Contemporary Advances in Physics, XXII

Transmutation

By KARL K. DARROW

In this paper are described experiments made at the Cavendish Laboratory, in Vienna, in Chicago and elsewhere during the last fifteen years in which atom nuclei have been disrupted by swiftly moving alpha particles ejected by radioactive materials. Whether an atom is an atom of gold, or of tin, or of praesodymium, or one of some other of the ninety-two varieties is determined solely by the magnitude of its nuclear charge.

When the disruption of atom nuclei occurs spontaneously, as it does among atoms of the radioactive elements, the fragments are nuclei of charge different from that of the exploded atom. When disruption is brought about by design, as it is in the experiments described in this article, we have again the disappearance of atoms of one species and the appearance of atoms of other species. The cases differ in that in the first the action goes on without let or hindrance, while in the second it is, to a certain extent, under the control of the experimenter. The experimenter may, if he chooses, congratulate himself on having solved the age old problem of the transmutation of elements. However, transmutation as such is not the object of these investigations. If it were their success would have to be rated as altogether negligible, for the quantities of material transmuted are much less than can be detected chemically.

The real object of the work, as is made abundantly clear, has been to verify and to extend our knowledge of the constitution of the nucleus. This is a subject about which a great deal is yet to be learned, but one on which the physicist has already many strong convictions based on a considerable array of interrelated and consistent data. The various conclusions regarding the constitution of atom nuclei which had been reached before any of these experiments on artificial disintegration were made, are discussed. The results of the investigations described confirm and extend our knowledge of the constitution of the nucleus.

IT is often said that the conversion of the elements into each other has been the dream of the human race for many centuries, nay even for millennia. In special and practical cases, this is probably true; I suppose that from the dawn of history most men possessed of stores of lead or silver have tantalized themselves by dreaming of these being changed to gold. But in the general sense it must be false. One cannot aspire to transform element into element, if one does not know what elements are; and no one had such knowledge centuries ago. Surely many of the chemical reactions which we consider commonplace, many of the compounds old and new which the modern chemist makes in his routine, would have seemed to ancient or to mediæval no less wonderful than any "transmutation" which he could possibly imagine. Could the Florentine or the Greek have been much more amazed by a change of silver into copper, than by the synthesis of a dye out of tar or coal, the growth of a diamond out of black carbon in a furnace?

It seems unlikely; for the very special wonderment and admiration, which the first-named change would evoke from a scientist of today were it achieved before him, would arise out of a wisdom denied alike to Greek and Florentine. Only the modern can know how much it would differ, in what particular way it would transcend all that has gone before.

For his power of appreciation, this modern onlooker would have two sciences to thank. These are the chemistry of the nineteenth and the eighteenth century, with its uncounted and uncountable attempts to analyze and synthetize and convert and transform, which led to the eventual conclusion that underneath the endless and changeable variety of visible matter there are certain substances which can neither be synthetized nor analyzed nor converted one into another; and the physics of the twentieth, which penetrated deep into the atoms of these unalterable substances, and there discovered the recondite and all-but-unassailable part, in which the character of each element is conserved. The former proved that all known chemical changes are made by combining these atoms or tearing them apart; the latter showed that what happens in every such event may be imagined as a rearrangement of flocks of electrons, which form the outer part of every atom. But chemistry further proved that such a change as that of silver to copper, or of mercury to gold, must of necessity involve something far more radical—something which the physics of alpha-particles and X-rays eventually made clear: in the atom there is an innermost *nucleus*, the centre of attraction whereby the electron-flocks are held together: this it is which must be reached and altered, if one element is to be transformed into another.

This statement, being as it is a description of the geography of the atom—perhaps I should say, a description of its astronomy, for these ultimate particles of matter are to be likened to a solar system rather than the earth—requires to be proved by exploration. The explorers sent out for this purpose are alpha-particles—corpuscles which are recognizable as such, for if they strike against a fluorescent screen each makes its separate luminous splash. Less than 10^{-12} of a centimeter in diameter, they are small enough to penetrate the electron-flocks of the atoms, which are spread over spaces tens of thousands of times as wide. The electrons near which they pass deviate them but little, being of less than one seven-thousandth their mass. Endowed with energy which may be as great as an electron could acquire from a potential-rise of *eight million* volts, they are able to approach the positive portions of the atomic structure though positively charged themselves. They are, in fact, extremely well fitted for the task of exploration which in 1911 Rutherford imposed upon them, and of which they reported to him that in the atom there is a massive particle positively charged, like themselves less than 10^{-12} centimeter in diameter. They could not perceive the electrons which surround this "nucleus," bearing charges of which the sum compensates its own; but other evidence makes us secure of the existence of this flock, and of the general theorem that *the atom of the Nth element of the periodic table consists of N electrons surrounding a nucleus of the tiny dimensions aforesaid, having a charge* $+ Ne$ *and a mass almost the same as the entire mass of the atom.*

This last, then, is the entity which anyone must attack who wishes to transmute the atom. It takes no part (as I remarked above) in chemical phenomena, in the emission of light or of X-rays, in the electrical effects which atoms can achieve when they lose charge and so become ions. This for the wouldbe transmuter is a fact of serious import; for if the nucleus has no influence on these, no more have they on it. Radioactivity, indeed, is a quality of nuclei—radioactivity *is* transmutation, natural and spontaneous; and it is not affected by anything chemical or electrical, by any temperature or any illumination which has ever been applied to a self-transmuting substance. These kernels of the atoms are well sheltered and highly resistent; they seem as oblivious of the world around them, as the interior of the earth is unconscious of the life upon its surface.

But the properties of the alpha-particle which enable it to penetrate to the neighborhood of the nucleus—extreme minuteness, high momentum, enormous store of concentrated energy—may they not also qualify it to impinge directly on the atom-kernel, to invade the nucleus and disrupt it, to shatter it if it be shatterable at all? We may be sure that the nuclei of atoms, hydrogen perhaps excepted, are complex. They cannot be the ultimate and irreducible particles of matter; for radioactivity proves that some of them disintegrate of themselves into smaller and lighter bits, while as for the rest, the facts that the charges of all are multiples of a common charge and the masses of all are nearly multiples of a common mass must surely be taken as meaning that all of them are structures built of electrons and protons. In principle, therefore, they must be breakable, if only they can be struck with sufficient force by hammers of suitable size. Now of all known vehicles of available force, alpha-particles best combine the qualities of smallness and great energy, and therefore seem the best adapted to the task.

Such must have been the ideas of Rutherford; it may be presumed that he was meditating them during the war, since in the first year thereafter he put them to the test, and so became the first to achieve transmutation beyond the shadow of a doubt. There was of course no certainty beforehand that he would succeed. On the contrary there were apparently grave grounds for pessimism. We must take note of these; the proof that they were not justified is not the least important part of Rutherford's achievement.

First, even the energy of the alpha-particles might have been too small to injure a nucleus. Indeed, for many kinds of atom-kernels it *is* too small, to judge from the work of Rutherford's school at the Cavendish Laboratory; and for the rest there is not much margin to spare; from the work of that school it appears that if the fastest alpha-particles moved with a speed as great as six-tenths as their actual speed, and no greater, the effect would never have been discovered.

Second, there was reason to fear that the nuclei are too small to be struck except by the rarest of chances, too rare a chance to be serviceable. The observations on deflected alpha-rays had proved that the kernels of atoms are less than 10^{-12} cm. across, the impinging particles no greater: a very thin missile and a very tiny target! Had they been a few orders of magnitude smaller than this maximum limit, "square hits" would have been too few to notice. As a matter of fact, in the first of the successful experiments, the proportion of these was about one to every million of alpha-particles traversing the layer of nitrogen gas which Rutherford was trying to transmute.

