the average might produce sufficient disturbance to start crystallization when the liquid had reached an extremely sensitive condition. If, however, before reaching so sensitive a state, the viscosity of the liquid had reached a great value, the likelihood of such an occurrence would be correspondingly small. Tammann's investigations[1] showed that many liquids could be cooled to amorphous solids without great difficulty. The method is merely that of cooling very quickly, and its effectiveness depends upon the avoidance of the necessary mechanical stimuli to crystallization by not allowing them time to occur.

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# RADIOACTIVITY.[2]

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Radioactivity comprises to-day a very large number of facts and theories of which it would not be possible to give a complete survey in a brief address. Nevertheless, I shall make an effort to bring out all the chief points of interest of the new science, the birth of which may be considered without exaggeration as the most important scientific event of the past few years.

Not only has this new science revealed the existence of extremely curious substances and brought a rich harvest of new natural phenomena, but it has led us to the attack of a problem which seemed absolutely chimerical only a few years ago—the problem of the transmutation of atoms or of the chemical elements; for it is now demonstrated that the phenomena of radioactivity are concomitants of the disintegration of atoms. Radioactivity may now be defined as the science of atomic transformations; it is not impossible that in time radioactivity may become the art of changing chemical elements into one another. The facts known at present leave no doubt as to the reality of atomic disintegrations; if as yet these transformations are entirely beyond our control, possibly some day we may learn how to bring them about and to control them.

The fundamental phenomenon, which was discovered by Henri Becquerel and has served as the point of departure for the development of radioactivity, is as follows: Certain substances emit spontaneously a peculiar radiation whose properties are analogous to those of the rays obtained in a Crookes tube. The new rays render gases conductors of electricity, act on a photographic plate, and produce fluorescence in certain substances. This spontaneous emission of rays was first observed in the case of uranium and its compounds, later also in the case of thorium compounds. Then were discovered new substances possessing the same property in a very high degree. All these substances are said to be *radioactive*. They constitute a new source of energy.

An apparently essential characteristic of the phenomenon of radio-

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[1] *Loc. cit.*

[2] A summary presented at the Second Decennial Celebration of Clark University, Worcester, Mass., September 17, 1909.

[3] Translated from the French by M. A. Rosanoff.

activity is its spontaneity: the emission of rays takes place without visible external cause. This characteristic permits of distinguishing the phenomena of radioactivity from those that take place in the course of certain chemical reactions. For instance, the oxidation of phosphorus is accompanied by phosphorescence and by electrical conductivity of the gases surrounding the phosphorus. The same phenomena may be brought about by the action of heat upon the sulfate of quinine. But in all such cases the phenomenon is not spontaneous; it is brought about by external causes which are easy to detect. Therefore, phosphorus and quinine sulfate are not considered as radioactive substances.

Another essential characteristic was brought out by the early researches of Madame Curie. Radioactivity is an atomic property. The spontaneous emission of rays is connected with the radioactive *atom*, and is not in the slightest degree influenced either by changes of state of aggregation of by chemical combination with the atoms of other elements. Thus, the intensity of the Becquerel rays emitted by the substances containing uranium, and measured by the conductivity of the surrounding gases, is always proportional to the number of uranium atoms contained in the substance and is independent of the form in which uranium may be present. Among the numerous other properties of matter, mass alone is so distinctly atomic in its nature.

Our realization of the atomic character of the radioactive property has had a directing influence on the science of radioactivity and has led to the establishment of its present theories. But first of all it had led to the discovery of radium itself and of the other strongly radioactive substances. I shall review briefly the genesis of the discovery of radium, which forms one of the most beautiful investigations ever carried out in the physical sciences, both as regards the logical keenness with which the research was carried on and as regards the material difficulties which had to be overcome. The novel method employed has since been constantly used in researches in radioactivity.

Among the elements that had previously been known, only uranium and thorium were radioactive, and the activity of any substance containing one of these elements was found to be proportional to the quantity of the active element present. Certain minerals, however, containing uranium showed a greater activity than metallic uranium itself. Pierre Curie and Madame Curie, thoroughly convinced of the atomic nature of radioactivity, assumed that these minerals contained new chemical elements, endowed with greater activity than uranium, and although physicists by profession, and with only rudimentary laboratory means at their disposal, they undertook a search after the new hypothetical elements.

