast alpha-particle, such as are spontaneously emitted by radon, or constitute the fragments springing out

[11] "Electrical Phenomena in Gases," pp. 52, 70–71.

of lithium bombarded by protons, has about eight million electron-volts; if it enters an ionization-chamber filled with gas so dense that it is brought completely to a stop, the ion-pairs appearing are about a quarter of a million. The upper limit occurring in practice is possibly twice as high, but is very rarely met with; there is no lower limit, but every incentive to push downward and ever downward the least amount of ionization which can be detected.

Twenty-five years ago, it would have been impossible to detect by electrical means so few as a quarter of a million ions. (The total number produced *e.g.* by an alpha-particle was determined by measuring the total ionization produced by a known and very great number of particles.) This problem was however destined to be solved in many ways, which I will group under four headings:

(C1) By arranging to have each particle touch off a brief but violent discharge, something like an invisible spark, in the gas of the ionization-chamber. There is a strong electric field applied between the electrodes of the chamber, whereby the "primary" ions which the particle forms as it travels across the gas are caused to produce (directly and indirectly) vast numbers of extra or "secondary" ions; and these suffice to make a sensible effect in the external circuit. The idea was first put into practice by Rutherford and Geiger in 1908, and the scheme is commonly known by Geiger's name. One of the electrodes must be either a fairly sharp point or a fairly thin wire, and there are a number of empirical rules (some partially understood, some not at all) about the size and shape of the chamber, the proportioning and the conditioning of the electrodes, the nature and the purity and the density of the gas, and the magnitude of the field. The voltage across the gas must lie within a definite range, often pretty narrow; if it is lower the particles do not produce discharges, if it is higher a single discharge may last indefinitely. The ratio of the number of secondary to the number of primary ions is usually not constant and usually not measured; most of the various forms of the device serve solely to detect or count the particles, and they are known as "Geiger counters." Often a loudspeaker is connected into the circuit of the ionization-chamber, and each discharge produces an audible clack, so that by the Geiger method one hears the passage of a corpuscle as by the Wilson method one sees it. Sometimes the discharges are recorded and the record examined at leisure.

(C2) By modifying the foregoing scheme so that the number of secondary ions shall be proportional to the number of primary ions, and a measurement of their total charge shall give at least a relative value of the ionizing-power of the traversing particle. This is a recent achievement of Geiger and Klemperer. The process may be called *internal amplification* of the primary ionization, the amplification being in a constant proportion, or, as people carelessly call it, "linear."

(C3) By developing an electrometer or electroscope so sensitive that it is able to detect and even measure the total charge of a few thousands of ions, without amplification. This was first achieved, or at any rate applied to transmutation, by G. Hoffmann of Halle, and his associate Pose; the latter was able to observe fragments of aluminium nuclei (ejected by alpha-particles) which produced as few as three thousand ion-pairs. The major difficulty seems to be, that the electroscope takes a large fraction of a minute to perform its deflection and then recover its readiness to respond to another particle. Pose in his experiments observed only some thirty fragments to the hour.[12]

(C4) By applying *external amplification* to the feeble impulse which the primary ions due to a single particle produce in the external circuit, and which is imperceptible to an electroscope of normal and convenient quickness of response. This is done by developing the superb techniques of amplification which modern vacuum-tubes have rendered feasible, and like the three foregoing schemes is an achievement of the last few years, having been carried on especially by Wynn-Williams of the Cavendish Laboratory and Dunning of Columbia.

I show as Fig. 6 three records made with Dunning's apparatus, wherein every vertical line is due to an ionizing particle, and is proportional in length to the number of ions which the particle produced in crossing a shallow chamber.[13] The lines of great and nearly uniform length which appear in record (*a*) are due to alpha-particles from polonium; these all had nearly the same speed and were moving in nearly parallel lines when they entered the chamber, and it is evident that in crossing the gas they all made nearly the same amount of ionization; they left with a good deal of their initial kinetic energy unspent. The lines in record (*b*) are caused by protons; their diversity in length is chiefly due to the wide variety of speeds which the protons had when they entered the chamber, for these were fragments of the disintegration of aluminium by alpha-particles, and therefore had a broad distribution-in-speed (page 147). As these words imply, and as I will stress presently, the ionization produced by a charged particle

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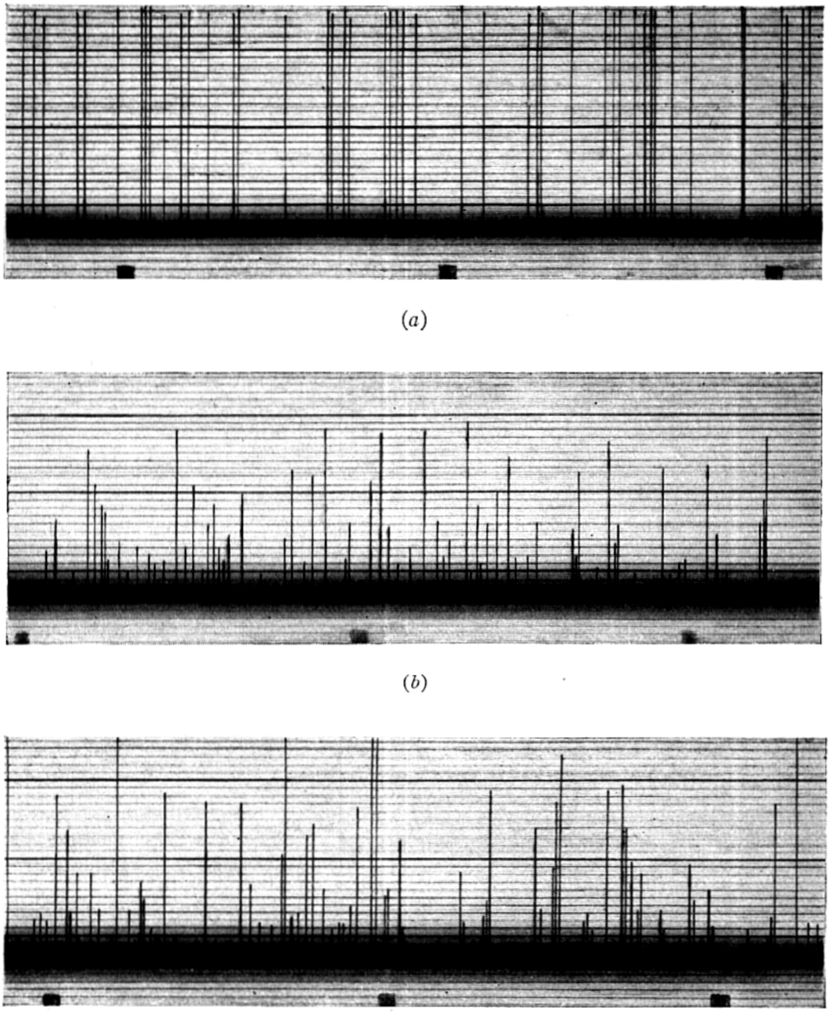
[12] It deserves to be recorded that in their blank experiments, Hoffmann and Pose during one research observed deflections at the average rate of 1.22 per hour, but observed altogether 197 of them!

[13] I am much indebted to Dr. Dunning for these pictures, made especially for this article. He writes of (*b*): "The minimum amount of ionization detectable here is well under 1000 ions; probably it could be pushed down to 250 ions." Consecutive dots at the bottom of each record mark off the minutes.

of given kind depends on its speed; the greatest amount which (in this particular chamber) a proton could ever produce, with its most favorable speed, is indicated by the longest lines in (*b*), and one sees that even these are definitely shorter than the lines in (*a*) due to



(*a*)

(*b*)

(*c*)

Fig. 6—Three records of the ionization produced by individual particles in a shallow ionization-chamber: (*a*) alpha-particles of nearly the same speed, (*b*) protons of various speeds, (*c*) particles of several kinds which had been set into motion by impacts of neutrons. The fogging along the base-lines is much fainter in the original records than in these reproductions. (J. R. Dunning)

alpha-particles.[14] The lines in record (*c*) were obtained when neutrons were traversing the chamber and a piece of paraffin outside of it; not they, but the charged nuclei which they strike and impel, are producing the record. Those lines which are longer than any in (*b*) are certainly not due to protons; they must be caused by recoiling nuclei of the atoms of the gas which fills the chamber (air), and which have various speeds because the neutrons strike them more or less glancingly (and probably do not themselves all have the same speed). The shorter lines are due in part to such nuclei, chiefly to protons ejected from the paraffin in such directions that they cross the chamber. Some are very short indeed, half-lost in the dusky haze due to the perpetual wiggling of the oscillograph mirror caused by gamma-rays; they are made by the fastest of the protons. Observations by expansion-chambers and with applied magnetic fields have proved this classification of the particles.

All of these methods are available for detecting charged particles which are protons or alpha-particles or corpuscles of a yet greater mass than these. For electrons the problem is harder.

An electron of given energy—say x thousands of electron-volts—is able to make roughly as many ion-pairs in a gas as could a proton or an alpha-particle of equal energy: that is to say, about $30x$. Nevertheless it produces much less ionization in an ordinary chamber than either of these last. This seeming paradox is due to the facts that the ion-pairs produced by the electron are relatively far apart and the loss of energy per centimeter of path is correspondingly low, so that in an ionization-chamber of reasonable dimensions and customary density of gas the traversing electron produces only a few hundreds or perhaps one or two thousands of ion-pairs before it reaches the opposite side of the chamber and plunges into the wall.

This is made evident by the Wilson method, the tracks of electrons appearing much thinner—less richly peopled with droplets, that is to say—than those of alpha-particles or protons. The expansion-chamber therefore is available for observing fast electrons, and so to a certain extent is the Geiger counter, which skilful observers can adjust so that it will react to these bodies. None of the other methods has yet been used with success. The ions produced by a single electron in an ionization-chamber are apparently too few to observe without amplification or even to amplify successfully, and the scintillations too faint. If one has neither expansion-chamber nor Geiger counter available, the only thing to be done is to measure the total ionization

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[14] The contrast is much more striking than the records suggest, for the amplification was fourfold greater when (*b*) and (*c*) were made than when (*a*) was made.

produced by great numbers of electrons, and attempt to estimate these numbers. This is done in the study of the beta-rays or fast electrons emitted from radioactive nuclei, and in the study of cosmic rays; but the method has not yet been applied to the rays emitted from atoms undergoing transmutation by impacts, and apart from Joliot's observations on positive electrons (page 102 *supra*) nothing yet is known of any electrons which may be emitted by these.

Since individual electrons are so difficult or impossible to observe by the customary methods, one might suppose that at any rate they never annoy the observer. This unluckily is not so; for if electrons are numerous, they may keep the electrometer needle (in the method C4, for example) in a perpetual tremor, producing a so-called "background" over which even the strong sharp impulses due to alpha-particles or protons may fail to stand out. It is even possible for a chance coincidence or near-coincidence of several electrons to make a record which cannot be disinguished from that of a single particle of greater ionizing power. The scintillation-method suffers from a like defect, for if the fluorescent screen is heavily bombarded with electrons—or with gamma-rays, which liberate electrons from the fluorescent stuff and the surrounding matter—it shines all over with a feeble glow, against which the flashes made by more massive ions are difficult to discern. The most casual student of transmutation cannot fail to notice that polonium is generally used, of recent years, as the source of alpha-particles for bombardment. Probably he infers that either it is especially abundant or else supplies especially fast particles. But in both respects polonium is inferior to another customary source, radon mixed with its descendants radium A and radium B. It is used because it emits no gamma-rays but feeble ones of low penetration, whereas the other source pours out abundant and powerful photons which flood any nearby ionization-chamber with electrons and confuse the electrometer. Dunning's amplifying circuit, whereby he detected charged nuclei set into motion by neutrons, was so devised as to discriminate against the feeble but many impulses produced by these electrons and in favor of the occasional stronger ones produced by the massive particles; and this device enabled him to use a source of the latter type providing fifty times as many alpha-particles to engender the neutrons, as the largest amount of polonium ever employed.