Third, the fragments of the broken nuclei might not have been observable. Delicate as are the methods of chemical analysis, they are not fine enough to detect alterations so infrequent as these were expected to be, and were actually found to be. Alpha-particles themselves are detected in three ways—by the luminous splashes or "scintillations" which they cause when they impinge on fluorescent screens; by the trails of water-droplets which they leave behind them when they dash through moisture-saturated air which is suddenly cooled just before or just after their passage; and by the electrical discharges (small-scale sparks) which they touch off when they pass through air in the neighborhood of a charged and sharply-pointed needle. The two last of these are due to ions which the particle forms by detaching electrons from molecules of the gas. The slower the particles, the fewer the ions; the less conspicuous are these effects and the more likely to be missed. As for the scintillations we know but little of their mechanism, but we do know that the slower the particles, the fainter the flashes. Thus it is altogether reasonable to suppose that when nuclei are broken into fragments, the fragments may be moving too slowly to be noticed by any of these three procedures! (One might even suspect that the pieces of a fractured nucleus may not have the power of forming ions or evoking scintillations, however fast they move; but this would be too pessimistic; there is every reason to suppose that they are charged corpuscles, therefore possessed of the same powers as alpha-rays.)

In all likelihood, many atom-kernels are disrupted and their fate goes unperceived, because the "products of disintegration" move too slowly; but sometimes these are fast enough to be detected in any of the three aforesaid ways, as we shall see. There is, however, yet another peril. Consider the alpha-particles which pass close to nuclei without disrupting them. They are deflected, but the nuclei themselves suffer a reaction which sets them into motion. If these belong to elements of atomic weight greater than 30, or let us say 40 to err on the safe side, their masses are so much larger than those of the alpha-corpuscle that the speed they acquire is negligible. But if they belong to one or another of the half-dozen lightest elements, they may acquire a speed so great that of themselves they can make ions in a gas or scintillations on a screen. If an alpha-particle, being itself a helium nucleus, flies straight against the kernel of a helium atom but does not fracture it, then obviously the struck nucleus must take up the entire speed of the striking corpuscle. If it is a carbon or an oxygen nucleus which is thus squarely struck, without being broken, its final speed must be one half or four tenths that of the alpha-particle. And if it is a hydrogen nucleus or proton which is the victim of a square and central impact, it must go off with no less than *sixteen-tenths* of the speed of the impinger. Incidentally, the latter is slowed down to compensate for the kinetic energy acquired by the kernel which it strikes.

The dangerous consequence is, that in a stratum of matter of low atomic weight which is bombarded by alpha-rays, there must be intact but rapidly-moving kernels which may be confused, which indeed one can hardly help confusing, with the expected products of disintegration. Moreover, even in a stratum of an element of higher weight, a metal film or a tube of gas, there may be hydrogen enough to provide so many low-mass targets for the alpha-rays, that the region is filled with fast-flying protons which are not tokens of disruption. In every case where corpuscles are observed which are thought to be parts of fractured nuclei, it must be proved that they are not of this kind, nor yet are scattered alpha-particles.

Now as an index of the initial speed of an alpha-particle, people generally take its "range." The trail of water-droplets which the particle leaves along its path through suddenly-cooled moist air comes to a sudden end (Figs. 10, 11); the length of the trail, measured to its end from the point where the particle entered the air, is its range in the air, and depends in a known way (known by experiment) on the speed which the particle had at the moment of entry. Or the range may be determined by moving backward a fluorescent screen placed opposite the point of entry of the corpuscles; the scintillations are at first undiminished in number as the screen recedes, but eventually they cease, and cease quite suddenly; the distance to the point of their cessation is the range. In air at normal pressure and 15° temperature,[1] the range of the fastest known alpha-particles (apart from a few very scanty classes) fresh from the source is about 8.6 cm. It has been determined for a number of other gases as well, and for any gas it varies inversely as the density.

It follows then that if the fluorescent screen is placed at a distance from the source of alpha-particles so great that it lies beyond their range in the substance intervening, whatever scintillations may appear upon it are not due to alpha-rays. But it does not yet follow that the screen is beyond the reach of protons speeded up in the way I just described. To find out about this, it is necessary to know the relation between the speeds of protons and their ranges. Now the cause of the slowing-down and stopping of charged corpuscles, protons and alpha-particles alike, is this: as they flash through strata of matter, they tear electrons loose from the atoms which they pass, and spend their energy in doing so. The range of either sort of corpuscle is substantially the distance through which it can fly, before the major part of its initial energy is dissipated in this way. An alpha-particle has twice the charge of a proton, therefore extracts electrons oftener from the atoms near its course, therefore loses energy more quickly. If particles of the two kinds have equal range, the former must initially have had the greater energy. A theoretical analysis (achieved by Bohr and Darwin) shows that the ratio is that of the squares of the charges—four to one. But since the ratio of the masses is likewise four to one, the speeds are equal. Alpha-particles and protons of equal initial speed have (approximately) equal range. Now as I stated above, hydrogen nuclei struck centrally by alpha-particles acquire a speed 1.6 times as great as these, therefore, a range equal to that of alpha-particles moving 1.6 times as fast as those which made the impacts. It is a fact of experience that the range of alpha-particles varies about (not exactly) as the cube of their speed. If, therefore, hydrogen is bombarded by rays of a stated range *R*, hydrogen nuclei which suffer central impacts will be projected forward with ranges amounting to

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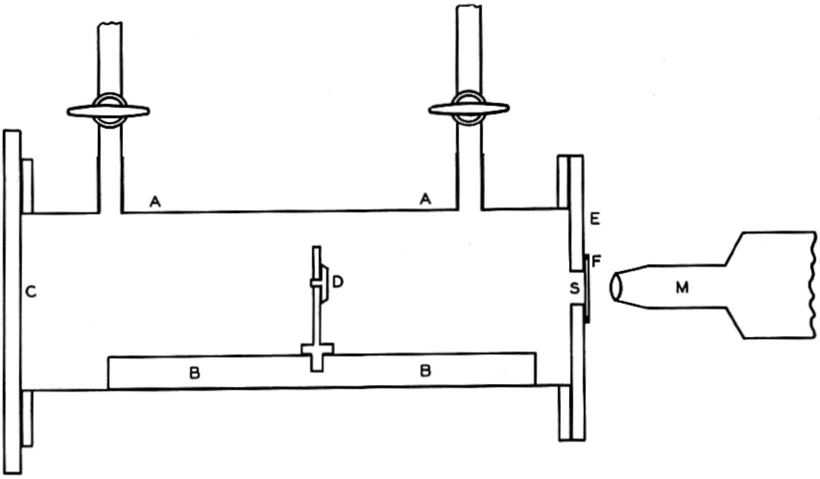
[1] This is Rutherford's convention. Certain physicists specify the range in air at normal pressure and zero temperature, which stands to the other in the inverse ratio of the densities of the air, about 273 : 288. In later pages I shall occasionally adopt this usage.

$(1.6)^3R$, or about 4.1 times R. And if (for instance) air at normal temperature and pressure is bombarded by the alpha-particles of radium C' which in this gas have a range of seven centimeters, and scintillations are observed on a fluorescent screen beyond, the observer must reckon with the chance that they may be due to the nuclei of hydrogen molecules mixed with the air, so long as the distance to the screen is less than 4.1 times seven, or say thirty, centimeters.

