Radioactivity—Artificial and Natural [1]

By KARL K. DARROW

RADIOACTIVITY is a world-famous word relating to a world-famous subject. In general, when a statement of this sort is spoken, it is more than likely to be foolish; for specialists are altogether too addicted to imagining that their special interests are of world-wide concern when perhaps not fifty thousand people have even heard of them. With respect to radioactivity, though, the statement *is* correct. It would have been difficult indeed for any literate person to miss making the acquaintance of this word, in any year since 1900. I might say that radioactivity has been the best-advertised topic in modern physics—and this is not to say that it has been over-advertised! It is in fact the only part of modern physics which has received something approaching its due renown. Such good fortune cannot of course be altogether due to the fundamental values of the subject. A great part of the fame of radioactivity comes from medical applications and even more from medical hopes, and some from incidental things, such as the tragic end of one of its great students and the sex of two others. Still it is a matter for rejoicing that whatever the reasons may be, one portion of physics now enjoys its proper quota of the glory to which so many others are entitled.

The discovery of radioactivity took place in 1896. Quite a number of things of the highest importance to physics—and to humanity at large—were begun between 1895 and 1900, and of these the study of radioactivity was the second. The study of X-rays was the first. The second was commenced only because the first had been, and therefore I speak of the first. Imagine a tube containing air and a couple of electrodes a few inches apart, and suppose that you have a battery which can supply a durable current at ten thousand volts or more, and an air pump as well. If the air is at atmospheric pressure, the ten thousand volts can be applied between the electrodes and nothing will happen. If with the pump you now reduce the pressure of the air to about a thousandth of the atmospheric value, the air which remains in the tube will become very luminous and splendid. If next you re-

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duce the air-pressure by yet another ten-fold, the splendor will fade out, but now the glass of the tube itself, in the region opposite the negative electrode, will be shining with a pale green glow. This too is a beautiful sight, but decidedly not one to be enjoyed for a long time at close range, for it is attended by invisible rays very dangerous to health and even life. These are the X-rays.

Many people have heard that Roentgen discovered the X-rays because he kept some photographic plates in a box which happened to lie near the tube, and found one day that the plates were fogged. It is true that he did observe the fogging of plates by the rays; it is true also that for years afterward, people were telling in various parts of Western Europe and America how they too had noticed that their plates were spoiled when left by accident in the neighborhood of discharge-tubes, but unluckily they had only felt annoyed and had resolved to keep their next batches of plates in safer places. However it was something else that led Roentgen to the discovery. He had in his laboratory some sheets of phosphorescent substances; and he found that whenever one of them was in the neighborhood of the tube it would shine; and what was more, *it would shine even when hidden from the tube by a sheet of black cardboard*. The X-rays (as he presently named them) were able to pierce substances opaque to light, and to cause phosphorescent substances to shine. Roentgen very soon discovered other properties of the rays, but these were the earliest. Moreover the greenish glowing of the glass in the X-ray tube itself resembles the light of phosphorescence; so, here were two apparent connections between penetrating X-rays on the one hand, and phosphorescence [2] on the other.

Now we come to radioactivity. There was a man in Paris whose attention was caught by these facts, and his name was not Curie. Curie is the second great name in the story of radioactivity; the first is Becquerel. I put down his first name (Henri) as well, for Becquerel—like Curie and Bernoulli and Darwin and others—is the name of a dynasty of scientists, of which Henri was the third. Henri Becquerel seems to have reasoned [3] after this fashion: "X-rays and phosphorescence are found together; therefore, wherever there is phosphorescence, there may be rays like X-rays." So he took photographic plates and wrapped them in dark paper, and then he took one phosphorescent substance after another and (after making them luminous by exposing them to light) laid them in succession beside the plates, and after an interval looked to see whether there had been fogging. Time after

[2] Or fluorescence: a careful distinction is drawn between phosphorescence and fluorescence by specialists, but need not detain us here.

[3] The idea is, however, ascribed to Henri Poincaré by Marie Curie.

time the result was completely negative, but at last he came upon a chemical compound of the element *uranium* which was phosphorescent and which fogged the plate. It is not recorded that he shouted "Eureka!" but he had as good reason so to do as Archimedes. He had discovered the first-to-be-known example of radioactivity.

Now comes the strange and paradoxical part: Becquerel had arrived at his great discovery by following a false clue. There is really no connection whatever between radioactivity and phosphorescence, and it was purely an accident that a compound which was phosphorescent had happened to contain an element which was radioactive. In trying to make a simile for what then happened, I have adopted the rather frivolous comparison which follows. Suppose that you were to meet a man who was wearing a blue serge suit, and notice that he was speaking a foreign language—Swedish, let us say. For some reason this would interest you particularly, and you would decide to look for other examples of people speaking Swedish. You would begin by reasoning that "Swedish speech was associated with a blue serge suit, and therefore any man who is wearing blue serge may speak Swedish." You would then listen to everyone whom you passed in the street who was wearing blue serge, and the first few whom you heard would prove to be speaking English. This would prevent you from believing that a blue suit necessarily entails the speaking of Swedish: but you might continue nevertheless, and eventually find another man who was wearing blue serge and speaking Swedish. Now if you were like some people, I am afraid you would send a communication to a scientific journal, announcing that it is a principle that everyone speaking Swedish is wearing a blue serge suit. But not if you were like Becquerel! If you were like Becquerel you would trail the man for weeks; and sooner or later you would come upon him wearing a grey suit or a brown one, and still he would be speaking Swedish. In the course of time you would doubtless come upon other people who never wore blue serge and yet spoke Swedish. Finally you would realize that it was just a piece of luck that you had happened to discover a man speaking Swedish, by making the fallacious assumption that all such men wear blue. Now in this case of Becquerel's, the phosphorescence was only a feature of the clothes which the uranium happened to be wearing, or more literally, the chemical compound in which it was involved. But the radioactivity was a feature of uranium itself, and that is what Becquerel proceeded to prove; first by testing various other chemical compounds of uranium which were not in the least phosphorescent, and then by testing the pure uncompounded metal itself.

Uranium, then, is a radioactive element. But it is not the only one; there were numerous others, even in the days before the physicists had started making new ones. This is where the elder Curies enter the story: Pierre and Marie Curie, in 1898. First they measured the activity of uranium, pretty carefully. Then they started measuring the activity of various minerals containing uranium, and they found too much: these minerals were more active than by virtue of their uranium content alone, they should be. The Curies suspected that some other radioactive element was lurking in the depths, and they undertook to get it out. This was of course a chemical problem primarily, and as a matter of fact, their Nobel prize was the chemistry prize, and quite rightly. Eventually they isolated their new element, or rather, two of them, which they named "polonium" and "radium." Having at last got their radium and weighed it, they found that it amounted to only two parts in a hundred million (by weight) of the rock from which they had extracted it. They required three tons of the rock, in order to get one one-hundredth of an ounce of the radium. Two parts in a hundred million! and yet, while it was still dispersed in that almost incredible scantiness through the rock, they had already been able to detect it! This is the point which I most wish to bring out, at this stage. A radioactive substance is far more easy to detect than any which is not. It is like salt in food, and the radioactivity is like the flavor of the salt, which shows the presence of a dash so insignificant that anything else in the food would go untasted if it were equally rare. Fortunately for us the instruments which are used to detect a radioactive body are not our tongues, but apparatus of a much less vulnerable kind.

Now I mention only one name before reaching the recent developments, but this the greatest name of all: RUTHERFORD. Rutherford was the first to understand radioactivity—the first to prove the contemporary atom-model—and the first to achieve transmutation. Any one of these achievements by itself would have secured undying glory to its author, but this great man made three. As lately as two years ago I wrote in a book that every leading figure in the history of transmutation was still living and still ardently at work. As lately as last October I could have repeated that, but now the Master is gone—quite suddenly gone in the fullness of his powers. This lecture is a memorial to Rutherford, not because it was expressly so designed, but because any lecture on the new radioactivity or on the old involves so much of his thought and so much of his work that it would be reduced to a few incoherent bits if everything not traceable to Rutherford should be left out.