Neutrons, I recall, are detected by observing the protons and more massive nuclei which they convert by impact into fast-flying ionizing particles, and photons by observing the electrons on which they have the like effect; the problems of getting the data are thus not new, it is the problem of interpreting them which is changed.

The next important question is, how the fragments are identified as protons, or as alpha-particles, or otherwise, from the data. Few as yet are the cases in which the identification is full and undeniable. In the earlier paper I described Stetter's measurements of charge-to-mass ratio for the fragments produced by impacts of alpha-particles against boron, carbon, fluorine and aluminium, which gave values identical with that for protons within the observational uncertainty of five per cent. As for the fragments produced by impacts of protons, the best direct evidence is that which appears in Fig. 7. Cockcroft and Walton had an ionization-chamber only 3 mm. across, and the fragments from bombarded lithium traversed it completely, producing a few thousand ion-pairs apiece which were detected and measured with the aid of an amplifying circuit of Wynn-Williams according to the method C4. When mica sheets were interposed in the path of the fragments from the lithium, they were slowed down but still kept energy enough (so long as the sheets were not too thick altogether) to travel across the chamber; and the curve of Fig. 7 represents the number of ion-pairs produced per fragment, as function of a quantity x proportional to the thickness of mica which the fragments have

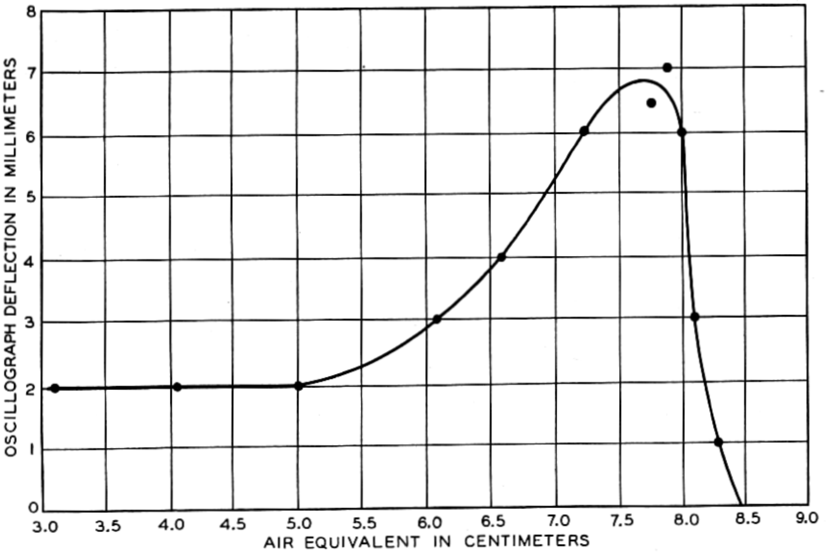

Fig. 7—Ionization produced in a shallow chamber by fragments (of the transmutation of lithium by protons) which have passed through screens of various thicknesses. (Cockcroft and Walton)

traversed ("air-equivalent" of the mica, p. 127 *infra*).[15] The point is, that exactly the same curve was obtained when a beam of alpha-particles was projected through the same thicknesses of mica into the same chamber. Mere similarity in the shape of the curves would prove nothing, for this is the shape obtained with all kinds of charged particles, electrons and protons and more massive charged nuclei; in particular, every such curve rises from zero to a maximum and thereafter descends continually as the energy of the particles is raised indefinitely upward from the least value sufficient for ionization.[16] However, the ordinates of the curve of Fig. 7 are *equal* to those of the alpha-particle curve, and about four times as great as would have been observed with protons; and this it is which proves the fragments to be alpha-particles. Almost as good a proof could be made by two measurements: by measuring the range of the fragments and the total ionization produced by any fragment in a chamber deep enough to swallow it up, and comparing the latter datum with the ionization produced in the same chamber by an alpha-particle of equal range. This proof, or some other substantially like it, has been adduced in certain cases. When alpha-particles are the agents of the transmutation, the same test has proved in several cases that the fragments are protons. In some cases the test has not yet been applied.

I have already had to speak of interposing mica in the path of the fragments, in order to learn something about them. This is a procedure with which it is necessary to be familiar. It would be very pleasant indeed to be able to apply electric and magnetic deflecting fields to a narrow stream of fragments all flying in the same direction, for one could then spread it out into a velocity-spectrum, and not only identify the corpuscles perfectly but also determine their distribution-in-range, which as we shall presently see is of the first importance. This has not yet been done, partly (I presume) because of the high fieldstrengths that would be needed, chiefly because the available streams of particles are too scanty. It will be a happy day when at last we get streams of fragments so intense that they can be dispersed into a velocity-spectrum which will appear imprinted on a photographic film, as has been feasible for years with beta-rays. For the time being we must be content with curves such as many figures in this article display, Figs. 8 and 9 and 11 for example.

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[15] The quantity plotted as ordinate is obtained from such records as those of Fig. 6, in which every fragment produces a vertical line. Cockcroft and Walton observed many such lines for each thickness of mica, and ascertained in each case the most frequently-occurring value of line-length.

[16] "Electrical Phenomena in Gases," pp. 40–44, 70–71. Such a curve as that of Fig. 7 is sometimes called a "Bragg curve."

These are curves in which the abscissa stands for the thickness of a special kind of matter (air of a standard density) interposed in the path of the fragments, and the ordinate for the number of fragments detected on the far side of that matter; I will call them "integral distribution-in-range" curves representing the number $f(x)$ of particles able to traverse thickness x. Were one to differentiate them, one would get the "differential distribution-in-range" curves, representing a function $f'(x)$ such that $f'(x)dx$ stands for the number of particles able to traverse thickness x but not additional thickness dx—the particles which are said to have "ranges" between x and $x + dx$.

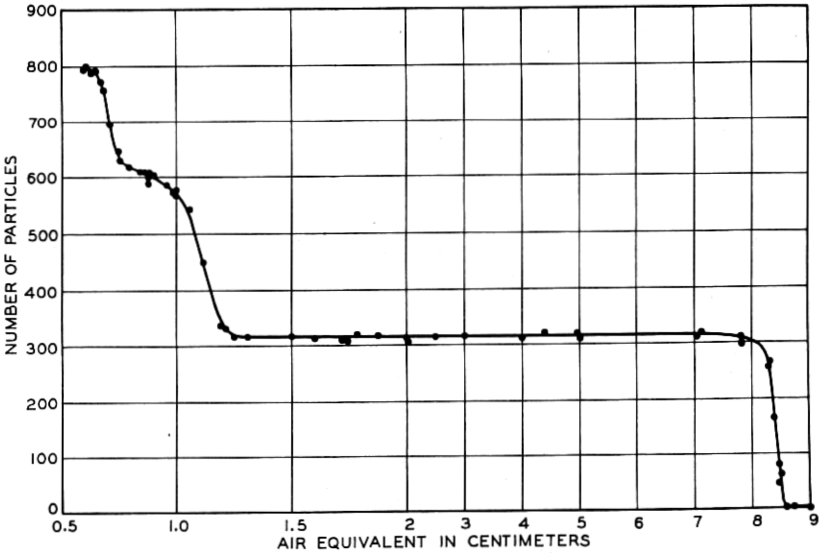

Fig. 8—Integral distribution-in-range curve of the fragments resulting from bombardment of lithium by protons. (Oliphant Kinsey & Rutherford)

These, however, are usually not plotted,[17] and one must accustom himself to draw the proper inferences from the integral curves.

The clearest of these to read are those which are shaped like a staircase, with steep rises connecting horizontal parts called paliers or plateaux. A steep rise extending over a narrow interval of x signifies a "group" of fragments all having ranges close together. A plateau extending over a broad interval of x signifies that no particle has a range comprised anywhere in this interval. An integral curve in the form of a staircase therefore implies the analogue of a line-spectrum,

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[17] One of the rare examples is reproduced in "Transmutation," *B. S. T. J.*, Vol. X, p. 650 (Oct. 1931), from the work of Bothe and Fränz.

the particles being classifiable into groups each with its characteristic speed. But if in such a curve there is a long sloping arc (as in Fig. 9), it implies the analogue of a continuous spectrum, there being particles of all ranges over a notable interval.

The "stopping" or "absorbing" screens which are used in determining these curves are usually sheets of mica or of aluminium. The curves are not however plotted against the actual thickness of the interposed strata of mica or whatever else the substance may be, but against the "air-equivalent" or thickness of the stratum of air of standard density[18] which is known by separate experiments to have the same effect in slowing down and stopping charged particles, the same "stopping-power." It is the air-equivalent which is the quantity x of the preceding paragraphs and the abscissa (often termed "absorption") of Fig. 8 and nearly all other such figures. The ratio between the actual thickness of a layer of matter and the equivalent thickness of air is roughly (but only roughly) the reciprocal of the ratio of their densities. The sheets of metal or of mica used in the experiments are therefore very thin (it has been possible to make screens of mica so tenuous that their air-equivalent is only 0.15 mm.) and the thinnest must be bolstered up by stiff metal grids, of which the wires block a considerable fraction of the beam. It is also possible

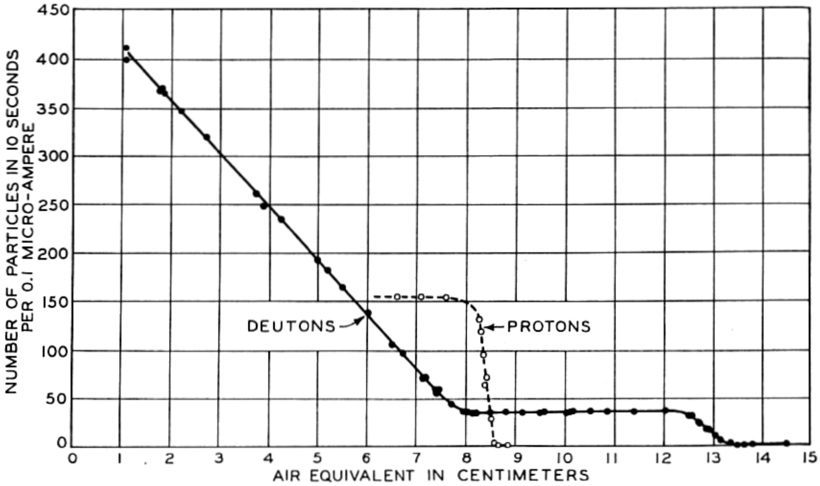

Fig. 9—Integral distribution-in-range curve of the fragments resulting from bombardment of lithium by deutons. (Oliphant Kinsey & Rutherford)

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[18] There are unluckily two standards of density, one being that of air at 0° C. and 760 mm. Hg, the other that of air at 15° C. and 760 mm. Hg; see "Transmutation," footnote on p. 643, *B. S. T. J.*, Oct. 1931. The latter is used in this article.

to use air (or some other gas) of adjustable density; when the scintillation-method is employed, the gas may fill the entire space between the source of the fragments and the fluorescent screen; with other methods of detecting the fragments, it must be contained in a cell which the stream enters and leaves through windows of mica or similar substance.