On the principle that the best way to deal with a possible source of trouble is to examine it minutely, Rutherford prepared for his attempt at transmutation by a study of the nuclei which are struck and which "recoil," as we say, when alpha-particles are fired into hydrogen. His pupil Marsden had begun on such a study in 1914, and had observed that scintillations appeared on a screen set up far beyond the ultimate reach of the alpha-rays—more than a hundred centimeters, inasmuch as in hydrogen the range of either kind of charged corpuscle is about four times as great as in air. Resuming the research in 1919 (one never needs to ask why things begun in 1914 should have lain so long uncontinued) Rutherford counted the scintillations and plotted their number for what, in effect, were various distances of the screen from the source. I must pause to say that in practice one does not draw the screen back so as to interpose thicker and thicker layers of gas between

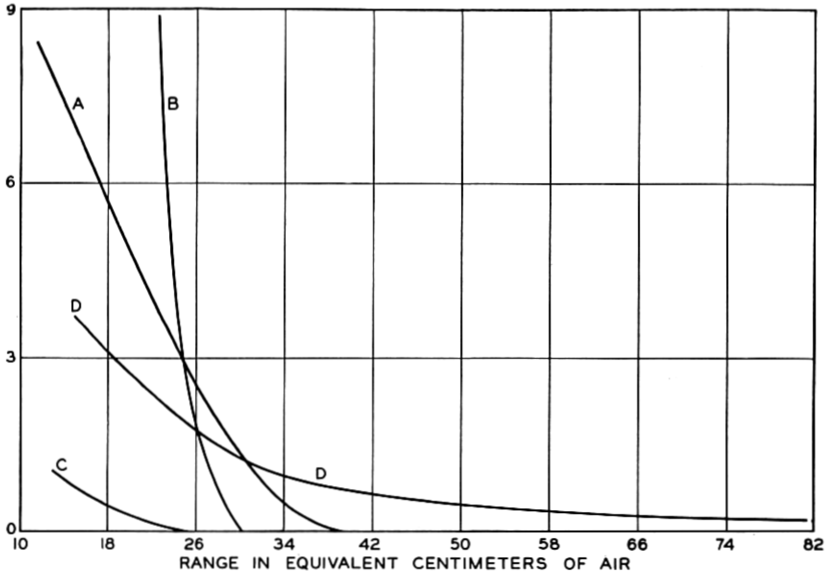


* Fig. 1—Rutherford's apparatus for detecting transmutation of gases by the scintillation method. Source of alpha-particles at D; gas in the tube; fluorescent screen (transparent) at S; microscope at M.

* From Sir Ernest Rutherford, James Chadwick and C. D. Ellis, "Radiations from Radioactive Substances," 1930. By permission of The Macmillan Company, publishers.

and the point of entry of the alpha-particles; instead one leaves it fixed and varies the pressure of the gas, or else interposes a series of thin foils of aluminium or some other metal or of mica, each of which slows down the particles to the same extent (in the technical language, has the same "stopping-power") as a known thickness of air. (For instance, a thickness of mica of weight 1.43 mg. per square cm. is equivalent in stopping-power to 1 cm. of air at 15° C. and 760 mm. Hg.) In curves of the sort in which we shall be interested, number-of-scintillations is usually plotted along the vertical axis, number-of-centimeters-of-air along the horizontal; but in general some other substance did duty for the air, and its thicknesses were translated into equivalent thicknesses of this standard gas (at normal temperature and pressure) before the curve was drawn.

Curves of this sort appear in Fig. 2. All of them were obtained with gases bombarded by alpha-particles of seven-centimeter range. Notice first the curve marked B: it corresponds to hydrogen, mixed with carbon dioxide; and it testifies that the scintillations did not cease until the screen was shielded by the equivalent (in mica) of thirty centimeters of air, the amount computed for the range of hydrogen nuclei



* Fig. 2—Number of protons falling on fluorescent screen, plotted as function of thickness of air which they have traversed since leaving the disrupted atoms.

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* From Sir Ernest Rutherford, James Chadwick and C. D. Ellis, "Radiations from Radioactive Substances," 1930. By permission of The Macmillan Company, publishers.

struck centrally by alpha-corpuscles as fast as these. (That many of the nuclei causing scintillations did not have so great a range is easily accounted for; it is due to the fact that most of the impacts are sensibly "off-centre," the struck particles flying off obliquely with less energy than they would have derived from a "square hit.") But at thirty centimeters of "air-equivalent," they cease entirely; this sustains us assuming that if with any other gas or any solid there are scintillations when the screen is so much shielded, they cannot be due to admixtures of hydrogen.

Curve *C* was obtained with oxygen; what there is of it is ascribed to commingled hydrogen; in any case, it does not extend beyond the critical point at which, were there any flashes still to be seen, they could safely be attributed to something else.

Curve *A* is more sensational: very definitely it extends beyond the critical length; very definitely there are corpuscles able to make their way through deeper strata of matter than either the primary alpha-particles or such nuclei of stray hydrogen atoms (so both theory and experiment assure us) as these might find to strike. This curve was obtained with air. Since with pure oxygen there was no sign of such extraordinary corpuscles, it is to be presumed that they were due to the other of the major gases of the air—an inference which the study of pure nitrogen made sure.

The most astonishing of all the curves is *D*. It stretches far beyond the critical point; flashes appeared on the screen when even as much as the equivalent of ninety centimeters of air lay between it and the substance which the alpha-rays were striking, which was aluminium in the form of a thin leaf. Thus, when foil of aluminium is subject to the impacts of these rays, it throws out corpuscles three times as penetrative as the very fastest which a critic might possibly discredit by ascribing to occluded hydrogen.

Are these, then, fragments of disrupted nuclei of aluminium or nitrogen? and are they protons?

In principle the second question is answerable by itself; it is sufficient to deflect the corpuscles by electric and magnetic fields, and measure their deflections; the value of their charge-to-mass ratio (which if they are protons is about .00054 of the value for an electron) could then be computed, and incidentally their speed also, which itself would be well worth determining in a way more direct than by inference from the range. But though such measurements have many times been made on other kinds of particles, and the technique is very well developed, the application to those of this especial kind is difficult because they are so few. Say that the apparatus is so built that they fall on only a part of the screen; if a magnetic field is applied in the proper sense to the region which they traverse, the spot on which they fall moves sidewise; but the flashes are so infrequent that the shift is not obvious, and only by lengthy countings can one be sure that more of them appear in one place and less in another when the field is on than when it is off. Rutherford however managed to make countings enough to prove that the shift is of the order of magnitude to be expected, if the particles are protons having the speed inferred from their range; and incidentally that they are positively charged, something which has been taken for granted but which requires proof. It was with the long-range corpuscles expelled from aluminium, from phosphorus and from fluorine that he achieved these results.

The problem was then taken up by Stetter in Vienna; he tried the scheme developed to so high a pitch by Aston in his famous series of experiments on isotopes—a scheme of which I shall say only that although it involves both electric and magnetic fields, they are so arranged that corpuscles having a common value of charge-to-mass ratio are brought to a common focus irrespective of their speeds (so long as these are not dispersed over too wide an interval); therefore, by locating the focus, one may recognize the kind of corpuscle. In Fig. 3 appears a part of his apparatus: the source of alpha-particles at Q, the sheet of transmutable substance at S or S', and beneath it the system of long narrow parallel channels which Stetter arranged so that only a beam of corpuscles following almost perfectly parallel paths should enter the deflecting fields below.

Shifting from place to place the microscope with which he examined the screen beyond the deflecting fields, and counting the scintillations, Stetter found three foci which in the curve of Fig. 4 appear as three peaks (the ordinate being the number of flashes in unit time over a given area, the abscissa the distance of the midpoint of this area from a point taken as zero). From the positions of these foci on the screen it followed that the one on the right was due to corpuscles having the charge-to-mass ratio of protons; the one in the middle, to alpha-particles; the one on the left of which only a part appears, to corpuscles having a charge-to-mass ratio half as great as that of an alpha-particle. Two then are proof of alpha-rays deflected by the metal at S, some of which had lost one-half of their positive charge through picking up an electron somewhere in their careers; the third is evidence of protons, and strong evidence, for Stetter estimates the uncertainty of his measurement of charge-to-mass ratio as no greater than five per cent. The curve of Fig. 4 was got with aluminium as the metal which the alpha-rays bombarded. Curves were obtained in the same way with carbon, with boron and with iron in place of the aluminium, and each had a peak at the proper situation for protons.