The first achievement of Rutherford in this field was to identify the rays emitted by radioactive bodies. He identified three kinds, and gave them the names which they still bear and assuredly always will: *alpha*, *beta* and *gamma* rays. The last-named (which are of the nature of light) are the ones whereby radioactivity was first detected, for they are the ones which fog the plates and produce the phosphorescence outside of a rather narrow space just around the radioactive substance itself. They are also the ones responsible for the great work already done in medicine by radioactive bodies, and on which (I am told) there is great reliance for the future. If this were a medical lecture the gamma-rays would require most of its content; but as it is not, I leave them with this brief allusion, and turn to the others. The beta-rays are electrons, which may be of either sign (Rutherford, like the rest of the world, was acquainted only with the negative ones until five or six years ago). The alpha-rays are also charged particles, much heavier than electrons; I shall be defining them more exactly before long. The beta-rays and the alpha-rays, and for that matter the gamma-rays as well, are detected by very ingenious devices of which most types are electrical, though the particular type which supplies the photographs seen in this lecture is not.

Now at last I exhibit the list of the radioactive elements.

This list (Fig. 1) is none other than the veritable Table of the Elements itself! *Of all the known elements there now remains just one of which no radioactive form has yet been discovered or invented.* Hydrogen is the exception (the listener may say "Of course!" but it is not excluded that some day a radioactive type of hydrogen may be produced). At the end of the list stands uranium, the first of the radioactive bodies to be discovered. It has stood there ever since Mendeleieff set up the table in this fashion, but actually it now must yield its pride of place, for physicists have lately created radioactive elements which lie beyond it. I have though gone ahead too rapidly in speaking of these already. Once more let me state the marvelous fact that of all the known elements, every one but hydrogen exists in a radioactive form, or perhaps in more than one.

In speaking of "forms" I have been alluding to something which the Table as it stands in Fig. 1 does not make clear. Everyone recognizes the "chemical atomic weights" there appended to the symbol of each element. If an element has only one kind of atom, this figure is the actual mass of the atom, expressed in terms of a unit which I will presently define. There are such elements; beryllium and fluorine, sodium and aluminium are examples. Most elements, however, have two or more kinds of atoms differing in mass. Thus, in Fig. 1, the

PERIODIC TABLE OF THE ELEMENTS

(Values of atomic weights taken from the seventh Report of the Committee on Atomic Weights of the International Union of Chemistry; G. P. Baxter, *et al.*, *J. Am. Chem. Soc.*, **59**, p. 219)

I	II	III	IV	V	VI	VII	VIII			O
1 H 1.0078										2 He 4.002
3 Li 6.940	4 Be 9.02	5 B 10.82	6 C 12.01	7 N 14.008	8 O 16.000	9 F 19.00				10 Ne 20.183
11 Na 22.997	12 Mg 24.32	13 Al 26.97	14 Si 28.06	15 P 31.02	16 S 32.06	17 Cl 35.457				18 A 39.94
19 K 39.096 29 Cu 63.57	20 Ca 40.08 30 Zn 65.38	21 Sc 45.10 31 Ga 69.72	22 Ti 47.90 32 Ge 72.60	23 V 50.95 33 As 74.9	24 Cr 52.01 34 Se 78.96	25 Mn 54.93 35 Br 79.916	26 Fe 55.84	27 Co 58.94	28 Ni 58.69	36 Kr 83.7
37 Rb 85.48 47 Ag 107.880	38 Sr 87.63 48 Cd 112.41	39 Yt 88.92 49 In 114.76	40 Zr 91.22 50 Sn 118.70	41 Nb 92.91 51 Sb 121.76	42 Mo 96.0 52 Te 127.61	43 53 I 126.92	44 Ru 101.7	45 Rh 102.91	46 Pd 106.7	54 Xe 131.3
55 Cs 132.91 79 Au 197.2	56 Ba 137.36 80 Hg 200.61	RARE EARTHS 81 Tl 204.39	72 Hf 178.6 82 Pb 207.21	73 Ta 180.88 83 Bi 209.00	74 W 184.0 84 Po	75 Re 186.31 85—	76 Os 191.5	77 Ir 193.1	78 Pt 195.23	86 Rn 222
87—	88 Ra 226.05	89 Ac	90 Th 232.12	91 Pa 231	92 U 238.07					

RARE EARTHS

57 La 138.92	58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61	62 Sa 150.43	63 Eu 152.0	64 Gd 156.9
65 Tb 159.2	66 Dy 162.46	67 Ho 163.5	68 Er 167.64	69 Tm 169.4	70 Yb 173.04	71 Lu 175.0	

Fig. 1

pigeonhole for hydrogen should contain three mass-values; that for helium, two; that for tin, no fewer than ten. It would make the table impossibly crowded to print them all in this way, and consequently I have broken it up into sections, of which Fig. 2 represents the first six elements.

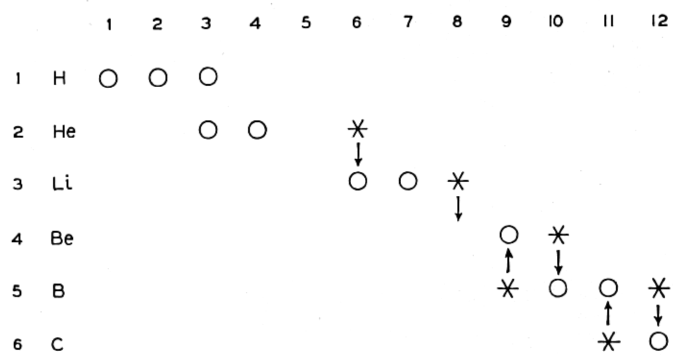

Fig. 2—Isotopes of the first six elements.

In this figure each element has a row to itself, and each value of mass has a column to itself, and each circle represents a stable kind of atom. I now introduce the technical term "isotope" to distinguish the different kinds of atoms common to a single element. Hydrogen, you see, has three stable isotopes (there is some doubt about the stability of the third, though none about its existence); helium two (again there is doubt about the stability of one); lithium two, beryllium only one, boron two, and carbon two of which the second will appear in the next figure. The unit of mass is a very small amount, about $1.67 \cdot 10^{-24}$ of one gram. I do not pause to give it as accurately as I might, for we are not going to be concerned with very exact mass-values in this talk. The masses of the isotopes are not exactly integer multiples of this unit; for instance, those of the three kinds of hydrogen atoms are 1.008, 2.016 and 3.017. The departures from integer multiples are, however, small, as you see in these three cases. Small as they are, they are mightily important; but it is permissible to ignore them for the purposes of this lecture, and I am going to ignore them from now on. I will, however, speak of the integers at the heads of the columns as "mass-numbers" rather than "masses."

Since the isotopes of an element differ in mass, what is it then that they have in common? I answer this question by describing Rutherford's second great achievement, the "nuclear atom-model." Rutherford was the first to prove that the atom consists of a positively-charged nucleus surrounded by a swarm of negative electrons. The nucleus is much more massive than the electrons, and this is one of the reasons for comparing the atom with the solar system, in which the sun is much more massive than the planets which perpetually swing in orbits around it. A less hackneyed and newer simile is that of Bragg, just now, by the way, appointed as Rutherford's successor in the Cavendish chair at Cambridge, who likens the atom to a man's head with a swarm of gnats buzzing around it. Normally—that is to say, when the atom is complete and electrically neutral—the negative charges of all the electrons put together just balance the positive charge of the nucleus. If Z be used to stand for the number of electrons in the normal neutral atom, and $-e$ for the charge of the negative electron, then $+Ze$ is the amount of the charge on the nucleus. Z is called the "atomic number" of the element in question.