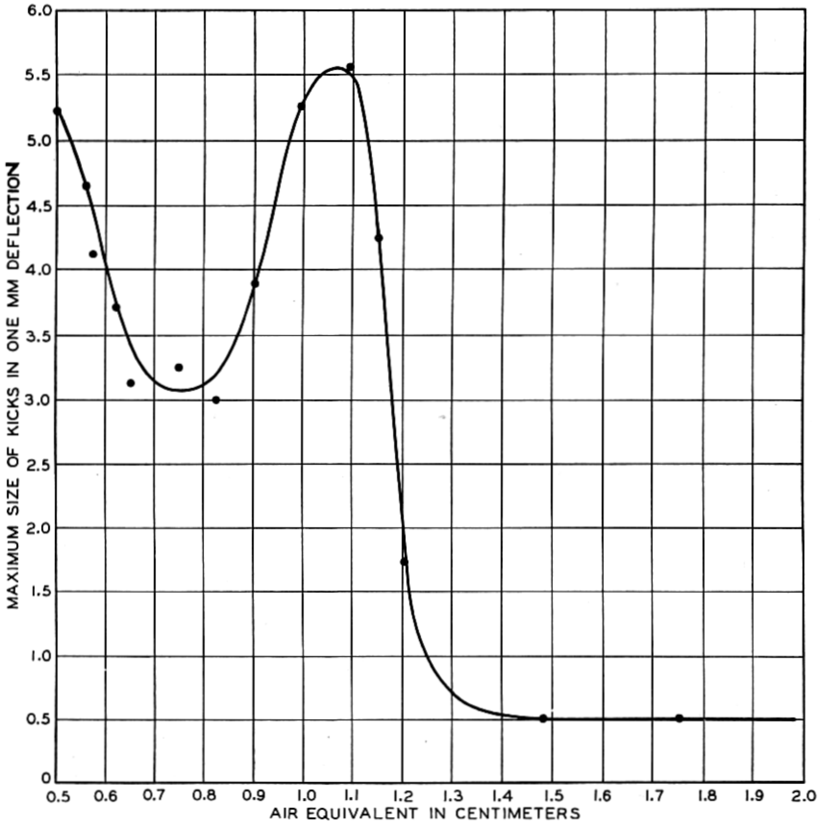

Fig. 10—Ionization produced in a shallow chamber by the least penetrating fragments from the transmutation of lithium by protons. (Oliphant Kinsey & Rutherford)

There is an interesting and important way of confirming the steps in an integral curve such as those of Figs. 8 and 9. Near the rise of such a step, the thickness of the intercepting matter is such that many particles are approaching the ends of their ranges when they emerge from the last of the screens. Suppose that this last screen is adjoined by a very thin ionization-chamber, like that with which the curve of Fig. 9 was obtained. Let the air-equivalent x of the total thickness of the screens be varied, and let the average number of ions produced per particle in the chamber be measured and plotted as function of x. Recalling Fig. 7 and what was said in respect to it, the reader will see that the resulting curve should have a peak wherever the integral distribution-in-range curve has a step. This has been verified several times, and there are cases in which these peaks have been taken as clearer evidence for the existence of groups than the shape of the integral curve itself (Fig. 10). Peaks may also appear in a curve of which the ordinate is the *total* ionization produced in the very thin chamber by all the fragments which enter it.

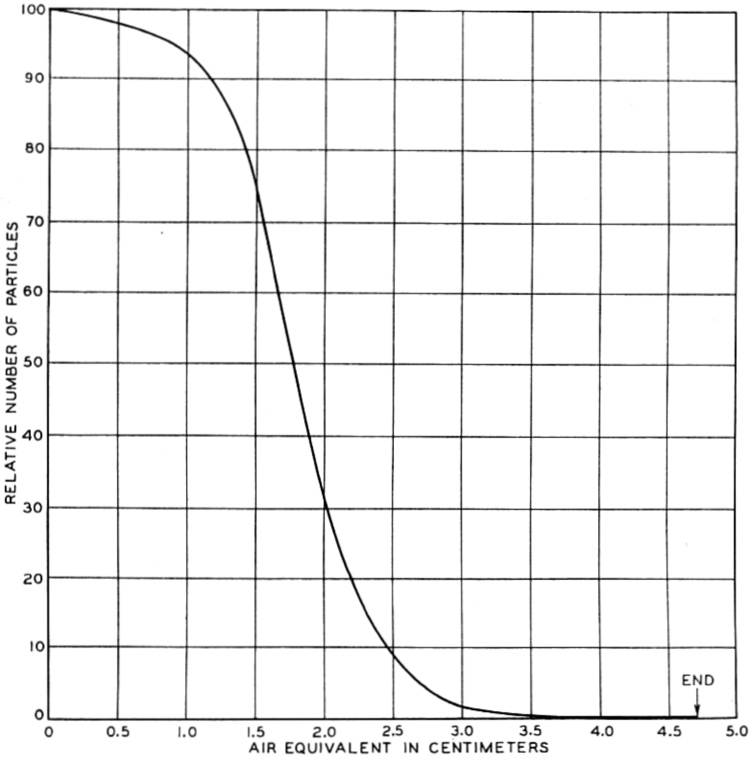

Fig. 11—Integral distribution-in-range curve of the fragments resulting from the bombardment of boron by protons. (Oliphant & Rutherford)

Anyone at all acquainted with physical experiments will readily suspect that the steps of actual integral curves "ought to be" steeper than they are. I mean: that he will form the hypothesis that perpendicular rises would be observed instead of rounded-off and sloping ones, if only the pencil of fragments passing through the absorbers were ideally narrow and cylindrical, and were produced by bombardment of atoms with particles all of the same speed; and he will attribute the rounding-off of the steps to the facts that the fragments actually form a divergent and conical beam, and the atoms from which they come have been struck by impinging particles of diverse speeds. This idea is strongly supported by the facts that the steps are notably steepened when the divergence or "aperture" of the beam of fragments is reduced, and when the diversity of speeds among the bombarding particles is narrowed.

The former of these variables is controlled by the slits and diaphragms which bound the beam, and the latter by the thickness of the bombarded target whence the fragments proceed; for the bombarding particles are slowed down as they dive deeper into the target, and nuclei at different depths receive impacts of different energy, and thus there is a wider diversity of speeds among the particles when they finally make their impacts than there is among them when they start from their source. But as one cuts down either the thickness of the target or the aperture of the beam of fragments, one reduces the number of fragments which come to the detecting apparatus, and reaches a limit when this number becomes too small to be observed in any convenient time. Progress in approaching ideal conditions therefore depends on progress in multiplying the number of fragments by multiplying the strength of the bombarding beam. We may count on a yet greater steepening of such steps as those of Fig. 8, when the enormous streams of bombarding protons produced by Oliphant and Rutherford are applied to very thin films and the distribution-in-range of the resulting fragments is measured. A corresponding improvement of the curves obtained when alpha-particles are the bombarders is still in the not-immediate future. Whether under ideal conditions the steps would be absolutely perpendicular, and all the fragments of a group have exactly the same speeds, is not as yet to be safely inferred from the data.

There remains the great problem of converting distribution-in-range curves into distribution-in-speed or distribution-in-energy curves, and thus determining the energy or the speed of fragments belonging to a group of which the range is known. The recent developments of research in transmutation and in cosmic rays have elevated this to the rank of the major problems of physics. For alpha-particles of ranges of 8.6 cm. and less, it is practically solved by empirical means; for such alpha-particles are supplied in such abundance by radioactive bodies that it has already been feasible to measure by deflection-methods the speeds corresponding to a large number of different ranges, and plot an empirical speed-*vs*-range curve which is fixed by so many points of observation that there is no important uncertainty in making interpolation between these. For alpha-particles of range superior to 8.6 cm., such as often occur among fragments of transmutation, it has heretofore been necessary to extrapolate; but very lately the empirical curve has been extended onward to 11.6 cm., thanks to a powerful new magnet at the Cavendish which is able to deflect the paths of alpha-particles of even such rapidity.[19] With protons our knowledge of the range-*vs*-energy relation is less extensive and less accurate, and an improvement thereof should be one of the first and most important by-products of the new methods for imparting high energies to ions. For charged nuclei of other elements than hydrogen and helium, relatively little is assured (what is known has been found out chiefly by Blackett and his school)[20]; but this lack has not as yet been much of an impediment to the study of transmutation, except in certain cases involving impacts by neutrons.

TRANSMUTATION BY IMPACTS OF PROTONS AND DEUTONS

The earliest element to be transmuted by protons in the laboratory —indeed the first to be transmuted by man with any agent other than the alpha-particle—was lithium. It was fortunate that Cockcroft and Walton began with this element, for its behavior turned out to be uniquely lucid. In most disintegrations, a single fragment is detected, and there must be a massive residue which remains unseen, staying hid within the substance of the bombarded target. But in some at least of the transformations which occur when lithium nuclei are struck by protons or deutons, there seems to be no hidden residue; every fragment is observed and recognized. These are processes of "nuclear chemistry" of which we fully discern both the beginning and the end; and they are described by the quasi-chemical equations:

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[19] Rutherford et al., *Proc. Roy. Soc.* **139**, 617–637 (1933). The empirical curve departs slightly from a third-power law (range proportional to cube of speed) and the results are expressed by an empirical formula for the departure. See also G. H. Briggs, *Proc. Roy. Soc.* **139**, 638–659 (1933).

[20] See N. Feather, *Proc. Roy. Soc.* **141**, 204 (1933) and literature there cited. The observations are made upon tracks which appear in Wilson chambers when the contained gas is bombarded by alpha-particles, and which are the tracks of objects of atomic mass that have suffered violent impacts. It is presumed (though not always proved) that these objects are solitary or "bare" nuclei, not accompanied by any of the orbital electrons which attended them before the impacts. Some (but not all) of the data conform to the empirical rule that the ratio of the ranges of two nuclei of masses m_1 and m_2 and of charges Z_1e and Z_2e, when the two have the same speed, is $(m_1/m_2)(Z_1/Z_2)^{1/2}$.

$$ {}_1H^1 + {}_3Li^7 + T_0 = 2\,{}_2He^4 + T_1, \qquad (1)$$

$$ {}_1H^2 + {}_3Li^6 + T_0 = 2\,{}_2He^4 + T_1, \qquad (2)$$

of which the first has already appeared in Part I. of this article.

These are to be regarded as equations for mass and energy, owing to the equivalence of these two entities. Attached to the symbol of each atom are its mass-number as superscript and its atomic number as subscript (and, incidentally, every such equation must balance when considered as an ordinary equation in either the mass-numbers or the atomic numbers). The symbols T_0 and T_1 stand for the total kinetic energy of the particles *before* and the particles *after* the transmutation, expressed in mass-units. (I recall from Part I. that a mass-unit is one-sixteenth the mass of an ${}_8O^{16}$ atom, and that one million electron-volts is equal to 0.00107 of one mass-unit.) The other symbols then stand for the rest-masses of the nuclei of the atoms in question. It would be proper, and in accordance with the spirit of relativity, to leave out the symbols T_0 and T_1 and consider each of the other symbols as standing for the *total* mass of the nucleus, viz. the sum of its rest-mass and the extra mass resulting from its speed. When hereinafter the symbols T_0 and T_1 are absent from such an equation, the others are thus to be interpreted.

The suggestion thus is, that when a proton meets with a ${}_3Li^7$ nucleus or a deuton with a ${}_3Li^6$ nucleus, either process ends in the formation of two helium nuclei—alpha-particles—out of the substance of the original bodies. It is further suggested that these nuclei share kinetic energy amounting to T_1; and if they are emitted in directions making equal angles with that of the impinging particles—the "symmetrical case" which (as we shall see) is most commonly observed—they must share T_1 equally in order to assure conservation of momentum. Now the rest-masses of all the nuclei figuring in equations (1) and (2) are accurately known through the work of Aston and of Bainbridge. Taking them from Table I and substituting them into the equations, and using the electron-volt for our unit, we get:

$$T_1 = T_0 + 16.8 \cdot 10^6, \qquad (3)$$

$$T_1 = T_0 + 22.2 \cdot 10^6, \qquad (4)$$

in the two cases,[21] and therefore expect alpha-particles paired with one another, their kinetic energies amounting altogether to these values.