It seems, then, that the particles *are* protons. They are of the same kind, whatever the substance they come from; though the speed which they have when expelled, and the plentifulness of the expulsions, varies notably from element to element. This suggests that they are constituents common to all elements, though the manner in which they are bound into the atomic structure differs from one to another. According to our knowledge of the astronomy of the atom, the nucleus is the only part where they can be. Moreover, though the masses of nuclei generally are not exactly integer multiples of the mass of the

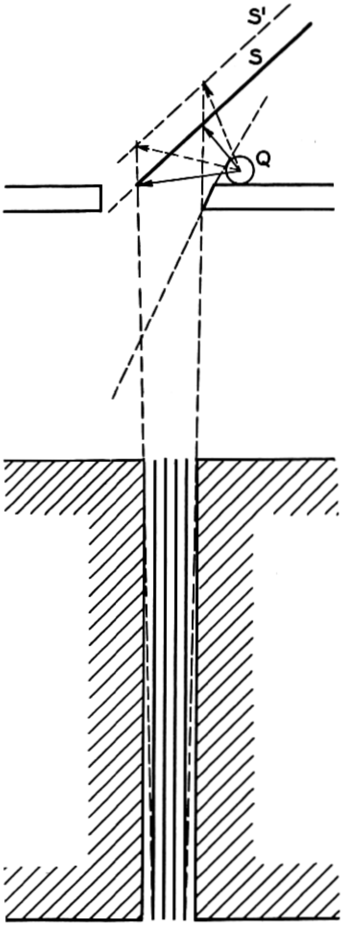

Fig. 3—Part of Stetter's apparatus for studying transmutation.

proton, this is so nearly the rule as to suggest very forcibly that the major part of every nucleus consists of protons. All this strengthens the belief that in witnessing these flashes of "long-range" particles one is witnessing the signs of transmutation.

The next step, then, consists in finding which of the elements may be transmutable. I repeat that for the present, a strict assessment of the evidence permits us to proclaim a transmutation only when there are corpuscles of greater range than either the primary alpha-particles, or hydrogen nuclei which suffer elastic impacts. The condition, however, is not quite so harsh as I have intimated. If hydrogen atoms be struck by alpha-particles, those and only those which are projected straight ahead have the full computed range; those which bounce off at an angle go less far; those which start off at 90° have no range at all which is to say, no elastic impact can send a nucleus off in the plane through the bombarded substance at right angles to the alpha-ray stream. Thus, if one stations the fluorescent screen somewhere in this plane, one may confidently count all of the scintillations as signs of transmutation, excepting such as may be due to primary alpha-particles deflected through 90° by kernels which they approach without disrupting them, or to hydrogen nuclei which after suffering elastic impacts got deflected. (The reader will have noticed in Fig. 3 that the angle between the paths of the α-particles to the metal foil and the paths of the protons from the foil is large, always more than 80°.)

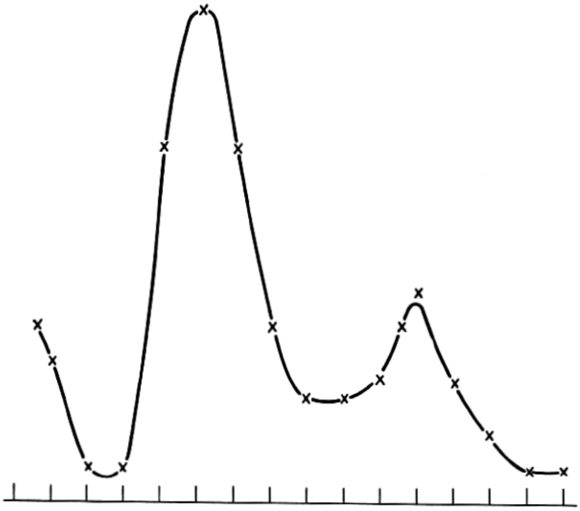

Fig. 4—Curve showing evidence that the particles emitted from aluminium bombarded by α-rays comprise protons and deflected alpha-particles (G. Stetter).

Evidently it was the first of these possible causes of confusion which Rutherford feared the most, for in setting up his screen in such a place, he shielded it by absorbers sufficient to stop the primary particles, and counted the flashes which appeared in spite of this obstruction. The datum therefore is a count of corpuscles having ranges greater than seven cm. With a few of the lightest elements, the critical range is somewhat lower; for an alpha-particle, when deflected through 90° by a close approach to a nucleus not many times more massive than itself, loses an appreciable part of its speed in the deflection.

The Cavendish school examined many elements—including all of the nineteen lightest, the first nineteen of the periodic table—in their quest for transmutation. Under the bombardment of seven-centimeter alpha-rays, most of these nineteen emitted corpuscles which satisfied their strict criterion. The first four (hydrogen, helium, lithium and beryllium) did not; neither did the sixth nor the eighth (carbon and oxygen); all of the others, beginning with boron the fifth, and ending with potassium the nineteenth, appeared transmutable. No element beyond potassium ejected corpuscles with a range great enough to exceed those of the two other kinds, which Rutherford and his school were so anxious to exclude.

One is never long satisfied with the assertion that a certain effect does occur in certain cases, does not occur in others. Invariably the questions follow: in the cases where it happens, how much does it happen? in the cases where it is not observed, what is the least amount of it which could have been observed?

As a rule it is much more difficult to answer these questions, than merely to establish that with given means of observation either the effect is found or it is not. The study of transmutation is no exception to this rule. No one has ever set up a screen which surrounded the bombarded substance on *every* side, and therefore no one has counted the corpuscles which go off in *all* directions, nor even in a moderately great fraction of all directions. Screens have been set up in various directions from the piece of matter suffering transmutation, and the data, far from encouraging us to assume that the protons are fired off at random, indicate instead that more of them go off at inclinations of less than 90° to the beam (prolonged in the forward direction) of the alpha-rays, than at inclinations more than 90°,—more go "forward" than "backward." The distribution-in-angle, however, requires much further research.

In answering the questions, Rutherford, Chadwick and Ellis say *inter alia* that when one million alpha-particles of seven-centimeter range are totally absorbed in nitrogen, some twenty of the rapid protons will probably emerge. This is the most efficacious degree of disruption which they claim. Aluminium follows in order of fragility, an equal bombardment producing eight of the fast-flying corpuscles instead of twenty. The least of the values given by the Cambridge school amounts to about one disruption per million alpha-particles; somewhat but not much smaller, I take it, is the least which they would deem observable, so that in their sense "immunity to transmutation" signifies something like this: when the substance is subjected to seven-centimeter alpha-rays, the number of protons coming forth with more-than-thirty-centimeter range is distinctly less than one per million thereof.

On the other hand, the physicists of the Vienna school have frequently maintained that transmutation is far less rare than those of the Cambridge school are willing to grant. Here, indeed, is one of the most famous controversies of modern physics. Vienna finds that most of the light elements, even carbon and oxygen, and even a metal so heavy as iron, yield scintillations, which are to be ascribed to protons ejected from nuclei; Cambridge holds to the list aforesaid. Where Cambridge admits scintillations, Vienna finds them several times more numerous. The contrast is accentuated by the fact that the Viennese scientists worked with alpha-particles of smaller energy than those at first employed by Rutherford, although the work of Pose, which I shall presently review, has destroyed what formerly seemed to be the natural assumption that the slower the alpha-corpuscles, the less must necessarily be their ability to transmute. The controversy was made peculiarly difficult to judge by the fact that for several years no one outside of these two schools essayed to enter the field. Eventually, however, several did; the researches of Bothe and Fränz, of Pose, and of Pawlowski, spoke for the lower efficiencies of transmutation believed in by Rutherford, rather than the higher ones accepted at Vienna. Many studies of scintillations, many comparisons of the scintillation method with the other methods, have resulted from this controversy, and will probably be regarded in the course of time as its enduring good. The latest announcements from Vienna indicate that the number of protons detected by the ionization methods is systematically less than the number of scintillations; and as these comparisons are still under way, I will leave the matter here, especially since the experiments which I am about to describe have superseded some of the earlier ones.

These new and striking experiments involve a more thoroughgoing study of such curves as appeared in Fig. 2: a study in which not merely the end-point of the curve is located, but the entire shape is considered, the conditions of the experiment being so fixed as to make this shape significant. The experiments are, in fact, made upon the distribution-in-range of the ejected protons. Strata of gas or films of solid are interposed in the path of these particles, and the number which get through various thicknesses of these obstructions is carefully measured. The "air-equivalent" of the obstructions is separately measured, and so one is able to plot a curve of which the abscissa *R* is range in air at conventional pressure and temperature (760 mm. Hg and 0° C., in the figures which I show next) while the ordinate is the number of corpuscles having ranges greater than *R*.