I cannot depict here all the difficulties that presented themselves in the search, which involved the chemical treatment of tons of material. Suffice it to recall the results obtained by Pierre Curie and Madame Curie after several years of uninterrupted effort. Those results fulfilled their expectations entirely. The minerals studied do contain strongly radioactive compounds, whose radioactivity is due to the presence of new chemical elements. In the case of one of these elements, namely radium, it has been possible to prepare a series of pure salts; further, its spectrum has been studied, its atomic weight determined and a place has been assigned to it in the periodic classification of the elements. Radium has become a marvelous instrument of research, and to it we owe all the most important discoveries in radioactivity.

It was soon recognized that radioactive substances may differ from one another, not only in intensity of radiation, but also in the character of radiation and in certain peculiarities in the mode of emission of the rays. On the basis of these properties it is as easy to recognize a given radioactive element with certainty as it is to recognize one of the older elements with the aid of spectrum analysis.

The principal new radioactive substances are polonium and radium, discovered by Pierre Curie and Madame Curie; actinium, discovered by myself shortly afterwards; radio-thorium, discovered by Hahn; and ionium, discovered by Rutherford and Boltwood. However, certain of these substances are really complex mixtures containing entire families of chemical elements: namely, the thorium family, the radium family, and the actinium family.

The rays emitted by radioactive substances may be subdivided into three groups, *viz.*, the $\alpha$ rays, the $\beta$ rays, and the $\gamma$ rays, which are analogous to the three groups of rays emitted in a Crookes tube, *viz.*, canal rays, cathode rays, and Roentgen rays. The $\alpha$ rays are constituted by the projection of positively charged particles; the $\beta$ rays by a projection of negatively charged particles; the $\gamma$ rays are not charged at all.

The particles of $\beta$ rays are *electrons*, and the rays are easily bent out of their path by a magnetic field. Certain $\beta$ rays are constituted by electrons projected with an extremely great velocity, a velocity approaching that of light, and it has been possible to verify on these rays an important deduction from the electron theory. For very great velocities, namely, the inertia of a particle ceases to be a fixed quantity; it may greatly increase with increased velocity of motion, and so the particle no longer obeys the laws of Newtonian mechanics. Finally, comparing $\beta$ rays and cathode rays, one finds them analogous, only the particles of $\beta$ rays move with greater velocity and are capable of penetrating a much thicker layer of matter (for instance, a plate of aluminium one mm. thick).

The $\alpha$ rays are constituted by the projection of *material particles*, charged electro-positively, having the dimensions of atoms, and moving with a smaller velocity than the particles of $\beta$ rays. The $\alpha$ rays are bent by a magnetic field with considerable difficulty, and can penetrate only a very thin layer of matter (aluminium foil $^1/_{20}$ mm. thick absorbs them completely). They have the peculiarity of suddenly stopping after having traversed a certain well-determined path in a given medium. The length of this path in air is a very important quantity, for it permits of distinguishing from one another the different species of $\alpha$ rays and consequently also the different radioactive substances. The $\alpha$ particles play a very important part in radioactive transformations, and their nature seems now to be clearly understood.

The $\gamma$ rays are not charged, and therefore are not deflected by a magnetic field. They suffer but slight absorption in matter (a considerable proportion of the $\gamma$ rays from radium passes through a lead plate one centimeter in thickness).

These several rays excite fluorescence in a number of substances (platinocyanide of barium, sulfide of zinc, uranyl salts, glass, paper, diamond, etc.). The action of $\alpha$ rays upon zinc sulfide produces the very peculiar phenomenon generally designated by the term *scintillation*; in this, the luminosity of the zinc sulfide screen is caused by an infinity of brilliant little points which appear and disappear continually and which are clearly distinguishable when the screen is examined with a lens.

The radioactive substances constitute a new source of energy; but during the earlier researches both the origin and the mechanism of this production were entirely unknown. Pierre Curie and Madame Curie advanced two distinct hypotheses to explain the production of this energy. The first hypothesis assumed that the energy was furnished from outside in the form of a special radiation, causing in the radioactive substances a phenomenon analogous to phosphorescence. According to the second hypothesis, the energy comes from the active substance itself, and hence the emission of energy must be accompanied by a change in the substance. Pierre Curie and Madame Curie, who had demonstrated the atomic character of the new property, believed thoroughly, even before radium had been discovered, that the transformation takes place in the radioactive atom itself, which must therefore change into a different atom and, consequently, gradually disappear in course of time. It is this hypothesis of atomic transmutation that has proved to be most fruitful and has formed the basis of the theories accepted at present.