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[21] For these numerical values and their uncertainties, see K. T. Bainbridge, *Phys. Rev.* (2), **44,** 123 (July 15, 1933).

It is the verification of these predictions which gives us such great confidence that we have recognized the processes which really happen.

I have already said how Cockcroft and Walton proved that the fragments, when lithium is bombarded by protons, are alpha-particles. The integral distribution-in-range curve of these fragments, obtained by Oliphant Kinsey and Rutherford with the apparatus of Fig. 2 and proton-currents running up to $50\mu a$, appears in Fig. 8; and that for the fragments created when deutons are used instead of protons appears in Fig. 9. In both of these one cannot but be struck by the beautiful long horizontal plateaux, and the sharpness of the steps which end them on the right. The groups of fragments of which these steps are the signs have ranges stated by the observers as 8.4 and 13.2 cm respectively, with uncertainties of ± 0.2 cm. (These figures are evidently taken from the bottom of the step, probably because it is assumed that under ideal conditions of narrow beam and thin bombarded film—the actual beam had a divergence of about 15° and the actual target was thick—the step would rise vertically from the point whence it actually begins to rise obliquely.) The corresponding energy-values are estimated as 8.6 and 11.5 MEV (millions of electron-volts) respectively; and as T_0, the energy of the impinging protons, is at most two-tenths of a million, these values may be compared directly with the halves of the numbers in equations (3) and (4). Meanwhile at Berkeley, Lewis Livingston and Lawrence were driving deutons with an energy of 1.33 MEV—no longer negligible—against lithium, and observing fragments with a range of 14.8 cm., corresponding to an energy of 12.5 MEV; and this is to be compared with half of 23.7 millions on the right-hand side of equation (4).

The agreement in the case of protons impinging on lithium is admirable, and well within the uncertainty of the data. The agreements in the cases of deutons impinging on lithium are ostensibly not so good, but this is not so serious as it seems at first glance, because of the required extrapolation of the range-*vs*-energy curve of alpha-particles (page 131), and because it is not always the "symmetrical case" which occurs. For the present there is no compelling reason to suppose that equation (2) is contradicted by the data.

A further point susceptible of test: if the processes described by equations (1) and (2) are actual, the alpha-particles of the stated ranges must be shot off in pairs, the two members of each pair flying off in almost opposite directions—in directions which would be exactly opposite were it not for the original momentum of the proton, but which because of that momentum must make with one another an angle slightly (and calculably) less than 180°. Cockcroft and Walton made the test with a pair of Geiger counters set on opposite sides of the bombarded lithium, and got a positive result; but it is the expansion-chamber which is suited by its nature for supplying the most magnificent of proofs. To achieve this, one must put the bombarded target of lithium in the middle of the chamber, and photograph the tracks from above; and since the bombarding stream must come through vacuum while the chamber must be filled with moistened air, the target must be separated from the air by walls of mica thick enough to withstand the pressure and thin enough to let the fragments pass. The scheme is clearly depicted in Fig. 12. One notices that the design is such that the pairs which are observed are those of which the directions are nearly at right angles to the proton-beam—the "symmetrical case" aforesaid.

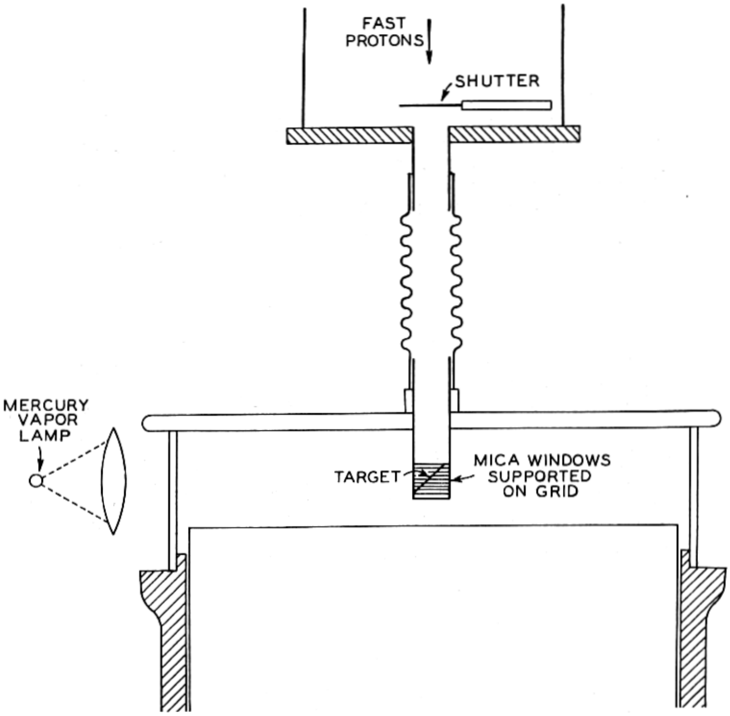

Fig. 12—Diagram of arrangement for observing tracks of fragments by the expansion-method. (After Dee and Walton)

This experiment was first performed by Kirchner of Munich, who got several pictures of paired fragments from lithium bombarded by protons. Fig. 13 shows an example. (The third track is rather annoying, but it was quite an achievement so to adjust the conditions as to get so few as three.) Many splendid examples have lately been published by Dee and Walton of the Cavendish, and Fig. 14 is outstanding among them because the bombarding stream was a mixture of protons and deutons, and the picture shows two pairs of fragments, one apparently due to each of the processes which I have been describing. Those of the pair marked b_1b_2 have the range of 8.4 cm. agreeing with equation (1), while those marked a_1a_2 go definitely farther and even escape from the chamber, which makes it impossible to measure their ranges. Dee and Walton therefore made the walls of the target-capsule thicker, so that more of the energy of the fragments should be consumed in them; the pairs which were obtained with bombarding deutons now ended in the chamber and in the field of view, and their ranges agreed with the 13.2 cm. obtained from the curve of Fig. 9. At least two more of these pairs appear in Fig. 15. Verification of a theory could scarcely go further or be more vivid! Yet there is the additional point, that Kirchner found the angle between the paired paths in his pictures to differ from 180° by just about the amount required by the momentum of the proton.

Fig. 13—Tracks of paired fragments, He nuclei resulting from impact of a proton on a Li^7 nucleus. (Kirchner; *Bäyrische Akademie*)

However not every fragment observed when lithium is bombarded, either by protons or by deutons, results from these superbly simple interactions. Notice in Fig. 8 the two very much rounded steps, suggesting groups of short ranges (1.15 cm. and 0.65 cm.); these are confirmed by the maxima in the curve of Fig. 10 which has already been explained (page 129). Only tentative theories of these have been made, and it would be of little use to expound them here.[22] Notice then in Fig. 9 the beautiful long *sloping* line adjoining the plateau, and implying a continuous distribution over a wide interval of ranges extending up to 7.8 cm. The numerous shorter tracks of Fig. 15 are due to particles belonging to this continuum. Observe last the integral distribution-in-range curve for the fragments from boron bombarded by protons, Fig. 11; notice that it displays no definite step, but consists of a single sloping arc implying a continuum extending to an upper limit, which on a magnified curve is found to be at 4.7 cm.

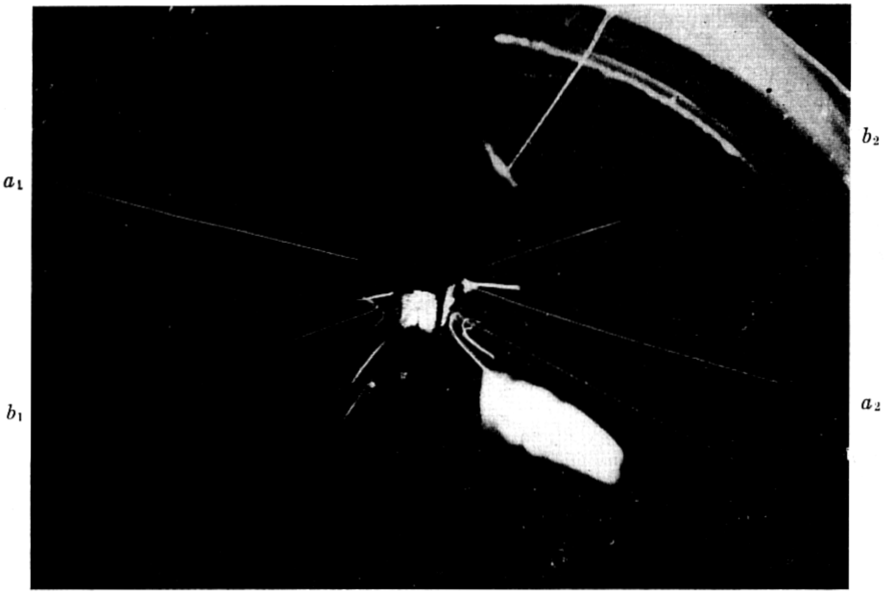

Fig. 14—Tracks of paired fragments, He nuclei believed to result from impact of a proton on a Li^7 nucleus and from impact of a deuton on a Li^6 nucleus. (Dee and Walton; *Proceedings of the Royal Society*)

It is now suggested that in both of these two last cases we have processes in which there are not two, but three final fragments:

$$ {}_1H^1 + {}_3Li^7 + T_0 = 2{}_2He^4 + {}_0n^1 + T_1, \tag{5}$$

$$ {}_1H^2 + {}_5B^{11} + T_0 = 3{}_2He^4 + T_1, \tag{6}$$

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[22] Dee has just announced (*Nature*, **132**, 818–819; Nov. 25, 1933) that these short-range fragments are frequently paired. In doing the experiment he admitted the primary protons into the expansion-chamber through a thin mica window, the target being within.

the symbol $_0n^1$ in equation (5) standing for a neutron. When there are three fragments, conservation of momentum no longer demands that the available energy be equally divided among the three, but admits of an infinity of distributions. It is not difficult to find the highest fraction of T_1 which either of the two alpha-particles in case (5), or any of the three in case (6), may receive; this amounts to very nearly one-half in the former, to two-thirds in the latter case.