This newest and sensational work was done by Pose at Halle. I show in Fig. 5 his sketch of his apparatus. In the evacuated chamber above, the button under the letter *P* carries the radioactive source—a layer of polonium, a substance of which the alpha-rays have a range smaller than those of which I have been speaking, 3.72 cm. only in air

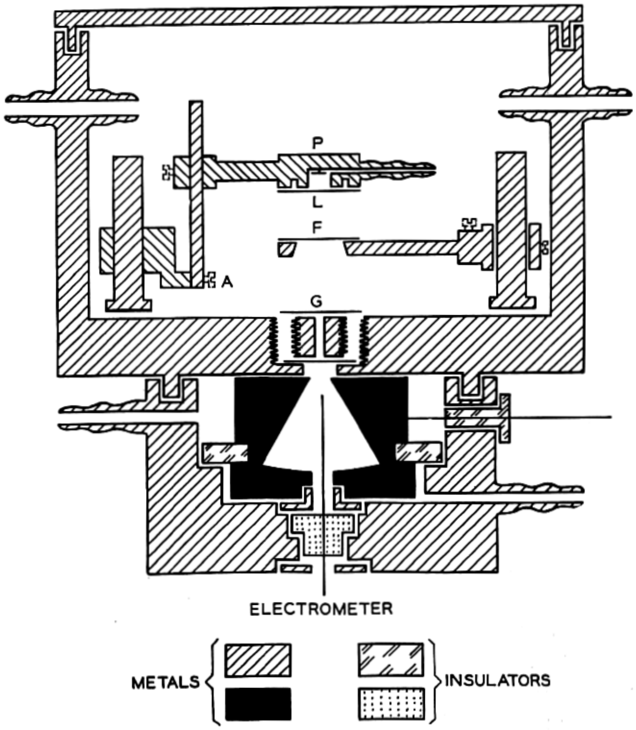

Fig. 5—Pose's apparatus for detecting transmutation of metals by an ionization method.

at 0° C. and atmospheric pressure.[2] The foil of aluminium destined to be transmuted stands either at L or at F. If at L, it receives the full impact of the unretarded alpha-particles. If it is placed at F, one or more foils of gold are located at L (one at least *must* be set there, so as to prevent "contamination" of the chamber by atoms of radioactive substances escaping from the layer of polonium and wandering around) and these reduce the energy of the alpha-particles before they strike the leaf of aluminium. At G are placed the tenuous sheets of mica which retard or stop the protons, enabling the observer to plot the aforesaid curve (and incidentally protecting the vacuum within the upper chamber against the gas without). Below is the device for counting the protons which have succeeded in passing the mica sheets.

This device for detecting protons is not a fluorescent screen, but a conical chamber filled with carbon dioxide, in which the corpuscles engender thousands of ions as they cross. Between the walls of the cone and the wire which runs part way along its axis, there is a voltage sufficient to draw ninety per cent of the negative ions to the one, of the positive ions to the other. An electrometer connected to the wire gives a kick whenever a corpuscle passes through; the deflection is a measure of the total charge borne to the wire by ions of one sign, therefore of the total number of these. The kicks are not overly frequent; in cases mentioned by Pose they amounted to thirty or thereabouts per hour. They are not all equal; on the contrary, they range from almost imperceptible deflections (corresponding to 5000 ions or less) to a maximum which indicates seventy thousand. They are not all due to protons, for some are observed when the conical chamber is closed on all sides; these are ascribed to alpha-rays emanating from radioactive atoms which happen to be in the gas of the chamber or in the walls thereof; they are counted in "blank" experiments, and a number equal to theirs is deducted from the total number observed when the protons from the aluminium are coming in. It appears from the data that all of the corpuscles which produce more than 25000 ions apiece are of this undesired type, while most of those which cause the smaller kicks of the electrometer do actually come from the metal foil which is suffering transmutation.

Every detail of the set of curves next following (Fig. 6) is worth examining. They are curves of the sort which I defined above, except that the ordinate is not the actual number of protons observed, but the quotient of this number by that of the alpha-particles expressed in

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[2] This is Pose's convention, to which I conform in the following pages; the range of alpha-rays from polonium is 3.92 cm. in air at 15° C. and atmospheric pressure; the other ranges mentioned in what follows should be increased in the same proportion if the reader wishes to hold to Rutherford's convention.

hundreds of millions—the number of protons received and detected in the conical chamber behind the absorption-foils of mica, per hundred million alpha-corpuscles impinging on the sheet of aluminium. This sheet was so thick that all of the impinging corpuscles were swallowed up in it. Thus, the uppermost of the curves relates to aluminium subjected to alpha-rays of all ranges from 3.72 centimeters down to nil; and the numbers attached to the others likewise stand for the *maximum* ranges represented among the particles as they approached the nuclei. By differentiating these curves one would get *distribution-in-range* curves for the protons. I will therefore refer to them, and to those of Figs. 2, 7 and 8, as "integral distribution-in-range curves."

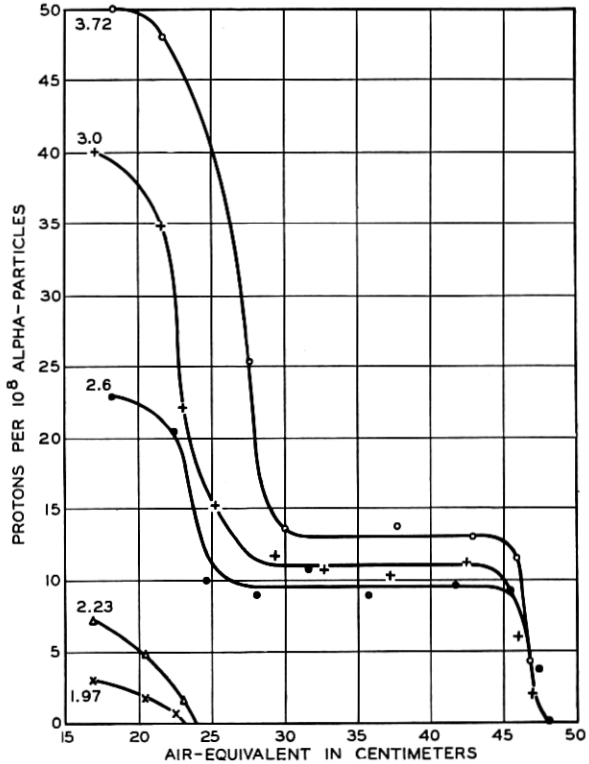

Fig. 6—Integral distribution-in-range curves for protons emitted from disrupted nuclei of aluminium atoms (H. Pose).

Ignoring for the moment the left-hand half of the diagram, consider the other. The two lowest of the curves do not reach it: hence, alpha-particles of 2.23-centimeter range or less do not have the power of expelling protons with 30-centimeter range or greater. The other three curves do enter it, and there is a very important feature of their trend: all are horizontal from 30 to 45, then all drop sharply to the axis at the same abscissa. Thus the piling-up of obstruction in the way of the protons does not stop them, so long as the air-equivalent is less than 45. But the adding of three further centimeters of air suffices to bar them all. It is as though the nuclei held protons in such a way, that if ejected at all they would automatically be ejected with velocities entailing ranges which lie within this narrow interval of 45 to 48; and alpha-particles acquired the power of setting off the mechanism by which these protons are ejected, when and only when their own range became as great as a critical value somewhere between 2.23 and 2.6.

Now travel back along the topmost curve into the left-hand half of the figure. The rise to the left of abscissa 30 suggests a second group of protons, having ranges slightly below this amount. But one notices, first, that the rise extends over an interval much wider than that of the steep sharp climbs at the right-hand ends of the curves; beginning at 30, it seems to be still going on at 18. This implies a broad distribution-in-range. One notices next that in the second curve, the corresponding rise begins at an abscissa somewhat smaller; in the third, at one which is smaller yet. Moreover, it is easy to draw a smooth curve through the starting-points of these three rises, which on being smoothly prolonged passes near to the points where the two remaining arcs in the lower left-hand corner ascend from the axis of abscissæ. All this suggests that in every one of these cases there are protons distributed over a wide interval of speeds, extending upward to a maximum which itself is greater, the higher the energy of the impinging alpha-rays.