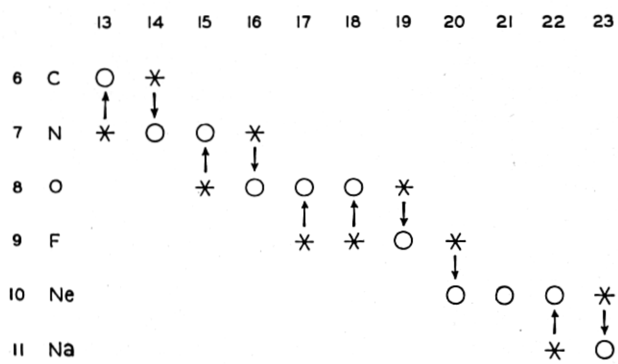

Fig. 3—Isotopes of the elements numbered 6 to 11.

This it is, of which all the isotopes of any one element have the same value. This it is which distinguishes an element, and is common to all of the different atoms of that element whatever their masses may be. For hydrogen it is 1; for helium 2; for lithium 3; for uranium 92. Each row in Fig. 2 and Fig. 3 is marked on the left not only with the chemical symbol of the element to which the row belongs, but also with the atomic number thereof.

Radioactivity is a feature of the nucleus. This accounts for some of its remarkable aspects, which greatly surprised the world of physicists and chemists when they were first established. Being a quality of the nucleus, it varies from one isotope [4] to another of any element, much more drastically than does the mass. Being a quality of the nucleus, it is immune to the physical state of the atom—*i.e.* it is the

[4] Isotopes were first distinguished from each other (by Soddy) by virtue of their differences in radioactivity.

same whether the atom is part of a solid, a liquid or a gas; it is immune also to the chemical state of the atom, *i.e.* it is the same whether the radioactive element is isolated or is part of a chemical compound. It is also immune to heat and to all of the many other agencies which physicists and chemists have at their command.

Radioactivity being a feature of the nucleus, every chemical symbol which I use from now on will refer to the nucleus of an atom and not to the atom as a whole. "Be" will stand for beryllium nuclei, "F" for fluorine nuclei, "Al" for aluminium nuclei. For most elements, though, there are two or more different sorts of nuclei distinguished from each other by their masses, and the symbol must tell us which is meant. The custom is to write the mass-number of the isotope in question as if it were an exponent: H^1 and H^2 and H^3 for the three kinds of hydrogen nuclei, He^3 and He^4 for the two kinds of helium nuclei, Li^6 and Li^7 to distinguish between the isotopes of lithium, and so on. If in addition one wants to remind the reader of the atomic number, one writes it as a subscript before the chemical symbol: ${}_1H^1$, ${}_1H^2$, ${}_2He^4$, ${}_9F^{19}$ and the like. Purists object that either the chemical symbol or the value of Z is superfluous when both are given, but others often like to see them both. And now for some names: there are three nuclei which have names of their own. The Greek words for "first" and "second" are applied to ${}_1H^1$ and ${}_1H^2$; they are the *proton* and the *deuteron*. The name for ${}_2He^4$ is *alpha-particle;* this nucleus is indeed the particle which, as Rutherford discovered long ago, makes up one of the three kinds of rays which radioactive bodies emits, and there never was a greater piece of good fortune in language than that whereby this all-important particle received the name of the first letter of the Greek alphabet, for indeed it is the alpha of modern nuclear physics. And now another reference to masses: the mass of the electron (when not moving extremely fast) is only about .0005 of the mass-unit which is being used throughout this talk, and therefore the mass-numbers at the heads of the columns in Figs. 1 and 2 and others are about as good approximations to nuclear masses as they are to atomic masses, and I shall use them as such.

Now let us notice not only the circles of Figs. 2 and 3, but the stars as well. The stars also stand for nuclei, but these are *radioactive*—or *unstable*, two words which have practically the same meaning when applied to a nucleus. At least one star appears in every row, the first in Fig. 2 excepted. If the figure had room for ninety-two rows, one for each element from hydrogen to uranium, there would appear at least one star in every row below the first, excepting three (atomic numbers 61, 85, 87) for which no isotope either stable or unstable known with certainty and the element itself must still be regarded as missing. (Furthermore there should be at least three more rows numbered 93, 94 and 95, and containing stars but no circles.) This is what is meant by saying that every known element, hydrogen alone excepted, has at least one radioactive form.

Figure 2 shows that at the beginning of the Table of the Elements, the stable types of nuclei outnumber the unstable ones. The preponderance is gradually shifted as Z increases, and Fig. 4 exhibits to us how greatly the radioactive nuclei outnumber the stable ones among the elements of which the atomic numbers range from 81 to 84. Indeed the circle which is lowest and most to the right in Fig. 4 represents the most massive and most highly charged of all the stable nuclei which are known (it is the solitary isotope of bismuth, atomic number 83 and mass-number 209). All the rows after 83 are occupied entirely by stars.[5]

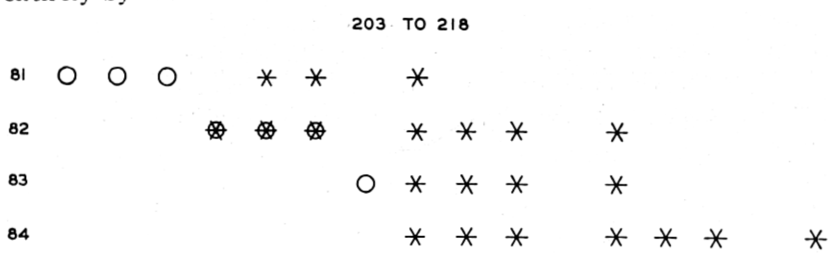

Fig. 4—Isotopes of the elements numbered 81 to 84.

As the title of this talk has already suggested, the radioactive nuclei are of two classes: the "natural" and the "artificial," the types already existing in the rocks of the earth and the types made in the laboratory by physicists employing the art of transmutation. Nearly all of the natural types lie beyond 80 in atomic number, and most of them were discovered in the first fifteen years after Becquerel found the first. Two of them are identical with two of the man-made types. Apart from these two, every one of the artificial types is a creation of the years since 1933. One guesses that while the natural radioactive bodies may be many, the artificial ones must surely as yet be few; how surprising then to learn that while there are some forty of the former, the latter after four brief years already number two hundred and thirty! Unlike the natural ones, these artificial isotopes are sprinkled liberally throughout the whole of the Table of the Elements, from the second onward to the end. Not only in number but in di-

[5] It must though be admitted that some of the heaviest nuclei, though demonstrably radioactive, may exist for hundreds of millions of years before they disintegrate; "instability" is indeed a very relative concept!

versity of mass and charge are the artificial radioactive bodies now outstanding by far.

These artificial examples forming now so large and important a group among the radioactive nuclei, I make a digression to speak of some of the transmutations from which they are derived. The art of transmutation is already so huge a subject that the digression must be severely limited if ever we are to come back to radioactivity. I must therefore make only a passing allusion to the fact that the first of the new radioactive nuclei were made by bombarding various light elements with very energetic alpha-particles. Here the second Curie generation must be introduced, for the daughter and son-in-law—Irene Curie and Frederic Joliot—of the first Curie pair were the ones who made this discovery. (It was not their entry into the field of radioactivity, they having already studied natural radioactive bodies for a number of years).

Returning to Figs. 2 and 3, notice that many of the radioactive isotopes lie just one step to the right of stable isotopes: Li^8, Be^{10}, B^{12}, C^{14}, N^{16}, O^{19}, F^{20}, Ne^{23} are the examples found in these two pictures alone. It seems as though they might differ from their neighbors on the left—Li^7, Be^9 and so forth—by possessing an extra particle of mass (approximately) 1 and charge zero. If only one could find such particles roaming freely about in Nature, might one perhaps succeed in adding them to the stable nuclei of lithium and beryllium and boron and the other elements, and so produce these radioactive nuclei?