The principal fact which has led to these theories is as follows: With the aid of radioactive substances, whose activity appears constant and permanent, it is possible to produce phenomena of radioactivity whose intensity diminishes in time. These phenomena of temporary activity may be observed under various circumstances. Thus, if any substance whatever is placed near a salt of radium, thorium, or actinium, the surface of the substance becomes radioactive, and this activity diminishes more or less rapidly in time. This is the phenomenon of induced radioactivity discovered by Pierre Curie and Madame Curie. Similarly, any gaseous atmosphere surrounding radium, thorium, or actinium, becomes itself radioactive, and its activity likewise diminishes in time. Rutherford, the discoverer of this last phenomenon, gave the name "emanation" to the cause of the temporary activity of the gases. Finally, as first observed by myself, in the case of actinium, substances temporarily radioactive may also be obtained through certain chemical separations in mixtures containing permanently radioactive substances.

These temporary radioactivities often follow complex laws of decrease. The study of these laws has shown that there exist really several different kinds of radioactivity succeeding one another in time. When one kind of activity has died out, another replaces it, and this may gradually cease to exist in its turn. Each kind of radioactivity is characterized by its own velocity of decrease and by a radiation peculiar to itself. Extraordinarily great temporary radioactivities may accumulate in an extremely slight quantity of matter.

Applying to these temporary radioactivities the idea which had guided to the discovery of radium, namely, that radioactivity is an atomic property of the elements exhibiting it, one is led to think that the temporary radioactivities which have been separated from radium, thorium, and actinium characterize new radioactive atoms. And, accepting the hypothesis of atomic transmutation as an explanation of the origin of radioactive energy, the decrease of a given radioactivity appears to result from the gradual disappearance of a radioactive element and its transmutation into another element.

The present theory of radioactive phenomena is based on these considerations. It was proposed by Rutherford and Soddy, who have published numerous observations in complete accord with it. At present the theory is accepted by all investigators of radioactivity. An extremely precious guide in research, it has again and again been confirmed by discoveries of great importance.

The various phenomena exhibited by radium may, then, be interpreted as follows: The radium atom, which emits a certain $\alpha$ radiation, produces continually a radioactive emanation. This emanation is considered to be a radioactive gaseous element resulting from the transmutation of radium, and hence the latter must gradually disappear in time. The emanation emits an $\alpha$ radiation different from that of radium and disappears quite rapidly (the decrease follows a simple exponential law and amounts to one-half in 3.8 days). The emanation produces deposits of induced radioactivity, which are considered as new elements resulting from the transmutation of the emanation. In these deposits it has been possible to identify a series of stages which have received the names of Radium A, Radium B, Radium C, and which succeed one another, radium A changing into radium B, which in turn changes into radium C. These different members of the group emit different radiations and undergo destruction with considerable velocities.

Following radium C is another sequence of terms, characterized by a much smaller rate of disappearance, *viz.*, Radium D, Radium $E_1$, Radium $E_2$, and Radium F. The last-named has been shown by Rutherford to be identical with polonium. Polonium itself disappears little by little, but the element succeeding it is as yet unknown.

It has been possible to determin with much precision the laws of formation and destruction of the different transition terms of the series. These laws are exponential expressions analogous to those which hold for monomolecular chemical reactions. Most of the terms have been isolated (by means of chemical reactions, electrolysis, heating, condensation at low temperatures, etc.), and the several exponential formulas followed by their rates of destruction have been determined separately, the formula corresponding to each term having a characteristic exponent, $\lambda$, of its own. The rate of destruction of a given term is frequently characterized by specifying the time T required to diminish by one-half the original intensity of its radiation. The quantity $1/\lambda$ may be considered as the mean duration of life of an atom of the substance under consideration; it is denoted by the symbol $\Theta$ and is usually referred to briefly as "the mean life." We have, then, $\Theta = 1/\lambda$ and $T = \Theta \ln 2$.