Turn now to Fig. 7. Here we have five curves corresponding to five foils of aluminium, one face of each being exposed to alpha-rays of polonium with their full energy and undiminished range of 3.72 cm. The bottom curve relates to the thinnest foil, equivalent in thickness to 0.15 cm. of air. Actually, the distance between its two sides was the equivalent of 1 mm. of air, but many of the alpha-particles traversed it obliquely, so that the atoms of the foil were exposed to the blows of particles varying in range from 3.72 to 3.57 cm.; to this interval of ranges, therefore, the lowest curve refers. Similarly, the second curve from the bottom relates to a foil of air-equivalent 0.62 cm. for the most oblique of the particles, therefore to atoms bombarded by alpha-rays of ranges varying from 3.72 to 3.1; the other three, to sheets with the air-equivalents marked beside them. The difference between the second curve and the first is the effect of alpha-rays having ranges between 3.57 and 3.1. Thus, in going from one curve of Fig. 7 to the next above it, one adds the effect of *slower* alpha-particles; whereas in Fig. 6, in going from one curve to the next above it, one adds the effect of *faster* projectiles.

The contrast between the lowest and the next-to-lowest curve of Fig. 7 is indeed amazing. So long as the impinging corpuscles are moving

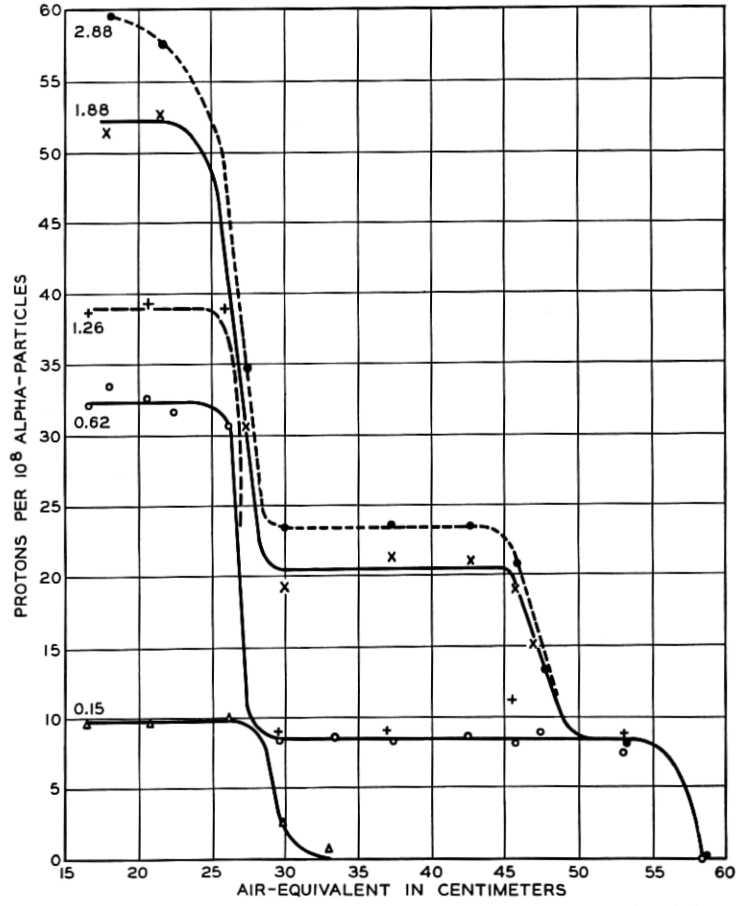

Fig. 7—More integral distribution-in-range curves for protons emitted from disrupted nuclei of aluminium atoms (H. Pose).

so fast that they still have 3.57 cm. of their range ahead of them, the protons which they eject are comparatively slow, with a maximum range of 30 or thereabouts; but *when they are slowed down* to some critical speed corresponding to some range between 3.57 and 3.1, *they acquire the power of dislodging extremely fast protons.* Here we have, in fact, another "group" in the sense of the previous pages: protons which are released, if they are released at all, with a speed corresponding to a range in the neighborhood of 57.5 centimeters. The upper curves coalesce with this second-lowest over the descending arc at the right-hand end; the addition of slower alpha-rays to the bombarding stream does not increase the rate at which the members of this group are liberated; the power of dislodging them is confined to particles of a narrow interval of speeds.

The second-lowest and the middle curve are indistinguishable over the right-hand half of Fig. 7. In going from them to the second-highest curve, however, we meet another significant contrast. Another "group" of protons makes its appearance: its distinctive range is close to 47, it is evidently the very one[3] which was detected by scrutiny of Fig. 6. As alpha-particles slow down, they reach a critical speed at which they acquire the power of releasing this group. The corresponding critical range must be lower than $(3.72 - 1.26)$ or 2.46 cm., for otherwise the rise near 47 would appear on the middle curve. It must be higher than $(3.72 - 1.88)$ or 1.84 cm., or the rise would not appear on the second-highest curve.

Evidently there are both an upper and a lower critical range, R_2 and R_1, such that alpha-particles can cause the ejection of the protons of this group if and only if their ranges lie between R_1 and R_2. The curves of Fig. 7 "bracket" the upper limit of this interval, fixing R_2 between 1.84 and 2.46. Likewise the curves of Fig. 6 bracket the lower limit, locating it between 2.23 and 2.6. The interval must therefore lie between 2.23 and 2.46. By a more minute analysis of the curves, Pose locates it in the neighborhood of 2.42.

From the left-hand parts of the curves of Fig. 7, one makes the same deductions as from those of Fig. 6. Whatever their speed (within the scope of these experiments) alpha-particles possess the power of liberating protons with a wide distribution in range. The breadth of this distribution, i.e. the difference between the longest and the shortest ranges comprised within it, decreases with decreasing speed of the particles; so also does the longest range.

It appears, therefore, that there are two mechanisms of disruption. One seems to be controlled by the internal structure of the nucleus; the alpha-particle serves only to touch it off; it can be touched off, or actuated (to use a more dignified word) only by alpha-particles of a narrowly-delimited range of speeds; once it is actuated, it ejects a proton with a velocity strictly defined. The other accords more closely

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[3] The group of range 57 cm. does not appear on the uppermost curve of Fig. 6, but Dr. Pose writes me that it was actually apparent in the data, and that he deducted it in order to make obvious the resemblance which exists between the right-hand ends of this and the next two curves when that group is disregarded.

with our idea of a smash. It can be achieved by alpha-particles of any speed, above (presumably) some minimum which in these experiments was not attained; the energy of the ejected proton increases with the energy of the projectile which brought about the crash.

Pose's investigation is one of several which in the last three years have been devoted to the ranges of the protons set free in transmutation. I chose to emphasize it because of the beauty and clearness of the curves, their long horizontal segments and sudden steep ascents which are the evidence for "groups" of protons; it is outstanding also because of the extent to which Pose controlled and varied the speeds of the alpha-particles. Other physicists, however, exposed a wide variety of elements to the bombardment of the alpha-rays, and observed the protons ejected at diverse angles to the direction along which the bombarding corpuscles came. These were Bothe and Fränz of the Reichsanstalt, and Chadwick, Constable and Pollard of the Cavendish Laboratory.

Bothe and Fränz attacked the light element boron; except for aluminium this is the element of which the transmutation has been most studied, for it seems to be much more liable to disruption by the relatively slow alpha-particles of polonium—those which have been used in most of the newer work—than the others commonly tested. Observing the protons projected more or less nearly straight ahead, these physicists plotted a curve comparable to those of Fig. 6; a curve, that is to say, whereof any ordinate represents the number of protons having ranges greater than the value given by the corresponding abscissa. Their curve had a horizontal segment—the first ever observed, so far as I am aware; for its historical interest I reproduce it here as the uppermost curve in Fig. 8. The sloping part to the right of that segment implies a group of protons having ranges between 33 and 23 cm.; the sloping part to the left, a distribution of ranges extending from some 20 cm. downwards. These inferences stand out more clearly from an inspection of the differential curve, which I exhibit here as Fig. 9.