In equation (5) the rest-masses of all the charged nuclei are known; that of the neutron is still subject to some controversy, but if we tentatively put Chadwick's value 1.0065 for it we get for $(T_1 - T_0)$ the value 16 millions of electron-volts. T_0 again is negligible, so that we are to compare half of this figure with the energy corresponding to the range 7.8 cm.—the right-hand end of the sloping part of the curve of Fig. 9—which is 8.3 millions. The agreement is entirely satisfactory. With boron the result is not so pleasing, for T_1 by equation (6) should be more than eleven millions, and two-thirds of this differs rather seriously from the energy-value corresponding to the end of the curve of Fig. 11, which is 6 millions. Kirchner got a photograph in which three coplanar tracks of the same appearance

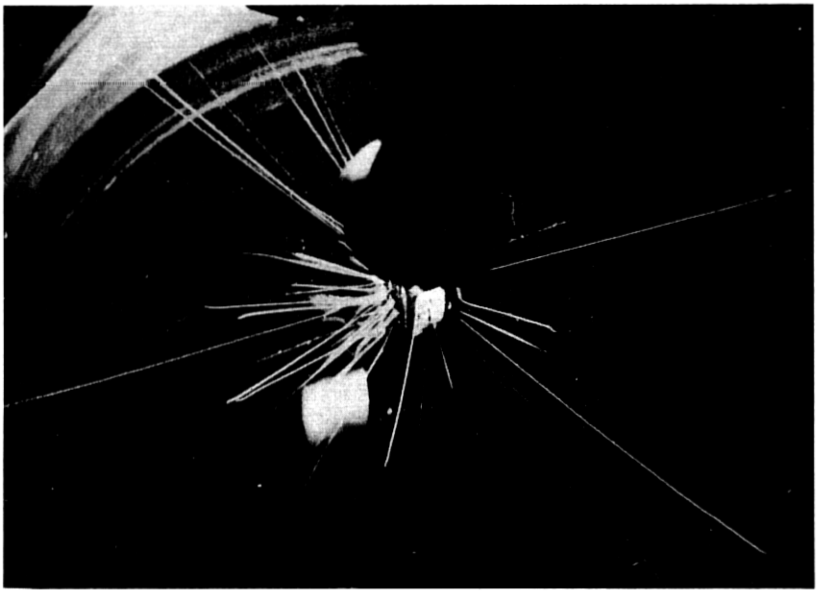

Fig. 15—Various tracks produced during bombardment of lithium by deutons. (Dee & Walton; *Proceedings*)

diverge at mutual angles of 120° from a point in a boron target bombarded by protons, and Dee and Walton have noticed a number of trios of paths springing from such a target, but without being quite sure that they are not mere coincidences.[23]

Having now met with a case in which there may *not* be a balance between the two sides of such an equation as (6), we should now pause to inquire what can be done about such cases. Of course, such a disagreement might mean that the actual process is something entirely different from the one postulated in the equation, but it may not be necessary to make such a complete surrender of the theory. In equations (1) to (6), it is everywhere assumed that all the energy is retained by the material particles, in the form of kinetic energy or of rest-mass. Suppose that the process described by one of these equations, (6) for instance, is confirmed in every respect excepting that the final kinetic energy of the fragments is found to be less, by some amount Q, than the value of T_1 computed from the equation. One might then assume that the missing energy Q is radiated away in the form of one or more photons. Alternatively one might assume that the missing energy is retained by one of the material fragments in the form of "energy of excitation"; the rest-mass of the fragment, so long as it retained this energy and remained in the excited state, would then be correspondingly greater than its normal rest-mass, and the equation would be balanced if this abnormal value of mass were inserted into it in place of the normal one. Such explanations are frequently offered nowadays. They suffer, of course, from the disadvantage of being too easy; one can always postulate the necessary photons or excited states to explain any observed positive value of Q. But if they can ever be supported by independent proof of these excited states or photons, they will become much more convincing.

Lithium and boron are by far the best-studied of nuclei, in respect to their interactions with protons and deutons. It is true that our knowledge of the distribution-in-range curves of the fragments is still confined to comparatively low values of the energy of the bombarding particles, values less than 300,000 electron-volts. With higher energies it is to be presumed that the steps at the right-hand ends of the curves in Figs. 8 and 9 would move to the right, to the extent pre-

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[23] If in the case of boron bombarded by protons it be assumed that two of the He nuclei fly off in directions making symmetrical angles $(\pi - \theta)$ and $(\pi + \theta)$ with the direction of the third, the distribution-in-θ of the disintegrations can be deduced from the curve of Fig. 14; it turns out that the most probable cases are those in which $\theta = 60°$ nearly, and all the three particles have nearly the same energy. A like deduction may be made for lithium bombarded by deutons, the neutron playing the part of third alpha-particle in the foregoing case; it is inferred that again the most probable types of disintegration are those in which all three share almost equally in the energy.

scribed by the increase of T_0 in equations (1) and (2); and so should the right-hand end of the sloping part of the curve in Fig. 9, and the extremity of the curve of Fig. 11. There is an indication of the first of these expected changes in the observation already quoted from Lewis Livingston and Lawrence, of 14.8-cm. fragments ejected from lithium by 1.33-MEV protons (page 133). We must wait for future data to test the others, and to see what happens to the heights of the steps and the general shape of the uninterpreted parts of the curves. Already however we have data bearing on the so-called "disintegration-function," or the relation of the total number of emitted fragments to the energy of the bombarding particles.

To speak of "total number of fragments" is to suggest too much. The present knowledge suffers from two limitations: the counts of fragments are made with apparatus which does not enclose the target completely and must be separated from the target by a screen, so that the fragments counted are only those which start off within a limited solid angle of deflections and have sufficient range to penetrate the screen. One generally makes a tentative correction for the former limitation, by assuming that the fragments go off equally in all directions and multiplying the number observed by the factor $4\pi/\omega$, where ω stands for the solid angle subtended by the detector as seen from the target. This factor may well be wrong, but perhaps does not vary seriously with the energy of the bombarding particles, so that at least the trend of the curve may not be distorted. For the latter limitation we have not the knowledge to make any allowance; it must always be stated that the count is of fragments having more than such-and-such a range, or such-and-such an energy. Every kind of device for observing transmutation suffers from some such lower limit, set either by the sensitivity of the device itself, or by the stopping-power of the wall which bounds it.

With their dense streams of protons and exceedingly thin films (page 113) Oliphant and Rutherford obtained the curves of Fig. 16: the disintegration-functions of lithium and boron, with respect to incident protons, up to proton-energies of some 200,000 electron-volts. The wall between the target and the gas of the ionization-chamber had an air-equivalent of 2.50 cm., and consequently the curves pertain only to fragments having ranges greater than this.[24] The rise from the axis is gradual, not abrupt; one might say that the shape of the curves suggests that the protons have, not a definite *capability* for transmuting which begins suddenly at a critical energy, but a *probability* of trans-

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[24] I hear from Dr. Oliphant that the trend of the curve for the short-range fragments is just the same.

muting which increases smoothly from zero (though this suggestion might not occur to anyone not having foreknowledge of the current theory!). The least energy at which transmutation is observable should then depend entirely on the strength of the proton-stream and the sensitiveness of the apparatus; von Traubenberg, with a stream perhaps as strong as that of Oliphant and Rutherford, observed one to three fragments per minute at 13,000 volts.

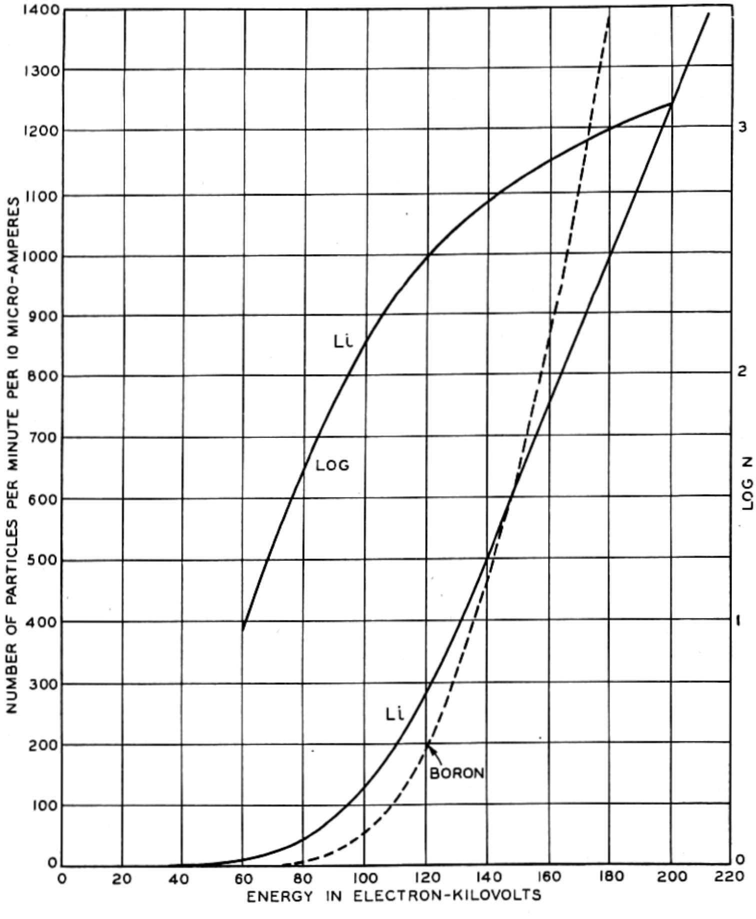

Fig. 16—Disintegration-functions of thin films of lithium and boron. (Oliphant & Rutherford)

The curve of Fig. 17 extends very much further—all the way to 1.125 MEV—but was obtained with so thick a target of lithium (lithium fluoride, to be precise) that the protons came to a stop in the mass, and the disintegrations observed at any voltage might have been produced by particles of any energy up to the maximum corresponding to the voltage. It comes from the Berkeley school, the data being procured chiefly by Henderson.[25] It refers only to fragments of ranges superior to 5.32 cm., a grave limitation, accepted in order to make sure that none of the primary protons could get into the detector (a Geiger counter). From 400,000 volts onward, the curve of Fig. 17 conforms to a simple and somewhat surprising assumption: *viz.* the assumption that a proton of energy superior to 400,000 is neither more nor less efficient in disintegrating lithium than a proton of only 400,000 electron-volts, and that the whole of the rise in the curve from this voltage onwards is entirely due to the fact that the faster the proton, the farther it dives into the target and the more chances it has to

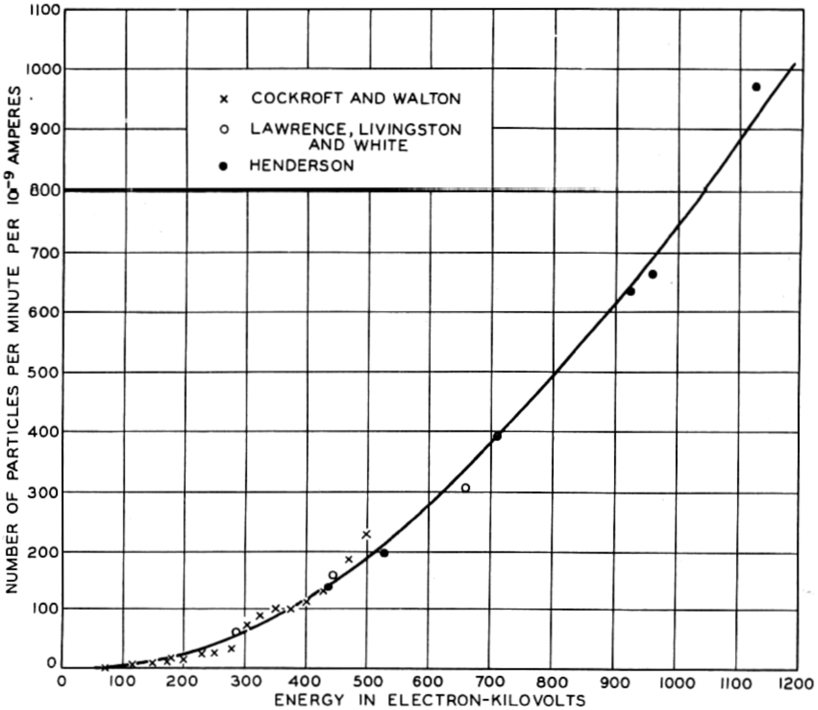

Fig. 17—Disintegration-function of lithium measured with a thick layer of lithium fluoride. (Henderson)

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[25] The curve also fits the data of Cockcroft and Walton within the uncertainty of experiment, due regard being had to the difference in the values of the solid angle (letter from Dr. Henderson). In their work the screen between target and detector had an air-equivalent of 3 cm. (letter from Dr. Cockroft). The curve of Fig. 8 shows that this had the same effect as Henderson's 5.32 cm.

impinge on a nucleus before it is slowed down and its energy reduced beneath this particular value. The curve of Fig. 15 for lithium should then become horizontal at abscissa 400. At lower voltages, both curves concur in implying that the probability of disintegration depends on the energy of the proton. I will revert to this topic in a later article.