Such particles may indeed be found roaming about in Nature, but not of their own volition. These "neutrons"—for such is their name—must themselves be set free by the art of transmutation. Free neutrons were first produced by bombarding certain elements with alpha-particles; the discovery was an international one, and its story is interesting, but to keep this digression within bounds I must again content myself with giving the names—Bothe and Becker in Germany, Curie and Joliot in France, Chadwick in England—of those who carried it through its consecutive stages from first intimation to triumph. More than a hundred different ways of freeing the neutron are already known, but of all this diversity I will take one only, which consists in projecting deuterons against deuterons.

The "deuteron-deuteron reactions"—D-D reactions for short—are produced by applying high voltage to deuterons (emerging from a discharge-tube containing heavy hydrogen, in which some of the atoms are divested of their electrons and the nuclei are left bare) and then directing them across a vacuum against a target containing other deuterons. (The target may be some solid compound of heavy hydrogen, such as ice in which plenty of the hydrogen atoms belong to the isotope H^2; or it may be gaseous heavy hydrogen). The high voltage is required, so that the impinging deuterons may override the electrostatic repulsion between the positive charges which they bear and the positive charges of the deuterons waiting in the target, and come into contact with these last. Generally in transmutation, "high voltage" signifies volts by the millions. These particular reactions are, however, among the easiest to produce, and with less than a hundred thousand volts it is quite possible to liberate neutrons at such a rate that their peculiar qualities can be well studied. (One reaction indeed has been detectably produced at 8000 volts, a figure so low that it arouses speculation as to what the course of physics might have been if the second isotope of hydrogen had been discovered say thirty years ago.)

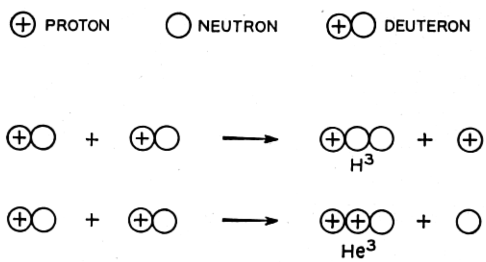

Fig. 5—Scheme of the deuteron-deuteron reactions.

To explain what is actually observed to happen, I ask the listener to imagine the deuteron as a composite of a proton and a neutron, as it is exhibited in Fig. 5. With this image in mind, one might well expect that when deuterons are hurled with great energy and speed against a plate of matter containing massive nuclei—lead, for instance—they would be broken in two. This has been sought for but apparently does *not* happen, showing that we must keep our imaginations under continual check by experiment. What *does* happen is displayed, for the impacts of deuteron against deuteron, in Fig. 5. It seems that one deuteron is after all broken in two, but only under the condition that either its component proton or its component neutron adheres to the other. Another metaphor: one deuteron snatches either the proton or the neutron away from the other, leaving the abandoned neutron or proton to go free. Both of these descriptions are too figurative, but what is certain is this: from the scene of such impacts, particles of all the four kinds shown to the right of the arrows in Fig. 5 are observed to be proceeding. The labels show (what should already be obvious) that the newborn particles of mass 3 are isotopes of hydrogen or helium, according as they contain two neutrons and one proton or two protons and one neutron. I now show pictures to support these statements.

In Fig. 6 the apparatus is shown in a sketch: the cloud-chamber or expansion-chamber of C. T. R. Wilson, being the hollow cylinder which is shown below in axial section, its top being a glass plate and its bottom a piston-head which can be pulled very suddenly downward

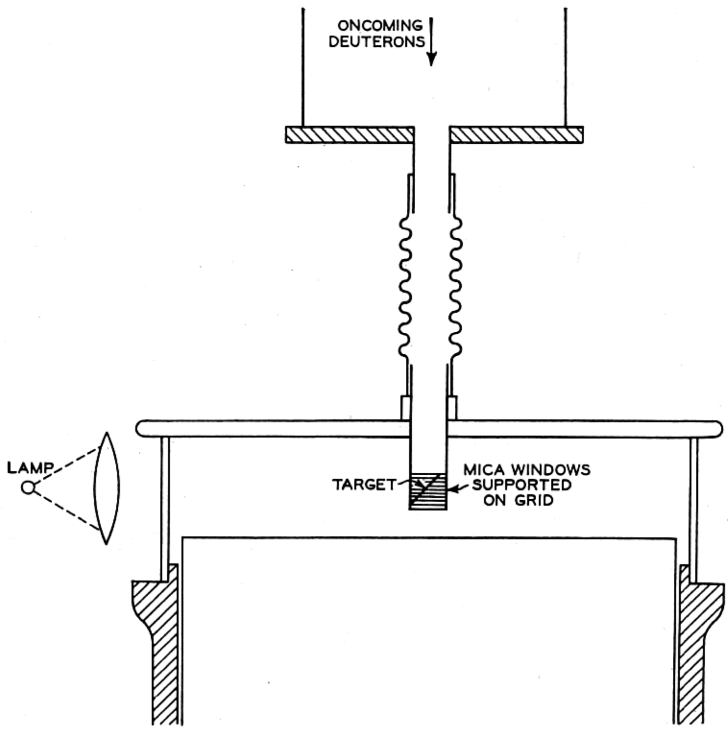

Fig. 6—Expansion-chamber arranged for detecting transmutation by deuterons.

by mechanism. Ordinarily the chamber is filled with moist but dustless air; when the piston-head suddenly drops, the air and the water-vapor are sharply cooled by expansion, and the vapor condenses in droplets upon whatever ions may be floating in it. The side-tube which enters the chamber from above is evacuated; through it come the impinging deuterons, to make their impacts upon the target at the knob-like closed end of the tube. The wall of the tube, thin as it may be made, is too thick to allow the deuterons to emerge into the air of the chamber. One might well expect that *a fortiori*, any new particles born out of the transmutation would be too slow-moving to pierce the wall; but many of these particles are much more energetic than the impinging deuterons themselves, for they draw upon a reserve of energy stored up in the nuclei.[6] They shoot through the wall into the air of the cloud-chamber itself, and if they are charged, they make long trails of ions along their paths. The expansion is then produced and the water-vapor, condensing upon these ions, makes trails of droplets which are the paths made visible.

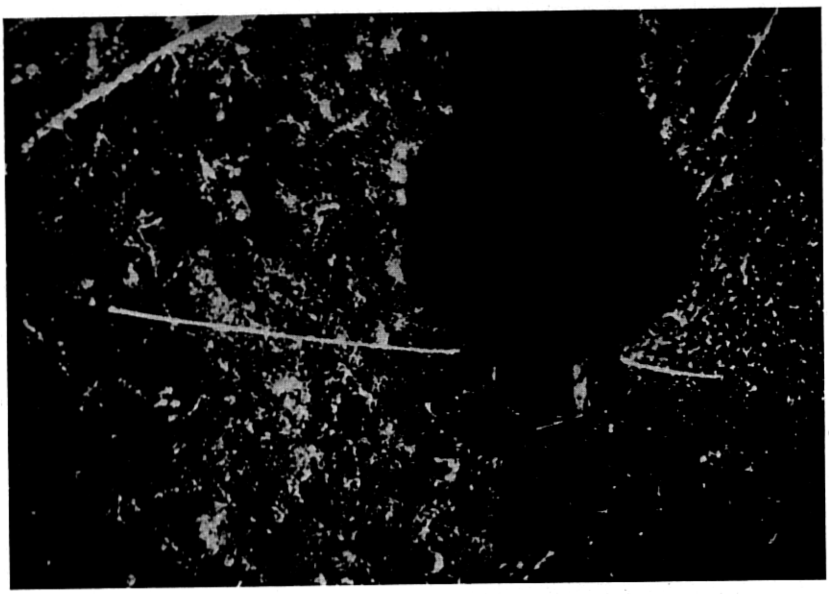

Fig. 7—Tracks of a proton and a H^3 nucleus resulting from one of the deuteron-deuteron reactions. (P. I. Dee, Cavendish Laboratory; *Proceedings of the Royal Society.*)

Figure 7 exhibits two of these visible paths of "tracks," made by particles which sprang from the scene of the transmutation (inside the knob) in practically opposite directions but with very different penetrative powers, since one of the tracks is seen to be much longer than the other. The long one is the track of a proton, the short one is that of a H^3 nucleus which is a deuteron augmented by a captured neuteron; this picture shows a single example of the upper reaction of Fig. 5. How can physicists be sure that these tracks are due to the nuclei which I have named? This question is far too deep to be answered in this place, and I can only assure the listener that while such pictures by themselves cannot suffice for the proof, an unassailable

[6] In the language employed in chemistry, these are "exothermic" reactions.

proof can be and has been given by other and electrical methods of observing these newborn particles.