Returning to this field of research (or, more probably, continuing in it uninterruptedly) Bothe and Fränz in 1930 published separate further papers. Bothe varied another factor—the angle between the direction along which the alpha-particles were coming, and that along which the particular protons which he observed were departing. In any one experiment, as we shall see, this angle varies over a wide range; one must specify its mean value, or some value near its mean; this I will denote by θ. Bothe, then, adjusted his apparatus so that to θ he could successively give several values between 0° and 116°; and some of the curves had a horizontal segment, or at least a flattish gentlysloping section, adjoined on the right by a steeper descent to the axis of abscissæ—the sign of a "group" of protons comparatively fast. This descent occurred at smaller values of range, the greater the angle θ. This implied that the mean speed of the group depends on θ—the mechanism for ejecting these protons functions in such a way as to give less energy to those which fly off more obliquely. Pose extended his own researches on aluminium and obtained curves corresponding to the topmost of Fig. 6, for various values of θ ranging up to 135°. At this last cited angle, the ranges of the three groups had sunk from 57 and 48 and 28 to 45 and 38 and 20 respectively.[4]

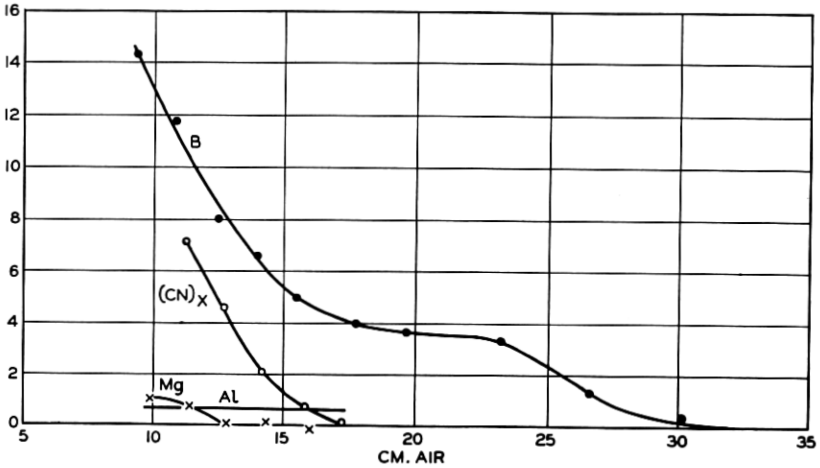

Fig. 8—Integral distribution-in-range curves for protons emitted from disrupted nuclei of boron and other atoms (W. Bothe and H. Fränz).

Whatever this fact may mean in regard to the mechanism, its practical consequence is clear. If the speeds of the protons depend on their direction of departure, then the interval over which these speeds are distributed for any given direction can be appreciated in its true narrowness (whatever that may be) solely by observing the protons which come off in that direction only. If in the actual experiment the paths of the alpha-particles falling upon the bombarded substance diverge over a wide solid angle, and if the paths of the protons which the counter or the fluorescent screen receives diverge likewise over a wide solid angle, then the sharpness of the groups must necessarily be masked. Now of course one would desire in any case to reduce these

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[4] Before the discovery of groups, it had been observed at Cambridge that the maximum range of protons projected straight forward is greater than the maximum found among those projected almost straight backward: for boron the two values were 58 and 38, for aluminium 90 and 67 (in air at 760 mm. and 15° C.)

solid angles to the least practicable values. But in practice they *cannot* be reduced to low values, because the ejection of a proton is so infrequent an event that if one observed only those coming off within say a degree of a certain chosen direction, they would be altogether too few to be profitably observed during any reasonable period of time. The same thing would happen, if one used a beam of alpha-particles of similar narrowness; the impacts would be few because the impinging corpuscles were few. It is therefore to be feared that under the best of possible conditions, the horizontal segments in the curves will be shorter, the descents broader and smoother, than under ideal conditions they would be.[5]

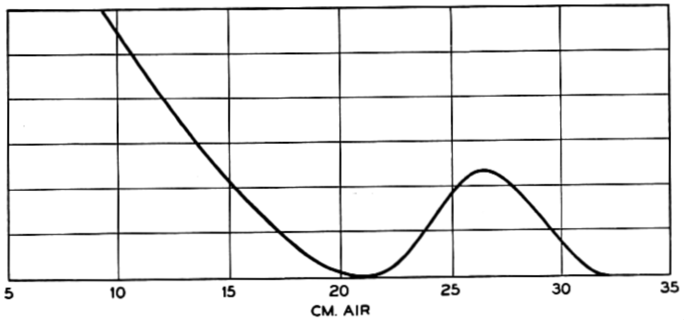

Fig. 9—Distribution-in-range curve obtained by differentiating the curve of Fig. 8 for boron (W. Bothe and H. Fränz).

Another result emerges from the experiments of Fränz, and those of the Cambridge school: the mean speeds of the groups apparently diminish with the speed of the α-particles. This is the effect which Pose observed with the slowest of the groups which he detected, not however with the faster and sharply-marked two; but from the experiments of the others, it seems to be the rule—not that the others tested all of the groups by varying the speed of the α-rays, far from it! but rather, for all which they did test, they found that sort of a dependence. Whether the constancy of speed of the groups which Pose studied is a peculiar feature of these, or his were the better experiments, I would not venture to say. At all events it is obvious that wherever this effect enters in, the natural sharpness of the groups is bound to be blurred by the differences in the speeds of the alpha-particles.

Another of Pose's discoveries—the remarkable fact that with aluminium, certain groups of protons are ejected only when the speeds of

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[5] Whether the beauty of Pose's curves is to be ascribed to the smallness of the solid angles aforesaid is difficult to say. In one place he gives 0° and 58° as the range of values of θ, in another a somewhat smaller amount. Bothe says that in each of his observations the values of θ for 83% of the impinging α-particles lay within 15° of the mean—an interval of 30°. The others are not so definite.

the bombarding alpha-particles are kept within certain limited intervals—remains thus far unique. Nobody else has reported a similar observation.

As for the substances for which the distribution-in-range curve of the protons has been traced, for at least one speed of impinging alpha-particles and one value of the angle θ, they number seven. Of the German studies of boron and aluminium I have already written; Chadwick and his colleagues also studied both, employing the alpha-particles of polonium with their pristine and with reduced speeds, and observing two groups with the former element, three (when the fastest particles were used) with the latter. With fluorine the Cambridge physicists observed three groups, with phosphorus one, with nitrogen a single group remarkably sharply defined. Sodium gave them a curve sloping smoothly downward without horizontal or even flattish segments. Lithium, carbon, oxygen, magnesium, silicon yielded under

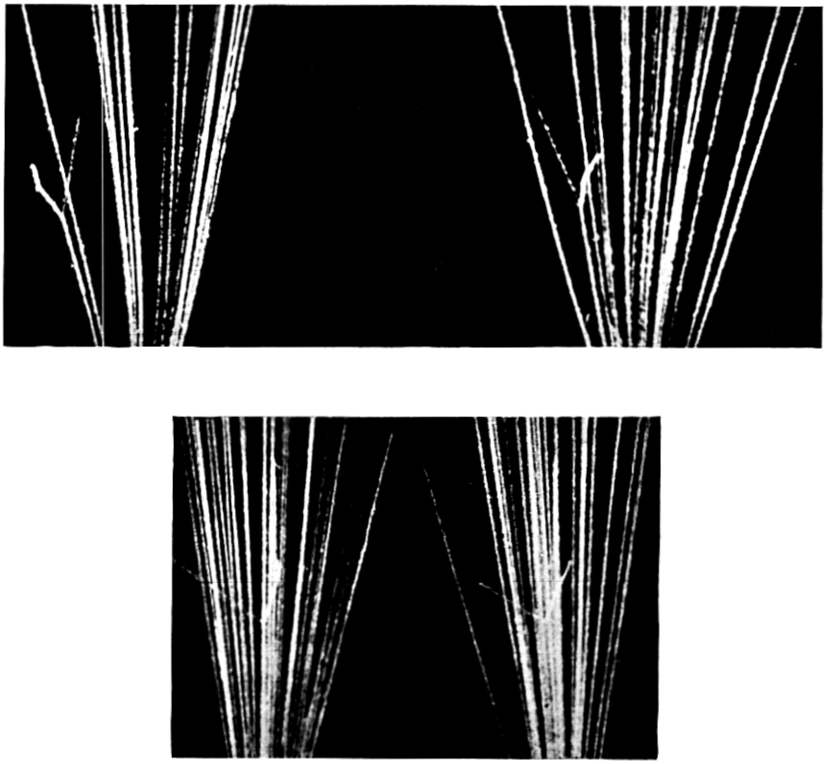

Fig. 10—Transmutation of a nitrogen atom attended by capture of the impinging alpha-particle (P. S. Blackett).

these bombardments no protons at all, or at least none surely due to disintegration of nuclei. Yet Bothe and Fränz had observed protons issuing from magnesium, as one of the curves in Fig. 8 gives witness.