The numerous researches which have been carried out on radioactive substances have resulted in fairly complete knowledge concerning the series of radioactive transformations in the several families, the properties of the different terms, and the properties of the rays emitted during the transformations. The knowledge gathered up to the present time is reproduced in the accompanying tables.

| Active substance | Destruction period T. | Radiation. | Path of α rays. | Absorption coefficient of β rays. | Absorption coefficient of γ rays. | Various properties. |
|---|---|---|---|---|---|---|
| *Uranium* | 6 × $10^9$ years (order of magnitude) | α | 3.5 cm. | | | At. wt. 238.5. Well known chemical properties. |
| ↓ | | | | | | |
| Radio-uranium | | | | | | Partly carried down by barium sulfate. |
| ↓ | | | | | | |
| Uranium X | 20.7 days | β,γ | | 2 groups:<br>$\mu_1 = 14.4$<br>$\mu_2 = 510$ | $\mu = 7.4$ | Prepared from uranium with iron hydroxide and bone-black, more soluble in water than in ether. |
| ↓<br>?<br>↓ | | | | | | |
| Ionium | 1500 years (?) | α | 2.8 cm. | | | Properties identical with those of thorium. |
| ↓<br>?<br>↓ | | | | | | |
| Radium | 2000 years | α | 3.5 cm | | | At. wt. 226.5. Group of alkaline earths. Luminous salts. Evolves heat (1 gram of radium in radioactive equilibrium evolves 118 calories per hour; 20 per cent. of this is produced by radium itself). The principal rays of the characteristic spectrum of radium are 4340.6; 3814.7; 3649.6. One gram of radium in equilibrium evolves 0.37 cubic millimeters of helium per day. The ionization produced by 1 gram of Ra in equilibrium equals that produced by 7,300,000 grams of uranium. |
| ↓ | | | | | | |

| Active substance. | Destruction, period T. | Radiation. | Path of $\alpha$ rays. | Absorption coefficient of $\beta$ rays. | Absorption coefficient of $\gamma$ rays. | Various properties. |
|---|---|---|---|---|---|---|
| Radium emanation.......... | 3.86 days | $\alpha$ | 4.23 cm. | | | Inert gas. Principal lines of the characteristic spectrum: 4349.8; 4166.6; 3981.6. The emanation in equilibrium with 1 gram of Ra occupies 0.60 cubic millimeter under a pressure of 1 atmosphere. |
| Radium A.................. | 3.0 minutes | $\alpha$ | 4.83 cm. | | | The deposit of induced activity is volatil at 800–900°. Soluble in strong acids. |
| Radium B.................. | 26.7 minutes | $\beta$ | | from 13 to 890 | | The deposit of induced activity is volatil at 600–700°. Precipitates together with $BaSO_4$. |
| Radium C.................. | 19.5 minutes | | | 13 to 53 | | The deposit of induced activity is volatil at 1000–1300°. Is deposited on nickel and copper in acid solution. Radium B and radium C can be separated by electrolysis. |
| Radium D.................. | 12 years (?) | No rays | | | | Properties identical with those of lead. Volatil below 1000°. |
| Radium $E_1$................. | 6.3 days | No rays | | | | Can be separated from radium D by boneblack and also by electrolysis. |
| Radium $E_2$................. | 4.8 days | $\beta$ | | 40 | | |
| Radium F or polonium...... | 140 days | $\alpha$ | 3.86 cm. | | | Is deposited on Bi, Cu, Sb, Ag, and even Pb. Sulfide insoluble. Carried down with basic salts of bismuth. Precipitated by $SnCl_2$. Volatil toward 1000°. |

| | | | | | | |
|---|---|---|---|---|---|---|
| ↓ | | | | | | The substance known as radio-lead is a mixture of radiums D, $E_1$, $E_2$, F. |
| ? | | | | | | |
| (unknown term) | | | | | | |
| *Thorium* | $3 \times 10^{10}$ years | $\alpha$ | 3.5 cm. | | | At. wt. 232.4. Known chemical properties. |
| ↓ | | | | | | |
| Mesothorium I | 5.5 years | | | | | |
| ↓ | | | | | | |
| Mesothorium II | 6.2 hours | $\beta,\gamma$ | | 20 to 39 | 0.5 | |
| ↓ | | | | | | |
| Radiothorium | 2.0 years | $\alpha$ | 3.9 cm. | | | |
| ↓ | | | | | | |
| Thorium X | 6.64 days | $\alpha$ | 5.7 cm. | | | Partly soluble in ammoniacal solutions. |
| ↓ | | | | | | |
| Thorium emanation | 53 seconds | $\alpha$ | 5.5 cm. | | | Inert gas. Condenses toward —120°. |
| ↓ | | | | | | |
| Thorium A | 10.6 hours | $\beta$ | | 140 | | The deposit of induced activity is soluble in strong acids. |
| ↓ | | | | | | |
| Thorium B | 55 minutes | $\alpha$ | 5.0 cm. | | | Deposit of induced activity. Is deposited upon nickel from acid solution. Carried down by boneblack. May be separated from thorium A by distillation or by electrolysis. |
| ↓ | | | | | | |
| Thorium C | very short | $\alpha,\beta,\gamma$ | 8.6 cm. | 15.7 | 0.5 | |
| ↓ | | | | | | |
| Thorium D | 3.7 minutes. | $\beta$ | | very penetrating | | |
| ↓ | | | | | | |
| ? | | | | | | |
| (unknown term) | | | | | | |