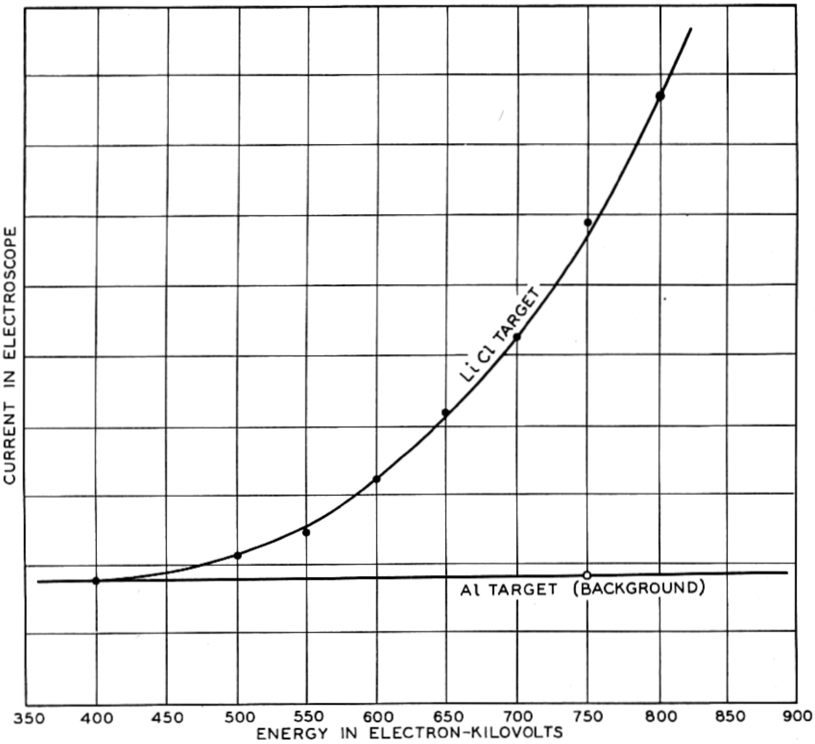

Fig. 18—Intensity of the mixture of neutrons and gamma-rays resulting when lithium is bombarded by deutons. (Crane & Lauritsen)

There are also modes of disintegration of lithium by deutons and by protons, in which neutrons and gamma-rays are emitted. These have been observed in Pasadena by Crane, Lauritsen and Soltan. Deutons are the more efficient of the two, but protons are sufficiently potent to have enabled Crane and Lauritsen to trace the curves of Fig. 18, in which the significant quantity is the difference between the ordinates of the two.[26] The ionization-chamber was walled inwardly

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[26] Dr. Lauritsen writes me that the readings from which the lower curve is drawn were unchanged when the high voltage was removed; presumably therefore they represent the "background" due to the natural leaks of the electroscope. I am indebted to his letter for other as-yet-unpublished statements.

with paraffin, to accentuate the effect of the neutrons; it was however found that the readings were not considerably lessened when the paraffin coating was absent, and consequently Lauritsen infers that most of the effect is due to gamma-rays proceeding from the bombarded atoms. This inference is sustained by the fact that when the rays responsible for the effect are caused to pass through leaden screens, the ionization falls off exponentially with the thickness of the lead; and the value of the exponent suggests that the energy of the photons is about 1.5 MEV. One can easily think of a process whereby deutons might evoke neutrons from lithium nuclei:

$$ {}_1\mathrm{H}^2 + {}_3\mathrm{Li}^7 + T_0 = 2{}_2\mathrm{He}^4 + {}_0n^1 + T_1, \tag{7} $$

but with protons no plausible interaction comes readily to mind. Perhaps there is a two-stage process, the protons producing the reaction described by equation (1), the resultant He^4 nuclei striking other lithium nuclei and evoking neutrons. Or perhaps the neutrons and the gamma-rays alike result from the same processes as produce the groups of short-range alpha-particles revealed in Fig. 8. Questions of this intricate kind will probably predominate in the study of transmutation, in the years to come; and experiments on thin films will play a very important part in settling them, both because the likelihood of two-stage processes will be reduced, and because it may be possible to learn which isotopes are involved.

Little indeed is definitely known about the disintegration, by protons or deutons, of any other elements than lithium or boron. Charged fragments have been observed proceeding, in relatively small but yet appreciable number, from bombarded targets made of a great variety. But in many of these cases they may be due, so far as any of the observations tell, to a minute contamination of the target by boron derived from the glass of the enclosing tube; and the danger of this possible source of error was vividly brought out by Oliphant and Rutherford, when at first they observed such fragments, but ceased altogether to observe them when the original glass of their tube was replaced by a special boron-free variety! Beryllium and fluorine are the only elements, other than lithium and boron, of which these experimenters were sure of detecting fragments; for those of fluorine they were able to plot a disintegration-function and a distribution-in-range, which differed sufficiently in aspect from those of lithium and boron to exclude the possibility that these might be responsible; those of beryllium were too scanty for such tests. The elements with which they got no charged fragments, or only a few per minute, were the following: Fe, O, Na, Al, N, Au, Pb, Bi, Tl, U, Th. But their observations were confined to protons of relatively low energy-values,—their upper limit was little over 200,000 electron-volts—and do not prove that faster particles are incapable of transmutation. The Berkeley school has already published a number of observations made with protons of energies ranging up to 710,000, and with deutons of energies attaining the unprecedented height of 3 MEV; and they find fragments in abundance from a wide diversity of targets.

Beryllium deserves a special paragraph, since it yields neutrons when bombarded, whether with alpha-particles from radioactive bodies; or with helium ions extracted from a discharge and endowed artificially with energies of 600,000 electron-volts and upward; or with deutons. The first of these processes is the one which led to the discovery of the neutron; the second, which incidentally marks the first employment of artificial alpha-particles (since these helium ions are alpha-particles in all but origin, except for the unimportant difference that each possesses an extra-nuclear electron while it is approaching the target) is a recent achievement of the Pasadena school (Crane, Lauritsen and Soltan); the third was achieved both at Pasadena and at Berkeley. These three processes are now in rivalry with one another, and it remains to be seen which will be producing the greatest number of neutrons, a year or five years hence. It is still very doubtful how the third takes place: perhaps the deuton merges with the beryllium nucleus, as in the other cases the alpha-particle is supposed to do (page 155), or perhaps it knocks a pre-existent neutron out of the beryllium structure and goes unaltered on its way. This too is a problem for the future, and one in the solving of which the charged fragments likewise observed will probably play a part.

The deuton itself is in all probability a complex particle; might it not be shattered in impinging against a nucleus, especially some heavy nucleus? This is the interpretation offered by Lawrence of the fact that in sending streams of deutons against targets of several different kinds, he observed charged fragments which were protons (not alpha-particles!) forming a group having a definite range and a definite energy not depending at all on the substance of the target. With 1.2-MEV deutons this characteristic energy of the protons is 3.6 MEV. A singular rule governs this quantity: if the energy of the bombarding particles is increased, that of the protons goes up by just the same amount—deutons of energy $(1.2 + x)$ MEV evoke protons of energy $(3.6 + x)$ MEV. The rule has been verified for values of x up to 1.8. Such a rule is just what one would expect, were there no other fragments than the protons, excepting fragments of such great mass that they could take up the necessary momentum without taking an appreciable amount of kinetic energy. The heavy nucleus by itself is able to do this. However there are also neutrons, of which the energy is sufficient to let them be detected, and therefore by no means negligible. This is gratifying for the theory, inasmuch as if a proton is separated from a deuton, the residue should be a neutron (or else another proton and a free electron); but one is then obliged to assume that the neutron always takes the same kinetic energy, whatever that of the impinging deuton may have been. This seems rather odd, but nothing prohibits it. Streams of alpha-particles have been sent against compounds ("heavy water") containing deuterium in abundance, but as yet no neutrons have been detected coming off.

TRANSMUTATION BY IMPACTS OF ALPHA-PARTICLES [27]

Impact of an alpha-particle against a nucleus may result in the springing-off of one or more (or none) of four kinds of corpuscles: protons, photons, neutrons, positive electrons.

Transmutation with production of protons

This is the earliest-discovered type, of which I told at length in "Transmutation." The discovery was made by Rutherford in 1919 in experiments on nitrogen. At present the Cavendish school considers that this mode of transmutation has been proved for thirteen elements, none of atomic number greater than 19: the list comprises B, N, F, Ne, Na, Mg, Al, Si, P, S, Cl, A, K. The most frequently and fully studied cases are those of boron, nitrogen and aluminium.

The evidence that the fragments are protons is rather variegated. In some cases this has been proved by deflection-experiments;[28] recently it has been proved in some other cases by measuring both the range of the fragments and the ionization which they individually produce in a shallow chamber or a deep one (page 125); some observers are able to tell the scintillations due to protons from those which are due to alpha-particles.

Integral distribution-in-range curves of the fragments have been obtained for boron, nitrogen, fluorine, sodium, magnesium, aluminium and phosphorus. Most of them show more or less conspicuous plateaux, of which the most magnificent appear in the celebrated curves of Pose for aluminium, reproduced in "Transmutation"

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[27] An expanded version of this section, with citations of additional data and reproductions of some curves, appears in the Physics Forum of the *Review of Scientific Instruments* for February 1934.

[28] "Transmutation," pp. 636–640, *B. S. T. J.*, Oct. 1931.

(Figs. 6, 7); from this there are all gradations of distinctness downward, ending with cases in which it is uncertain whether the ideal curve would be a smoothly-descending one, or would have a succession of short plateaux which in the actual curve are rounded off into indistinguishability.

By "ideal curve" in the foregoing sentence I mean, as heretofore (page 130), that which would be obtained with an infinitely narrow beam of fragments proceeding in a single direction and produced by alpha-particles all of a single speed and proceeding in a single direction. I must also add that many thousands of fragments should be counted, as otherwise the results are likely to be distorted by statistical fluctuations. It appears that in most of the experiments with bombarding alpha-particles, the departure from the ideal is much more considerable than in the best of the experiments with bombarding protons. The targets are usually so thick that the speeds of the alpha-particles vary considerably as they go through, and often so thick that these are swallowed up and every energy of bombarding particle, from the initial maximum down to zero, is represented among the impacts. This matters much more than it does with protons, because here the energy of the primary particles is often much greater than that of the fragments, and a small percentage variation of the former may entail a big one of the latter. The solid angles subtended by the exposed part of the target as seen from the source of the alpha-rays on the one hand, from the detector on the other, are frequently both large. This is particularly serious, because it appears that the ideal distribution-in-range curve would vary with the angle between the directions of the impinging particle and of the fragment. In some experiments the number of fragments observed has been too small to be immune to statistical fluctuations, and it is surprising that the plateaux in Pose's curves should be so clear despite this handicap.

Where two or more observers have studied a single element, there is generally enough concordance among their statements to assure the onlooker that at least the major groups of protons are recognizable. The prettiest case thus far is that of nitrogen: three researches on the integral distribution-in-range curve agree in showing a sharply-marked group of range about 17.5 cm (for protons ejected forward by full-speed alpha-particles from polonium, energy 5.3 MEV). The flattest plateau and sharpest step are to be seen in a curve by Chadwick Constable & Pollard, who approached very nearly to the ideal experiment in one respect, by using a stratum of nitrogen so thin that its air-equivalent was only 3 mm. All the protons of range superior to about 6 cm. belong to this group; there is another of inferior range, lately discovered by Pollard. Phosphorus and sodium have been studied only by Chadwick Constable & Pollard, who find for the former a single group, for the latter a smoothly-descending integral curve which may betoken total absence of groups, or may be resolved, by some future and closer approach to the ideal curve, into a close succession of bends and corners. The four remaining elements—B, F, Mg, Al—show at least three groups apiece, and indeed Chadwick and Constable deduce four *pairs* of groups for aluminium and three for fluorine. To illustrate the degree of concurrence between different observers, I quote the values for the groups of aluminium—that is to say, values of the ranges of the protons belonging to these groups, ejected forward by 5.3-MEV alpha-particles—from the four authorities. Pose gives 28.5, 49.6, and 61.2 (cm of air-equivalent); Steudel, 33, 49, 63; M. de Broglie and Leprince-Ringuet, 30, 50, 60; Chadwick and Constable give 22, 26.5, 30.5, 34, 49, 55, 61, 66. More detailed comparisons had best be left to those who have practice in this field.