There remains the third method for detecting transmutation, the most beautiful and spectacular of all—the Wilson method, the one in which the trails of small charged particles are made visible by water condensing in droplets on the ions which the particles leave behind them as they tear through the gas. This seems a very inefficient scheme, considering how often one must photograph the trails of alpha-particles which do not effect a transmutation, before having the good fortune of finding on one's plate the record of one of the very rare alpha-particles which do. Inefficient it certainly is; nevertheless, by setting up apparatus which automatically repeats the experiment over and over and over again and automatically takes a new photograph at each repetition, one is able to assemble data enough to provide evidence of transmutation. Patience and perseverance are required, for there is one part of the process which cannot be delegated to a machine:

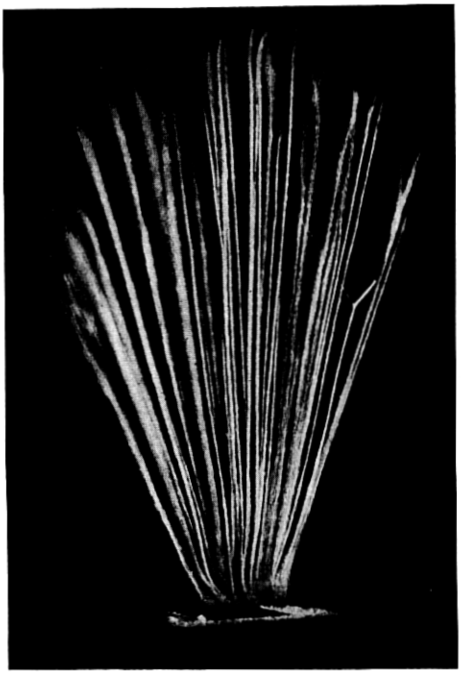

Fig. 11—Transmutation of a nitrogen atom attended by capture of the impinging alpha-particle (W. D. Harkins and A. E. Schuh).

the personal inspection of the myriads of photographs, to locate those few which display "forked trails."

These forked trails were first studied by Blackett of Cambridge, bombarding nitrogen with very fast α-particles of 8.6 cm. range. Most of the few which he found are signs merely of elastic impacts: the alpha-particle has rebounded from an atom-nucleus leaving it intact, as one elastic ball rebounds from another; one of the two tines of the fork is the path of the recoiling nucleus, the other that of the rebounding alpha-particle. Nevertheless, among the trails of *two hundred and seventy thousand* alpha-rays of 8.6 cm. range,[6] Blackett found eight which were bifurcated in an evidently different way. Not, as he had expected, that there were three prongs to the fork instead of two. One would anticipate a long thin track for the proton (long because of its great range, thin because it produces fewer ions and therefore fewer droplets per unit length of its path), a short thick one for the alpha-ray after its impact, another short thick one for the recoiling residue of the nucleus. Actually in these eight cases there was a long thin track, undoubtedly that of the proton; and one, but only one, short heavy track. Harkins and two of his pupils, Shadduck first and later Schuh, made a similar search; chance was not so gracious to them as to Blackett; in the first research two forked trails were detected (not counting those resulting from elastic impact) among two hundred and fifty thousand; in the second, the same small number among an equal multitude.

This lack of a third prong to the fork probably means that the α-particle coalesces with the nucleus which it has just bereft of a proton, the solitary short track being the path of the resultant lately. This must be a nucleus of charge $+ 8e$; for the charge of the nitrogen nucleus is $+ 7e$, and to it has been added the charge $+ 2e$ of the alpha-particle, and from it has been deducted the charge $+ e$ of the proton. [As usual, e here stands for the magnitude of the fundamental electric charge, $4.77 \cdot 10^{-10}$ electrostatic unit.] Further, it must have a mass approximately equal to 17, on the familiar chemical scale on which the oxygen atom has mass 16; for the masses of nitrogen nucleus, alpha-particle and proton are approximately 14, 4 and 1 upon this scale. The ordinary atoms of oxygen have nuclear charge $+ 8e$ and mass 16. This new particle thus has the nuclear charge of an oxygen atom, not, however, its mass. It is consequently an "isotope" of ordinary oxygen.

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[6] Actually, there were somewhat more than half as many additional trails due to α-rays of shorter range (5 cm.). The calculations mentioned in the next paragraph but one indicate, and practically prove, that all of the transmutations were performed by the faster rays.

To be so explicit about a particle, the existence of which is deduced from a set of a dozen forked alpha-particle trails which have one prong too few to the fork, may seem audacious. The evidence of the trails is, however, pretty strong.[7] Blackett measured with great accuracy the angles between the three trails, "stem" and "prongs" of the fork; to do this it was necessary to double the number of photographs, taking two simultaneous pictures from different directions every time the machine operated, so that by combining the two one could in effect "view" every fork in three dimensions. The two prongs and the stem always lie in one plane; and this is a necessary condition for conservation of momentum in a process in which the entire momentum of the impinging particle is shared by two and only two. If one could determine with perfect accuracy the speeds of the three corpuscles reasponsible for stem and prongs, one could tell whether or not the condition of conservation of momentum is obeyed, the masses of the corpuscles being put equal to 4 and 17 and 1, respectively. Or in other words, if the speeds of the corpuscles and their directions could be determined absolutely, one could compute by well-known formulæ the masses which they must have, in order to assure conservation of momentum. The speed of the alpha-particle is quite well-known; but for those of the two others, one is forced to depend on measurements of the lengths of their paths, combined with none-too-certain semi-empirical relations between their ranges and their velocities. Nevertheless, it was shown by Blackett that if the masses of the corpuscles responsible for the prongs of each fork are 17 and 1, the lengths and directions of their paths are such that so far as one can tell, momentum is conserved.[8]

Such is the present status of the art of transmutation. To the moment of this writing, it has proved so difficult that no one has been able to succeed in it except by using alpha-particles, nor to detect his success except by employing the delicate methods fit for perceiving individual fast-flying electrified corpuscles. Almost any day now, the first and perhaps also the second of these statements may cease to be true. Few scientific campaigns have ever enlisted so numerous, determined, energetic and powerful an array of talents and devices, as are now being

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[7] Since these photographs were taken and interpreted, evidence has been found in band-spectra for the existence of an isotope of oxygen of atomic weight 17, very rare by comparison with the well-known one.

[8] Urey went further, and computed the mass of the residue to seven significant figures, utilizing the latest published values for the masses of alpha-particle and proton; he employed relativistic instead of Newtonian mechanics; in the former, the expression for momentum involves rest-mass and speed in such a way that conservation of momentum requires definite values for each, and these he calculated from Blackett's data (so, at least, I interpret his paper, but for the details I must refer the reader to it). The values which he gets range from 17.00504 to 17.00135 for the forked trails; these differences he believes to be real, inferring that the residual nucleus is left in different states by the different impacts.

devoted in the hope of imparting to free electrons and to protons such values of kinetic energy as heretofore only alpha-particles has possessed.

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