| Active substance. | Destruction, period T. | Radiation. | Path of α rays. | Absorption coefficient of β rays. | Absorption coefficient of γ rays. | Various properties. |
|---|---|---|---|---|---|---|
| *Actinium* | very long | No rays | | | | Group of rare earths. |
| ↓ | | | | | | |
| Radioactinium | 19.5 days | α | 4.8 cm. | | | May be separated by electrolysis or by fractionation with ammonia. |
| ↓ | | | | | | |
| Actinium X | 10.5 days | α,β | 6.55 cm. | 170 | | Soluble in ammoniacal solutions; can be separated by electrolysis. |
| ↓ | | | | | | |
| Actinium emanation | 3.9 seconds | α | 5.8 cm. | | | Inert gas. Condenses between —120° and —150°. |
| ↓ | | | | | | |
| Actinium A | 36.1 minutes | β | | highly absorbable | | Deposit of induced activity. Soluble in strong acids. Volatil at 400°. |
| ↓ | | | | | | |
| Actinium B | 2.1 minutes | α | 5.5 cm. | | | Can be separated from the preceding by electrolysis. Volatil at 700°. |
| ↓ | | | | | | |
| Actinium C | 5.1 minutes | β,γ | | 29 | 2.0 to 3.6 | Carried down by boneblack or by platinum sponge. |
| ↓ | | | | | | |
| ?<br>(unknown term) | | | | | | |

*Remark I.*—The absorption coefficients of the β and γ rays refer to aluminium and are expressed in cm.$^{-1}$ units.

*Remark II.*—Potassium salts possess a slight radioactivity, which seems to come, not from radioactive impurities, but from the potassium atom itself; β rays are emitted.

The inter-relation between the different terms of one and the same family is not the result of theoretical interpretation. It is a thoroughly established experimental fact. According to present-day theory, each term represents a certain chemical element which differs from the ordinary elements only by its ephemeral existence and by its emitting a special radiation. The disappearance of the radioactive atom is the result of its transformation into another atom, the special radiation representing the energy which accompanies that transformation. According to this theory, then, the study of radioactivity has led to the discovery of some thirty new elements.

The theory outlined above permits of an easy interpretation of all phenomena thus far known. Still, it was a matter of great importance to obtain a direct experimental demonstration of the reality of atomic transformations, and of the existence of chemical atoms having a very short life, corresponding to the ephemeral radioactivities. Such direct experimental demonstrations have actually been produced, and hence the theory rests on an extremely solid basis.

The reality of atomic transformations accompanying the phenomena of radioactivity has been demonstrated by the experiments of Ramsay and Soddy on the production of helium from radium. Radium, whose character as a chemical element is established by its chemical properties, by its atomic weight, and by its spectrum, continually produces the gas helium, which is itself a well characterized chemical element. This production of helium cannot be reasonably interpreted in any other way than by recognizing atomic transformation.

Some time after Ramsay and Soddy, I showed that the same phenomenon takes place in actinium, which also continually produces helium gas. Recently, Soddy has discovered the production of helium also from uranium and from thorium.

The production of helium from radioactive substances is the first case ever discovered of the transformation of chemical atoms.

That an ephemeral radioactivity is due to the existence of a corresponding chemical element has been experimentally demonstrated in the case of the radium emanation. This emanation has been isolated in a pure state, its spectrum determined, and its volume measured. Somewhat numerous experiments were first carried out by Ramsay and his collaborators, and though the published results are not in perfect agreement, they still leave no doubt whatever as to the material existence of the emanation, which is characterized by a spectrum of its own. The isolation of the substance was effected by utilizing its property of easily condensing at low temperatures. These experiments were later repeated by Rutherford and Royds, who obtained agreeing measurements of the volume occupied by the pure emanation produced by a given quantity of radium, and who described completely the spectrum of the emanation. Recently, I have carried out analogous experiments: my volume measurements agree perfectly with Rutherford's, and my spectrophotographs are identical with those of Rutherford and Royds. I have observed besides that the volume of gas produced does not increase proportionally to the time, owing to the spontaneous destruction of the substance. The observed volume is invariably proportional to the radioactivity of the emanation, no matter what the duration of its production from radium. In the experiments mentioned above, all investigators have observed the production of helium from the emanation: the spectrum of helium gradually appears, while that of the emanation disappears. Finally, Rutherford, and also Ramsay, have succeeded in determining the point of liquefaction and the point of solidification of the emanation.