But how about the lower reaction of Fig. 6—the one which really concerns us, since all this digression is designed chiefly to exhibit the origin of free neutrons? In Fig. 7 no track appears which can be attributed to either a He^3 nucleus or a neutron; and no such tracks appear in other similar pictures. The absence of He^3 is, however, due to a simple cause; these nuclei are born with insufficient energy to traverse the wall of the tube. To observe their tracks it is necessary to suppress the tube-end, to fill the expansion-chamber with heavy

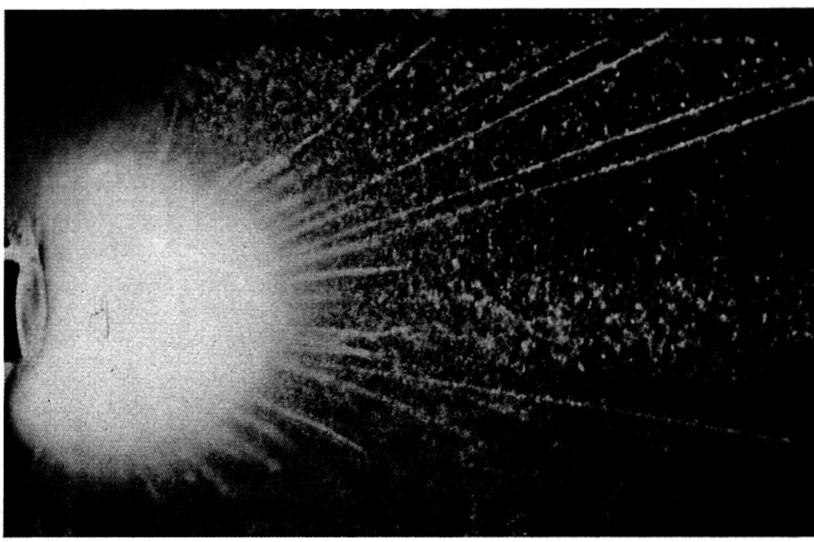

Fig. 8—Tracks of protons, H^3 nuclei and He^3 nuclei resulting from the two deuteron-deuteron reactions. (P. I. Dee and C. W. Gilbert, Cavendish Laboratory; *Proceedings of the Royal Society.*)

hydrogen in the gaseous form, and to project the deuterons directly into it. When this is done, all of the region of the gas which the impinging deuterons can reach becomes completely filled with the ions formed along their many tracks, and appears as a flare on the photograph (Fig. 8). Out of the flare project the tracks of the newborn nuclei. Those which stretch clear across the picture are in part those of protons, in part those of H^3 nuclei born from the first reaction. But in addition one sees a number of short tracks which terminate not far from the edge of the flare itself. These are the tracks of He^3 nuclei—not merely guessed, but proved, to be such.

Where, however, are the tracks of the neutrons? They are not seen upon this picture, nor in any; for neutrons make no tracks. Neutrons bear no electric charge, and hence they do not ionize the molecules of the air or any gas as they go through, for ionization is effected only by electrical forces which can tear electrons out of their places in molecules. Not making ions, they afford no footholds whereby the water-vapor can condense and mark their passage. The expansion-chamber is frustrated; and worse yet, so are the electrical devices which serve for detecting charged particles like fast protons or fast electrons, since they, too, depend on the ions which these can make. The neutron indeed might slip through all of our apparatus completely undetected, were it not liable to make collisions with nuclei so sharp and sudden

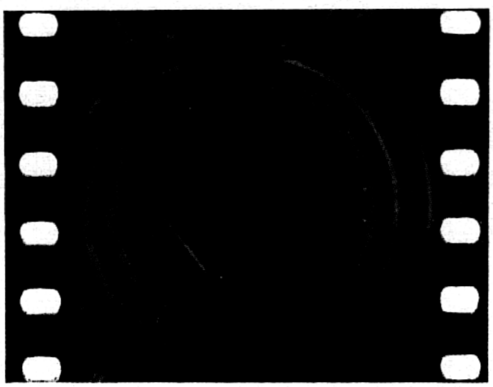

Fig. 9—Track of a proton recoiling from the impact of a neutron. (I. Curie and F. Joliot, Institut du Radium; *Journal de Physique.*)

that they might be compared with impacts of one billiard-ball upon another. Comparisons with billiard-balls are rife in physics, but seldom with so much justification. When neutrons are streaming through a gas, such impacts are suffered by nuclei of occasional atoms of the gas; and like a struck billiard-ball they recoil, and in recoiling they are able to make ions and the ions then serve to reveal them.

The track of such a recoiling nucleus, made visible in a cloud-chamber, is seen in Fig. 9. This was taken soon after the discovery of the neutron, and at a time when these particles had as yet been released only by using natural radioactive substances to project alpha-particles against various targets. Such ways of producing free neutrons are not very efficient, and accordingly one sees in the whole expansion-chamber one track and one only (though I must interpolate that according to our present knowledge, many thousands of neutrons must have traversed this chamber without happening to strike any nucleus). See now the contrast with the present time, as illustrated by Fig. 10 which shows an expansion-chamber traversed by the

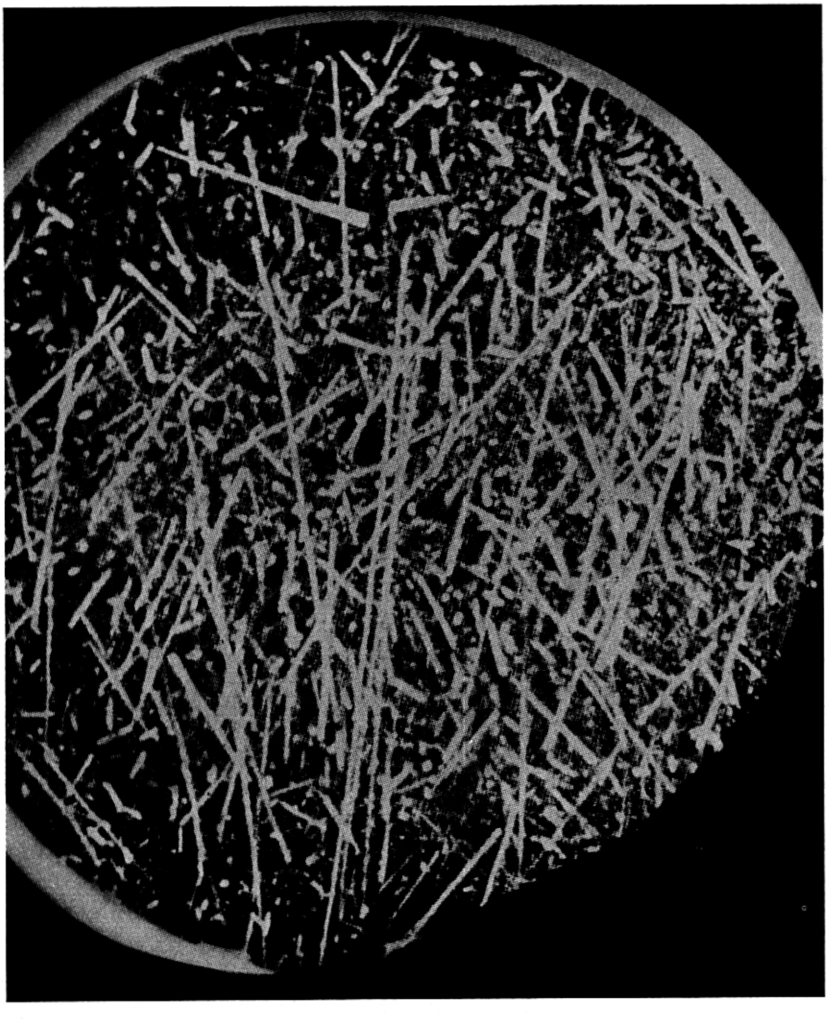

Fig. 10—Tracks of protons recoiling from impacts of a dense stream of neutrons. (F. N. D. Kurie, University of California.)