While nearly all of the data have been obtained by other methods than that of the expansion-chamber, a few beautiful pictures have been taken in which there appears the track of an alpha-particle passing through nitrogen, and this track is seen to end at a fork.[29] One of the tines of the fork is a long thin track, apparently that of a proton; there is only one other, and this is short and thick. It is inferred that these reveal the only fragments which there are, and that, in the usual though somewhat objectionable phrase, the alpha-particle has fused with the residual nucleus. The process is then expressed by the equation:

$$ {}_7\mathrm{N}^{14} + {}_2\mathrm{He}^4 + T_0 = {}_8\mathrm{O}^{17} + {}_1\mathrm{H}^1 + T_1, \tag{8} $$

the symbols being chosen according to the same principles as in equation (1). It is commonly assumed, though in no other case with such good evidence, that this happens in most if not in all cases, so that when a nucleus of atomic number Z and mass-number A is transmuted by an alpha-particle, the process often is:

$$ {}_Z\mathrm{M}^A + {}_2\mathrm{He}^4 + T_0 = {}_{Z+1}\mathrm{M}^{A+3} + {}_1\mathrm{H}^1 + T_1, \tag{9} $$

with an obvious symbolism. This is called "disintegration with capture" (though it is the case in which the objection to the name "disintegration," page 117, is gravest). The other conceivable case of "disintegration without capture" would be described thus:

$$ {}_Z\mathrm{M}^A + {}_2\mathrm{He}^4 + T_0 = {}_{Z-1}\mathrm{M}^{A-1} + {}_1\mathrm{H}^1 + {}_2\mathrm{He}^4 + T_1. \tag{10} $$

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[29] "Transmutation," Figs. 10 and 11.

Disintegration-with-capture is very advantageous for the theorist, since when there are only two fragments after the interaction the principle of conservation of momentum suffices to determine the kinetic energy of either in terms of that of the other and that of the alpha-particle. In equation (9), T_0 stands for the kinetic energy of the alpha-particle, T_1 for the sum of the kinetic energies of the proton and the residual fragment, which call T_p and T_r respectively. Now excepting in the cloud-chamber experiments, it is only the proton which is detected, and therefore only T_p can be estimated from the data; but if the disintegration is by capture, then T_r and consequently T_1 can be deduced from T_0 and T_p. If however there are three or more final fragments, measurement of T_p is not sufficient to determine T_1. Also even in the case of disintegration-by-capture there will be uncertainty if the transmuted element is a mixture of two or more isotopes, since the value of T_r corresponding to an observed T_p will depend on the mass of the atom which is transmuted.

In a case of disintegration-by-capture, the simplest possible assumption is that $(T_1 - T_0)$ has a perfectly definite value, independent of T_0: there is conversion of a definite amount of kinetic energy into rest-mass (or vice versa), whatever the velocity of the alpha-particle may be. This may be tested by varying T_0; it may also be tested to some extent by observing protons ejected in various directions (relatively to the initial direction of the alpha-particles) since although the sum of T_p and T_r (which is T_1) should be the same for all of these protons those two quantities individually should vary, and T_p in particular should depend in a definite manner on the direction of the protons. Yet in nearly all such tests, the target is so thick that the alpha-particles impinging on various nuclei have very various speeds. How then shall we know which speed of proton to associate with which speed of alpha-particle, which value of T_p belongs with which of T_0? One naturally begins by assuming that the fastest of the primary particles produce the fastest of the protons. But plausible as this assumption seems at first, there are several cases known in which it is not true: cases in which a definite group of protons is evoked by alpha-particles of a definite interval of speeds, and neither faster nor slower particles are capable of producing them.

This phenomenon of "resonance," as it is called,[30] was first observed by Pose in the experiments on aluminium to which many pages were devoted in "Transmutation." It is evidently an important quality of nuclei, destined to be prominent in experiment and theory both.

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[30] There is a tendency to use the term "resonance" to express the mere existence of groups, irrespective of whether they are evoked by alpha-particles of narrowly limited speeds. This is to be deprecated.

This makes it desirable to consider at some length how resonance may be detected. There are the following ways:

(*a*) When the target is thick, one may vary the energy K_0 which the particles possess when they strike the target-face K_0 (usually by varying the density of gas between the target-face and the source of the alpha-particles) and plot the integral distribution-in-range curve for many different values of K_0. Let us suppose that there is a certain proton-group evoked only by alpha-particles having energy between K_a and K_b, the notation being so chosen that $K_b < K_a < K_0$. Then it will be found that as K_0 is lowered, the step and plateau which reveal the group will remain unaltered until K_0 drops below a certain critical value (to be identified with K_a) after which they will fade out.

(*b*) In the foregoing conditions, one may use a very thin ionization-chamber and plot instead of the integral distribution-in-range curve a curve of the sort in Fig. 10, or the sort described on page 129 of which the ordinate stands for the number of fragments producing more than a certain chosen amount of ionization in the chamber. There will be various peaks in the curve corresponding to various groups, and if any of these is produced by "resonance" it will at first remain unaltered and then gradually disappear as K_0 is lowered.

(*c*) When targets thin enough to be completely traversed by the alpha-particles are available, one may leave K_0 unchanged and increase the thickness t of the target. The energies of the impinging particles in a target then vary from K_0 down to a minimum value K_1 which depends on t. If curves of any of the foregoing kinds be plotted for various values of K_1, and if any of the groups is produced by resonance, then the step or the peak corresponding to this group may be absent when K_1 is high (i.e. with the thinnest target) and will then make its appearance when K_1 is lowered past a certain critical value (again to be identified with K_a).

(*d*) If the target is so very thin that the loss of speed suffered by the alpha-particles in going through is negligible, and K_1 is sensibly equal to K_0, then when K_0 is varied the groups should appear and disappear when it becomes equal to K_a and K_b, respectively.

(*e*) Without subjecting the fragments to any analysis, one may simply measure the total number thereof (or rather, the total number having ranges superior to some fixed minimum) as function of K_0. Suppose the target to be thick; then, if all the proton-groups are evoked by resonance, the curve should display a sequence of steps and plateaux; if in addition to such there are groups which are evoked by particles of any energy over a wide interval, the steps need not vanish, but the plateaux should slope upward and may be curved.

If the target is very thin (in the sense of the previous paragraph) the curve ought to show a peak for each group. Such curves, by the usage of page 139, may be styled "disintegration functions" (the term "excitation-function" is also used).

(*f*) Finally, when the target is thick the mere existence of sharp steps in the integral distribution-in-range curves, may be taken as a suggestion of resonance, since if a group were evoked by alpha-particles of a wide range of energies it would probably have a broad distribution of speeds. But this is not a very strong argument by itself.

Despite this great variety of ways of testing for resonance, the situation is still confusing and confused.

Aluminium has been the object of most of the tests, doubtless because it figured in Pose's discovery. He used methods (*a*) and (*c*) and found resonance distinctly and even vividly displayed by the 60-cm. and the 50-cm. group, and not at all by the 25-cm. group. Chadwick and Constable used (*a*) and (*b*), and concluded that there is resonance for six at least of their eight groups, the two members of a pair appearing and disappearing together. (The remaining pair was elicited by alpha-particles of a limited interval of energy-values extending from a lower limit K_b to the highest value of K_0 which they had available.) They also used (*e*) with a very thin sheet of aluminium (air-equivalent 0.8 mm.) and got a curve with two well-defined peaks. But Steudel also had recourse to method (*e*), and the curve he got swept smoothly upward; it is true that his target was notably thicker (air-equivalent 5.2 mm.) and yet one would not expect such a thickness to blot out the peaks if they exist. Harder yet to explain away is the evidence of M. de Broglie and Leprince-Ringuet, who made test (*d*) with sheets of aluminium of air-equivalent 2.5 mm., and observed all three of Pose's groups over a wide range of values of K_0.—As for the other elements: boron and fluorine and magnesium have all been tested by method (*a*), and there are strong indications of resonance for all three, strongest for fluorine. Nitrogen has been studied by Pollard with a modification of (*e*), and he finds that resonance is displayed by the 6-cm. group but not by the stronger and better-known group of longer range.

Evidently this is a field which yearns for further cultivation, with more powerful sources of transmuting particles to make possible the use of narrower and more homogeneous beams of these, narrower pencils of fragments and thinner strata of matter. The discovery of the capacity of protons to transmute has probably diverted from it some of the attention which otherwise it would by now have received, but the lost ground will doubtless be made up in the course of years, after the developments which that discovery has hastened shall have brought about the generation of streams of artificial alpha-particles more numerous by far than the natural ones. Meanwhile we must be content with scanty data and with fragmentary tests of the important question already mentioned: whether the energy transformed from rest-mass to vis viva or reversely—the quantity here denoted by $(T_1 - T_0)$, elsewhere commonly by Q, designated in German as the *Tönung* of the process—is a definite and characteristic quantity.

Certainly about resonance is essential to these tests; for if resonance exists, we have to correlate the energy of a group of protons with that particular energy of the alpha-particles which evokes the group; but if resonance does not occur, then probably the best we can do is to correlate the energy of the fastest of the ejected protons of a group with that of the fastest of the impinging particles—and if we make the latter guess when it ought not to be made, there will be trouble! Perhaps the most impressive evidence is that available for aluminium. Chadwick and Constable evaluated $(T_1 - T_0)$ for all of their eight groups: the six for which they demonstrated resonance, and the two which were evoked by alpha-particles of a limited interval of energies extending up to the highest which they used, which was 5.3 MEV. They find that $(T_1 - T_0)$ has a common value of $+2.3$ MEV for four of their groups—to wit, the longer-range members of their four pairs—and a common value of zero for the other four. Haxel plotted the integral distribution-in-range curves for the protons ejected by alpha-particles of several yet higher energies, running up almost to 9 MEV; he detected two groups; they did not display resonance, but he correlated the highest energy represented in each with the highest represented among the impinging particles, and he too found $+2.3$ MEV and zero for $(T_1 - T_0)$ in the two cases![31] Blackett analyzed eight examples of transmutation of nitrogen observed with the cloud-chamber (here he had the unique advantage of being able to observe the track of the residual nucleus and estimate its energy) and he reported for $(T_1 - T_0)$ a mean value of -1.27 MEV with a mean deviation of 0.42 from the mean. Future confirmation awaited this work also: Pollard, analyzing his integral distribution-in-range curves, made a computation of $(T_1 - T_0)$ for the 6-cm. group which exhibits resonance, and another for the 17.5-cm. group which does not, correlating in this latter case the energy of the fastest protons with that of the fastest alpha-particles; the results were -1.32 and -1.26 MEV.

[31] The precision of these values can hardly be estimated from what Chadwick and Constable say, but some idea of it can be gained from a graph in Haxel's article, *ZS. f. Phys.* **83**, p. 335 (1933), and *loc. cit.* footnote 27.