neutrons released when deuterons from a high-voltage machine bombard a target.[7] The machine in question was the famous cyclotron of E. O. Lawrence; there is no more striking illustration of the powers

[7] This was another reaction than the one just mentioned, the target being of beryllium.

which this instrument has conferred upon the scientific world, over and above those which radium has already granted.

Our digression now ends, and we return to the artificial radioactive substances, being now equipped with knowledge as to how these—or rather, many of them—can be made. As I said earlier, many radioactive isotopes differ from existing stable isotopes only in possessing an extra neutron in the nucleus; and this extra neutron can be supplied to the stable nucleus, combining it and converting it into the radioactive type. I have just exhibited one way in which the extra neutron may be, and often is, supplied. In the first-mentioned of the deuteron-deuteron reactions, a neutron is taken away from one of the deuterons by the other, which latter is thus converted from H^2 into H^3. There are many stable isotopes, of many elements, which are able to take away neutrons from impinging deuterons in this manner; a recent list gives no fewer than fifty. The resulting nucleus-types are not in every case radioactive; several are stable, including H^3 itself (at least, no one has yet discovered evidence that H^3 is unstable, though there are doubts about it). Most however *are* radioactive. The reactions in question are known as (d, p) reactions, in allusion to the fact that deuterons enter the target and protons spring out. One might imagine that the deuteron consists of a proton leading along a neutron, which it pushes into the nucleus which it strikes, itself continuing its career as a free particle.

Neutrons, however, do not have to be escorted into nuclei by protons; those which are already free, such as the ones which are released in the second of the D–D reactions, are quite well able to creep in themselves and make themselves permanently at home. My use of the verb "creep" is not entirely fanciful, for the slower the neutrons are moving as they approach a target, the better their chance of entering its nuclei. Those fresh from their origin in reactions of transmutation are usually moving much too rapidly to be able to come to a halt in a nucleus—or to be liable to capture, whichever way of putting it one may prefer. It is necessary to interpose, between the source and the target, a block of paraffin or a can of water several inches thick. If the source consists of a natural radioactive substance bombarding another element with alpha-particles and thus releasing free neutrons, the two may be mixed with each other and enclosed in a capsule which is then embedded in the centre of a paraffin sphere or immersed in water. As the neutrons make their way out, they collide again and again with the nuclei of atoms in the paraffin or the water, and these recoil from the impacts. It is not, however, their recoiling which is now of importance, but the fact that at every such impact the neutron loses some of its energy. The point about choosing water or paraffin is that they are rich in hydrogen and consequently full of protons, and the elastic impacts of the neutrons against these entail a greater average loss of neutron-energy per collision than do impacts against any other nuclei.[8] There is good reason to believe that most of the emerging neutrons have energies no greater than those which the atoms of the water or the paraffin possess by virtue of their thermal agitation. These are the neutrons which are most effective in converting stable into radioactive nuclei by letting themselves be captured.

Even yet I have not mentioned all of the ways in which radioactive substances can be and are being made. Time does not suffice for commenting on the others, but some are exhibited in Fig. 11, which

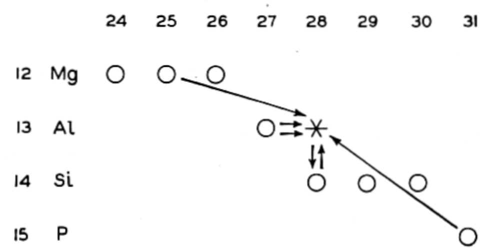

Fig. 11—Various ways of making the radioactive nucleus Al^{28}.

displays all of the stable but only one of the unstable isotopes of the four elements numbered 12 to 15. This one radioactive type, which I have tried to make more conspicuous by leaving out the rest, is the isotope 28 of aluminium—one of the few elements, which, very conveniently for physicists, has one stable isotope only. The arrows converging onto the star show the different ways in which Al^{28} is made. The two coming from the left signify that it is made by adding a neutron to the stable isotope Al^{27}; there are two of them, because the Al^{27} nucleus can either absorb a slow free neutron or annex the neutron from an impinging deuteron, whichever it has the opportunity of doing. The arrow slanting downward from the left signifies that Al^{28} can be made by bombarding magnesium with alpha-particles; some of these are absorbed by nuclei of the isotope Mg^{25} which thereupon at once emit protons. The arrow slanting upward from the right signifies a process in which phosphorus is bombarded by neutrons (fast ones, in this case!) and some are absorbed by the nuclei P^{31}

[8] Energy-transfer between an initially-moving and an initially-stationary elastic sphere is greatest when the latter is of the same mass as the former, and for protons and neutrons this equality of mass is realized within 0.1 per cent.

which thereupon eject an alpha-particle apiece. The arrow pointing straight up signifies a process in which silicon is bombarded by neutrons; some are absorbed by nuclei Si^{28}, which instantly throw out protons. With no fewer than five ways of making a single radioactive type at his command, the physicist is in a position of power which seems all the more remarkable when one recalls that as lately as five years ago he had not (knowingly) made any radioactive substance by any way whatever.

Consider now the arrow pointing away from the solitary star in Fig. 11, and the arrows pointing away from the many stars in Figs. 2 and 3. These signify what is really meant by calling an isotope "radioactive." *A radioactive nucleus is one which spontaneously changes itself into a nucleus of another element by emitting a charged particle.* (Usually it lasts an appreciable time before it does so, and this delay is to be mentioned in a complete definition of the word "radioactive.") The arrows pointing away from the stars will serve to specify these changes. All in these figures are vertical; every one of these unstable isotopes transforms itself by emitting a particle of which the mass is very small (compared to the mass-unit which we are using) while the charge is $+e$ or $-e$, according as the transformation is to the element preceding or to the element following. These particles are positive and negative electrons. All of the man-made unstable nuclei are radioactive after this fashion, being electron-emitters; and so are more than half of those which are found in Nature.

What decides whether it shall be a positive or a negative electron which a given nucleus-type emits? Physicists cannot explain this as yet, in any adequate sense of the verb "to explain"; but we can readily see the law which governs the choice by examining the pictures. In Figs. 2 and 3 it will be seen that from each star the arrow points in whichever sense—upward or downward—it finds a circle to point at. Becoming completely animistic for the moment, I may say that the unstable nucleus wants to be stable—knows that one of its two neighbors, of identical mass-number but greater or lesser charge, is stable—knows *which* of the two is stable—and deliberately proceeds to identify itself with its stable neighbor by emitting an electron of the necessary sign. Putting the situation more drily: each of these unstable nucleus-types tends to transform itself into its adjacent stable isobar. Here "isobar" is a technical term for "nucleus of the same mass-number," and "adjacent" is a short way of saying "belonging to the preceding or the following element."

Suppose the star has circles both above and below it, *i.e.* that both of the adjacent isobars are stable (and prove themselves so by existing in Nature): how will the unstable nucleus resolve its dilemma? Such cases are rare, but not entirely absent. An example appears in Fig. 12. The elements palladium and cadmium have isobaric isotopes of mass-number 106, in spite of the fact that their atomic numbers (46 and 48) are not consecutive; silver, with atomic number 47, lies between. There is no stable silver isotope 106, but a radioactive one can be and has been created, and for this the dilemma is posed. It handles the

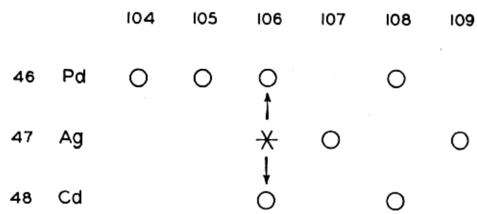

Fig. 12—Illustrating an example of isomers.

dilemma by grasping both horns! electrons of *both* signs come out of the radioactive silver. I must say that there is something which indicates that the nuclei which make one choice may be slightly different (in mass, for instance) from those which make the other. It may therefore be well to speak of silver as having two isotopes of the same mass-number 106, and a word has already been coined: they are called "isomers" of one another. This does not alter the fact that where alternative choices exist, both are elected.

On Fig. 2 we notice an arrow which points to a vacancy. No stable nucleus Be^8 is known, though there has been a very diligent search for it conducted by many ways in many places. Practically no doubt exists that Be^8 bursts of itself into two pieces (two alpha-particles) almost as soon as it is made. We thus have here an unstable (radioactive) nucleus—Li^8—which does *not* find stability by ejecting an electron, but instead hastens onward to a completer ruin. In the lower reaches of the Table of the Elements there are so many stable isotopes that the unstable ones can almost always turn themselves by one electron-emission into one or another of these, and such catastrophes are rare. Among the natural radioactive substances in the upper reaches of the Table they are common, as I now show in returning to natural radioactivity for the close of this talk.

Notice again Fig. 4, in which the stars are so many and the circles so few. If arrows were to be inserted to show the transformations, they would crisscross into a maze. I have therefore separated the figure into three: all of the circles, stars and rosettes in it will be found in Fig. 13 (which is really a pair of figures, as the caption says) and Fig. 14.

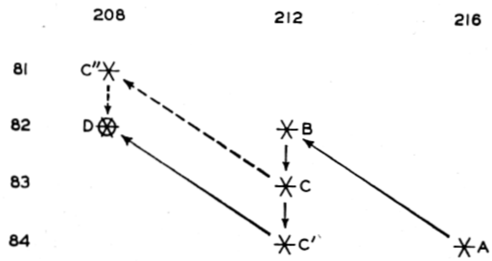

Fig. 13—Part of the thorium series of radioactive nuclei. To obtain the actinium series, imagine each star and rosette transposed one unit to the left.

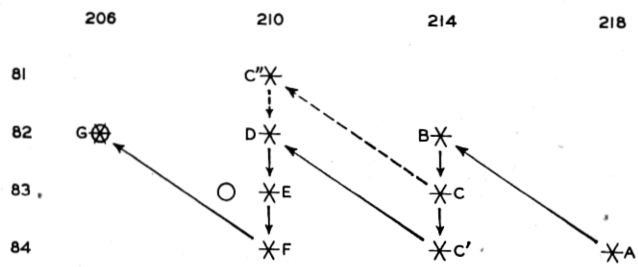

Fig. 14—Part of the radium series of radioactive nuclei.

Taking Fig. 13 as it stands, we see five of the stars and one rosette of Fig. 4 connected by arrows; each star marks a nucleus which transforms itself by emission of a particle into the one next following along the arrow-chain. The rosette stands for a stable nucleus, and would be replaced by a circle were it not distinguished by being the terminus of such a chain. These five radioactive isotopes and one terminal nucleus-type belong to the "thorium series," and are known as thorium A, thorium B, thorium C′ and so on, according to the letters which adjoin their stars. This is an unlucky bit of terminology, for it suggests that all are isotopes of the same element, which is clearly far from the truth.

Taking Fig. 13 again and imagining each star moved by one unit to the left (so that *e.g.* the star A goes to 217), we now are thinking of five more stars and another rosette of Fig. 4, duly connected by arrows. These constitute (a part of) the "actinium series" and are known as actinium A, actinium B and so forth.

Taking Fig. 14 as it stands, we find ourselves confronted by eight more of the stars and the last rosette of Fig. 4, connected by arrows. These constitute a part of the "radium series" and are known as radium A, radium B and so on. The "so on" covers more than it did in the other two cases, this chain continuing to the terminus here marked as radium G, though usually known by a different name.

Surveying the scene of these *massive* radioactive nuclei, one is struck by the fact that not all of the arrows are vertical. Many are slanting, and by their slant and their length they show that they represent the emission of alpha-particles. It is a feature of some (not of all) of the unstable nuclei of mass-numbers greater than 200, that they strive toward stability by emitting these. For this feature we should be very grateful, since it was by the use of alpha-particles from natural radioactive bodies that Rutherford achieved the first of transmutations; though physicists now can transmute without their aid, no one can guess how long they would have waited without trying had they not had that encouragement. Vertical arrows also are seen, but again there is a contrast to the lighter isotopes; all of the electrons emitted by radioactive nuclei of mass-numbers beyond 200, or by natural radioactive isotopes of whatever mass, are negative. But for the fact that positive electrons had been observed among the cosmic rays in 1932, they would have been discovered along with the first examples of artificial radioactive isotopes in 1934, and what a sensation that would have been!

More than by anything else, probably, one is impressed by the concatenation of these radioactive nuclei. A long journey to stability lies ahead of thorium A and actinium A, a longer one still ahead of radium A; but the total lengths of the journeys are greater yet, for they begin farther back. In Fig. 15 we behold the three series of radioactive isotopes in their entirety, and it is seen that the three "A-products," as they are called, are midway in the evolution and not at its beginning. The manner of drawing of this figure is changed from the preceding, atomic number being laid off along the horizontal axis and mass-number along the vertical; also, crosses and circles and dots are used to mark the members of the actinium, radium and thorium series respectively, and have no bearing on stability or instability. The actinium series should lie lower than it is drawn, with its terminus AcD lying midway between ThD and RaG; the mistake is incurred so as to diminish the overlappings which would otherwise confuse the picture.

Except for a few created in the last three years by transmutation, every known nucleus-type of mass-number greater than 209 and atomic number greater than 83 (as well as a few of slightly lower values) is found in Fig. 15. It appears that 83 and 209 are critical values of nuclear charge and mass, beyond which the constituents of nuclei—neutrons and protons, presumably, and whatever others there may be—cannot unite into stable systems.[9] All of these nuclei beyond 209 which are found in Nature are seeking for stability by the emission of particles, but never finding it until they have emitted

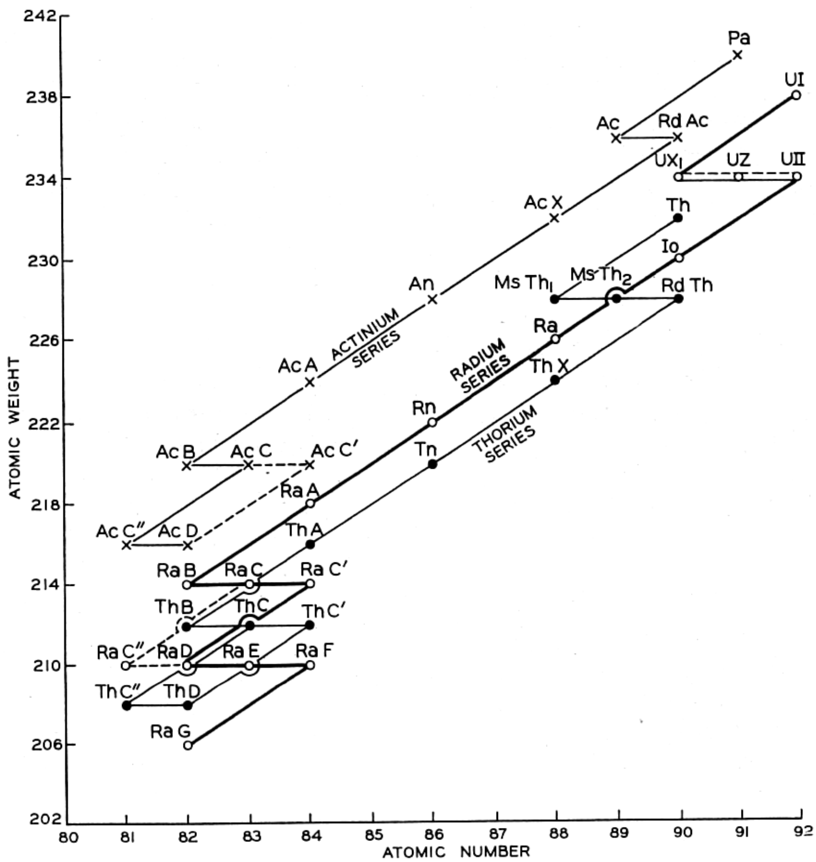

Fig. 15—The three series of radioactive substances.