Such are the cases where there is the strongest proof for the twin doctrines that disintegration is by capture, and that a definite amount of energy is transformed between rest-mass and vis viva. The reader will have noticed in the latter case, that $(T_1 - T_0)$ appeared to be the same for a group which exhibits resonance and for another group which does not. This if certain may be taken to mean, that a particular group of protons—one may speak more graphically, and say: a particular proton in a particular level of the nitrogen nucleus—can be extracted by alpha-particles of a narrowly-limited range of energies between critical energy-values K_a and K_b, and can also be extracted by alpha-particles of *any* energy superior to a third critical value K_c which is greater than K_a and K_b. There is a good interpretation of this notion in the contemporary theory, which I reserve for the next article. It will also have been noticed that two different values of $(T_1 - T_0)$ were given for a single case, that of aluminium (there are also two for fluorine). This is to be taken as meaning that the residual nucleus may be left in either of two conditions, one of which may be the normal state, while the other must be an excited state (page 138). One then infers that the nucleus when left in the excited state will presently go over to the normal state, emitting a photon having an amount of energy equal to the difference between the two values of $(T_1 - T_0)$. It is very tempting to suppose that the gamma-rays known to be emitted from some elements during alpha-particle bombardments have this origin, but the measurements are not yet precise enough to prove this.[32]

In a case of disintegration-by-capture, the residual nucleus denoted by ${}_{Z+1}\mathrm{M}^{A+3}$ in equation (9) might or might not be exactly the same as the nucleus of the known chemical atom (if such there be) of atomic number $(Z + 1)$ and mass-number $(A + 3)$. Can this be tested by comparing the rest-mass of the former with the mass of the latter as measured by Aston or Bainbridge? Unfortunately nothing of value can be concluded unless the atoms ${}_{Z+1}\mathrm{M}^{A+3}$ and ${}_{Z}\mathrm{M}^{A}$ have both had their masses determined with an accuracy permitting them to appear in the Table on page 109; and on inspecting this table one finds (with some surprise) that this is true for only one of the known processes, *viz.* the transmutation of fluorine. Assuming disintegration to be with capture, the process would be the following:

$$ {}_{9}\mathrm{F}^{19} + {}_{2}\mathrm{He}^{4} = {}_{10}\mathrm{Ne}^{22} + {}_{1}\mathrm{H}^{1} + (T_1 - T_0) \tag{11} $$

Putting for $(T_1 - T_0)$ the value $+1.67$ MEV given by Chadwick and Constable, and for the rest-masses of the nuclei the values given in the

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[32] Heidenreich has analyzed the data for boron, and concludes that they permit of this interpretation. (*ZS. f. Phys.* **87**, 675–693; 1933.)

Table, we get 23.002 for the left-hand member and 23.0043 for the right-hand member. The agreement is within the uncertainty of the data; so also would it have been, had $(T_1 - T_0)$ been ignored. Its importance is perhaps enhanced by the fact that it is *ex post facto:* the mass of Ne^{22} was inaccurately known at the time of the experiments of Chadwick and Constable, and there was ostensibly a disagreement.

I repeat that it is not proved that transmutation occurs in every case by capture; and an isolated value of $(T_1 - T_0)$, such as one often sees computed from a single observation on a particular group evoked by a particular beam of alpha-particles, is not necessarily valid.

Transmutation with production of neutrons

This mode of transmutation has been proved, according to the Cavendish school and the Joliots, for the elements Li, Be, B, F, Ne, Na, Mg, and Al. The outstanding cases are those of beryllium and boron, with lithium and fluorine following after. Negative results have been reported by the Joliots for H, C, O, N, P and Ca, and there is no record of a positive result for He. Positive results have been reported for quite a number of elements both light and heavy by the Vienna school.

There is nothing which can properly be called a distribution-in-range curve for neutrons; but there is something which is potentially as useful—the integral distribution-in-range curve of the protons emanating from a thin layer of matter rich in hydrogen, placed between the source of the neutrons and the detector. If one can measure the speed of a proton recoiling in a known direction from the impact of a neutron, one can deduce the speed of the neutron; in particular, if one can measure the speeds of the protons projected straight forward by central impacts of the oncoming neutrons, one may consider their speeds as practically the same as those of the neutrons themselves.[33] It is thus a proper procedure to obtain the integral distribution-in-range curve of the protons projected forward, and convert it into a distribution-in-energy curve which is that of the protons and the neutrons alike. It has however not been an easy procedure, on account of the sparseness of the available sources of neutrons and hence of the streams of recoiling protons. Chadwick has published a solitary curve of this sort, relating to the neutrons from beryllium ejected by the alpha-particles of polonium; and Dunning has obtained a curve displaying good plateaux and steps, relating to the neutrons from beryllium ejected by yet faster alpha-particles.[34] Steps and plateaux, as heretofore, signify groups of protons and consequently groups of neutrons. Feather has

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[33] Cf. Part I, page 300.

[34] To be published in the article mentioned in Footnote 27, and by Dr. Dunning himself.

achieved the feat of taking and examining no fewer than 6900 cloud-chamber photographs in order to deduce the distribution-in-speed of neutron-streams from the tracks of the recoiling nuclei of various kinds of atoms. Most observers publish no curves, but give only verbal accounts in which they state the thickness (in air-equivalent) of the intercepting screens athwart the proton-beam, for which they observed a notable falling-off of the strength of that beam; or else they state what groups they believe in, inferring them presumably from observations of that type. This makes tiresome and unsatisfactory reading.

Much of recent research is meant to detect the very fastest neutrons emitted from a given element, for a reason which will presently be obvious if it is not already. Chadwick gives 3.35 MEV for the energy of the fastest neutrons ejected from boron by polonium alpha-particles, and 12 MEV for those similarly ejected by beryllium, while Dunning gives 14.3 MEV for those which beryllium emits when bombarded by the somewhat faster alpha-particles from radon.

Curves called "disintegration-functions," or more commonly "excitation-functions," have been plotted several times for the neutrons from beryllium and once at least for those from boron. One must realize an important distinction between them and the curves obtained when the fragments are alpha-particles or protons, as in Figs. 16 and 17. When the fragments are charged particles, it is practically certain that *all* of them which reach the detector at all are duly detected. When the fragments are neutrons it is certain that the only ones detected are those which strike protons (or other nuclei) hard enough and squarely enough to give them a considerable amount of energy and enable them to produce a good many ions in the ionization-chamber; and it is equally certain that those constitute but a small fraction of the total number of neutrons, most of which go through the expansion-chamber unperceived. Would that this were at least a *constant* fraction! we could then rely on the shape of the so-called excitation-curve, while realizing that all its ordinates must be multiplied by some unknown but constant factor. But we must not suppose even this; it is practically certain that the factor varies with the speed of the neutrons, and hence in all probability with the speed of the primary alpha-particles; and hence the so-called excitation-curve must be distorted from the true curve of number-of-atoms transmuted *versus* energy-of-alpha-particles. (Also the distribution-in-range curves must be distorted.)

With these severe limitations in mind, one may consider the published excitation-functions. The most striking are those obtained with very thin films of beryllium, one by Chadwick and one by Bernardini, which agree in showing a rather sudden rise of the curve from the horizontal axis, then a peak, then a valley and then a sweeping rise. It is hardly likely that the peak and the valley are entirely due to distortion of a truly smoothly-rising curve by the aforesaid agency; and the argument of paragraph (*e*) of page 149 leads us to infer a group of neutrons displaying resonance, in addition to other neutrons for which perhaps there is no resonance. Curves obtained with thick targets of beryllium or of boron have conspicuous steps, carrying the same implication. Those for boron (Chadwick and the Joliots) and some of those for beryllium (Rasetti, Bernardini) suggest but a single group, but there are other curves for beryllium suggesting two (in recent work of Chadwick's) and even four (Kirsch and Slonek). Thus, although the first four tests of resonance which I listed above (page 149) have as yet remained untried for emission of neutrons, the fifth has given some pretty convincing evidence in its favor.

It is always assumed that transmutation with emission of a neutron is a case of disintegration-by-capture, though no one has proof of this yet. The imagined process may be symbolized thus:

$$_Z\mathrm{M}^A + {}_2\mathrm{He}^4 + T_0 = {}_{Z+2}\mathrm{N}^{A+3} + {}_0n^1 + T_1 \qquad (12)$$

Such equations as this are used for evaluating the rest-mass of the neutron, it being assumed that the rest-mass of the residual nucleus $_{Z+2}\mathrm{N}^{A+3}$ is identical with that of the nucleus of the atom of mass-number $(A + 3)$ and atomic number $(Z + 2)$. One encounters at once the difficulty that there are neutrons of a wide range of speeds, and consequently a wide range of values of T_1. It is necessary to assume that the slower neutrons leave behind them a nucleus in an excited state (page 138) and that only the very fastest leave behind them the normal nucleus which is to be identified with that of the isotope $(A + 3)$ of the element $(Z + 2)$. Doing this, Chadwick got consistent values for the mass of the neutron from the observations on boron and on lithium, assuming the nucleus M of equation (12) to be that of B^{11} and that of Li^7 respectively.[35] To obtain a consistent value from the neutrons of beryllium, one would have to observe some at least having an energy as great as 12 MEV (when $T_0 = 5.3$ MEV). Those observed in the earlier work on beryllium were all much too slow. One of the driving motives of recent research has been the desire of finding at least a few of adequate energy; and it appears that this desire has at last been fulfilled.

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[35] Were we to assume B^{10} and Li^6, the nucleus N would correspond to an isotope as yet unknown; this is a powerful but not an absolutely imperative argument against these choices. There is also the question of whether, if resonance occurs, the right correlation is being made between values of T_1 and values of T_0 (page 151).—The equation for the transmutation of boron has been worked out in Part I., pp. 323–324.

To guess at the total number of neutrons emitted (say) from beryllium it is necessary to know the excitation-curve and to make an estimate of the factor aforesaid. I confine myself to quoting from Chadwick: "The greatest effect is given by beryllium, where the yield is probably about 30 neutrons for every million alpha-particles of polonium which fall on a thick layer."

Transmutation with production of positive electrons

This mode of transmutation, as I mentioned earlier, has been observed by the Joliots with Be, B and Al, the primary corpuscles being polonium alpha-particles. Nothing has yet been published about distribution-in-range or disintegration-function. Positive electrons of energy as high as 3.1 MEV have been observed proceeding from aluminium.

Aluminium thus affords a case of an atom which under alpha-particle bombardment may emit from its nucleus a particle of any of three kinds: a proton, a neutron, a positive electron. It has been suggested by Joliot that there is actually only one process, in which a proton emerges either intact, or else split into a neutron and a positive electron which are its hypothetical components. If this can be verified it will have important bearings on various fundamental questions, including that of the mass of the neutron.[36] Boron also emits particles of all three kinds, but here the situation is complicated by the possibility that not all of the three proceed from the same isotope.

TRANSMUTATION BY NEUTRONS

Transmutation by neutrons has been observed only with the Wilson chamber, and therefore rarely: there are a few scores of recorded cases, the fruit of twenty or thirty thousand separate photographs taken some by Feather at the Cavendish, some by Harkins and his colleagues at Chicago. What is observed is a pair of tracks diverging from a point in the midst of the gas contained in the chamber; it is inferred that the (invisible) path of a neutron extends from the neutron-source to the point of the divergence, and that the observed tracks are those of two fragments of a nucleus which that particle has struck. "Fragment" must be taken in the generalized sense of page 117: the substance of the neutron may be comprised in either or both of the two. Each case must be separately analyzed, taking into account the directions and the ranges of the fragments (it is here that the question of the range-*vs*-energy relations of massive nuclei, footnote 20, becomes crucial). It is possible to infer that in many cases the neutron is ab-

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[36] See the reference in Footnote 27.

sorbed into the fragments—"disintegration with capture"—and even to estimate $(T_1 - T_0)$, which turns out to be usually if not always negative. There are some difficulties here, since in certain cases the process which is observed seems to be the converse of one of the well-known processes of generating neutrons, and yet $(T_1 - T_0)$ does not appear to have values equal in magnitude and opposite in sign for the two. The most startling feature of transmutation by neutrons is, that it occurs with nuclei which seem to be immune to other transmuting agents, notably carbon and oxygen. Other elements with which it occurs are nitrogen, fluorine, neon, chlorine and argon.

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