sufficiently many to convert themselves (or rather, the residues of themselves) into one or another of the three isotopes of element 82—*lead*—which are marked by rosettes in Fig. 4. For an obvious reason these three are called thorium lead, actinium lead and radium lead. "Ordinary" lead as it comes from most mines is a mixture of many isotopes, but the lead which is found in close association with thorium or with uranium proves its origin from vanished atoms of these metals

[9] I recall from an earlier footnote that some of these very heavy nuclei (notably thorium 232 and uranium 238) are so very long-lasting that "unstable," while strictly correct, seems much too strong a word for them.

by being preponderantly the isotope 208 or the isotope 206 as the case may be.

I pause to mention, in justice to Rutherford, that it was he who proved by study of some of these natural radioactive bodies that each is transforming itself into a different element; also it was his associate Soddy who by similar studies was led to distinguish the first-to-be-recognized isotopes, that is, different radioactive forms of one and the same element. The way for making such diagrams as Figs. 2 and 3 and 4 was prepared before 1914 by these two men, though some of the facts embodied in Fig. 4 were not then available because of want of knowledge of atomic numbers, and all of the knowledge embodied in Figs. 2 and 3 was non-existent because no radioactive isotopes of these elements had yet been created and nobody knew as yet how to distinguish their stable isotopes. Also it should be mentioned that only the extraordinary potency of radioactive substances in affecting our instruments of measure enables the physicist or the chemist to recognize the element to which a radioactive isotope belongs, nay even to detect its presence. With radium and a few others, it has been possible to amass enough of the substance to see and to weigh; with the great majority of natural and with the totality of artificial radioactive isotopes, nothing of the sort has even been approached, and we should still be unacquainted [10] with them if they had been stable.

Three examples of transmutation which occur in these upper ranges of the Periodic Table deserve to be recorded in even so brief a report.

In Fig. 14, notice the circle in row 83 and column 209 which (as I earlier said) represents the highest stable nucleus—bismuth 209. Radium E, represented by the star to its right, is clearly bismuth 210; by the testimony of its mass-number and atomic number, it differs from stable bismuth nuclei by the possession of an extra neutron. If bismuth should be bombarded by neutrons, either free or bound into deuterons, would it be transformed into radium E? Livingood at Berkeley did bombard ordinary bismuth with very energetic deuterons, and did succeed in producing a radioactive substance which agreed with radium E not only in emitting negative electrons, but also in converting itself into a substance emitting alpha-particles, and the agreement extended to details of the emission. No doubt exists that he was making radium E out of bismuth 209 by enabling deuterons to transfer their constituent neutrons to this latter, just as H^3 is made from H^2 in the first of the deuteron-deuteron reactions.

[10] This statement should be qualified slightly, for some of the artificial radioactive nuclei spring from reactions of transmutation which are so well understood that the observer could justifiably infer the existence of the nuclei in question even if he did not observe them.

In Fig. 15, notice that all of the members of the thorium series have mass-numbers divisible by 4, or equal to $4n$ with various integer values given to n. This is accordingly called the "$4n$ series," and one readily sees what is meant by calling the radium and the actinium series by the names of "$4n + 2$" and "$4n + 3$" series respectively. One begins at once to wonder whether there is not a "$4n + 1$" series. Such a series was long sought after in vain, and no member of it has yet been discovered in Nature; but in the laboratory of the Curies in Paris thorium has lately been strongly bombarded by neutrons, and a new sequence of radioactive bodies has thus been engendered which has already been followed through several steps, and is in all probability the series so long missing.

As to the remaining feat—the creation of elements beyond uranium —it is now beyond doubt. Fermi and his school at Rome, Hahn and Meitner in Berlin, Curie and Joliot in Paris have all borne witness to it. In one way it seems the most romantic of all the feats of transmutation, for Nature had apparently set 92 as the limit of nuclear charge, and now man has transgressed it. The process is begun by exposing uranium to bombardment by streams of neutrons. It appears that when a uranium nucleus has captured a neutron, it finds itself not strongly enough charged to hold together, and proceeds to emit one negative electron after another in its search for stability. Each emission transfers the nucleus to an element one step higher, without affecting its mass-number; and the authorities agree that there are at least four consecutive emissions, after the last of which the atomic number is 96! This addition of four new elements to the Periodic Table opens a new field to chemists, one which they can scarcely have expected ever to be able to enter. The four have no proper names as yet, a curious circumstance in view of the fact that discoverers of new elements have thus far been in great haste (sometimes too great haste) to name them. Mendeleieff long ago used to denote an expected but undiscovered element by prefixing "eka" to the name of the element just above the vacant place in the Periodic Table; these new four are sometimes called eka-rhenium, eka-osmium, eka-iridium and eka-platinum, but on looking at such words one is inclined to prefer the atomic numbers.

Now to summarize. The world as we knew it before the days of transmutation was constructed out of some two hundred and fifty kinds of atoms, each consisting of a nucleus surrounded by a family of electrons. Of these 250 kinds of nuclei the great majority were stable and perpetual, but some forty were unstable—doomed to perish in due time, by ejecting either alpha-particles or negative electrons.

These were the natural radioactive bodies. To these forty kinds of radioactive nuclei already found in Nature, physicists have added in a scant four years no fewer than two hundred and twenty more by the art of transmutation. Every chemical element which is known to exist at all, with the sole exception of hydrogen, has at least one radioactive type of nucleus or isotope, and many have more than one. These man-made radioactive nuclei are often made simply by adding neutrons to nuclei which already exist and are stable. There are, however, other and more complicated processes, in which neutrons or protons or deuterons or alpha-particles impinge on nuclei and seem to enter them, and other particles leap out. Many radioactive bodies have already been made in two or three different ways, some in as many as five.

Few things are riskier than to suggest a limitation either on the scope of Nature or on the possibilities of science, and many a scientist is remembered chiefly for such a suggestion which later the course of events proved foolish. Yet there are circumstances in this case which give some ground for suspecting that already we may know nearly all of the stable and may have created nearly all of the radioactive nucleus-types. Several hundreds of types have now been made by the art of transmutation, but of them nearly all which seem to be stable are not new, and nearly all which are new are radioactive. This implies that the earth has already been stocked with almost all the stable nucleus-varieties, but not necessarily that we have yet come near to making all of the possible radioactive kinds. There are however reasons for believing that most of the remaining types have so little durability, that even if they were to be made they would not last long enough to be identified as radioactive. Nature probably has come quite close to building all the imperishable forms, we possibly almost as close to creating all of those which are capable of a little but not a perpetual life. Perhaps it is fitting that people who are not immortal should not be able to construct new elements which are immortal; but we at least can rejoice in having diversified the scene of the world with a surprising number of new substances which are none the less remarkable for being transitory.