It thus appears entirely certain that the emanation is a material gas—a fact which corroborates very strongly Rutherford and Soddy's theory.

The production of helium by radioactive substances is directly related to the emission of $\alpha$ particles, and the hypothesis early advanced by Rutherford, that each $\alpha$ particle is an atom of helium, is to-day confirmed. In fact, Rutherford has shown that the $\alpha$ rays and the helium produced by the radium emanation pass through thin layers of matter in a similar manner. Other properties of the $\alpha$ particles are in complete accord with this conception of their nature.

Now, if we assume that in all transformations accompanied by the emission of $\alpha$ particles each radioactive atom changes into the next in order by loss of a single $\alpha$ particle or helium atom, it becomes possible to calculate the atomic weights of the several transition elements of the radium series. The atomic weight of helium being 4, we have, namely: Radium 226.5 ⟶ Emanation 222.5 ⟶ Radium A 218.5 ⟶ Radium B 214.5 ⟶ Radium C 214.5 ⟶ Radium D 210.5 ⟶ Radium E 210.5 ⟶ Radium F, or Polonium, 210.5 ⟶ a last unknown substance 206.5. This last number represents exactly the atomic weight of lead, which suggests the idea that this element is the final product of the transformation of radium. It is probable that this idea can be subjected to experimental verification.

The mother substances, uranium, radium, actinium, and thorium, ought to gradually disappear in course of time, as they are transformed into other elements. But the destruction is certainly very slow, and no diminution of their activity has been directly detected. The laws of their destruction may, however, be determined indirectly. Since the transformation of each radioactive atom produces an emission of rays, it is natural to assume that the more intense the radiation produced by a gram-atom of the substance, the more rapid is the transformation. Thus, radium ought to have a much shorter life than uranium or thorium. The comparison of the radiations may be carried out quantitatively, and thus the ratio of the mean lives of two radioactive substances may be readily obtained.

On the other hand, if it is assumed that the emission of a single $\alpha$ particle corresponds to the transformation of a single atom, it will suffice to determin the number of particles emitted per second by a given mass of the active substance under consideration, in order to ascertain its velocity of transformation. Indirect determinations were first made by measuring the total positive charge emitted in the form of $\alpha$ rays by the active substance and making an assumptiion concerning the charge of a single particle. The results so obtained have been confirmed by directly counting the $\alpha$ particles emitted by a certain quantity of active substance.

The first direct results were yielded by the scintillations produced by $\alpha$ particles on a screen of zinc sulfide. Each scintillation being assumed to be produced by a single $\alpha$ particle, the number of scintillations was determined, produced in a given time by a known quantity of the active substance. This gave the number of $\alpha$ particles emitted by the substance, and consequently the number of atoms transformed in a given time. Another, and very ingenious, method was first employed by Rutherford and Geiger, who utilized the ionization produced in a gas by $\alpha$ particles. These investigators succeeded in determining the ionizing effect produced in a rarefied gas by each $\alpha$ particle by making use of the phenomenon of ionization by shock. The entrance of each single $\alpha$ particle into the gas affects the electrometer, and all that is necessary is to count the number of disturbances produced in a given time. The two methods have yielded well agreeing results, which indicate that radium ought to be one-half destroyed in about 2000 years.

The destruction of radium is too slow to be capable of being detected by direct experiment. Nevertheless, in order to account for the presence of radium in minerals, it is necessary to assume that radium is continually produced in those minerals, the destruction being thus partly compensated for. The element which appears evidently to be the most capable of changing into radium is uranium.

In fact, radium is always found in uranium minerals and, furthermore, uranium is radioactive and hence in a state of decomposition. Since the radioactivity of uranium is much less intense than that of radium, its duration of life must be much greater than that of radium, and this explains the occurrence of uranium in considerable quantities in nature.

An extremely important argument in support of the accepted relationship between uranium and radium lies in the constant ratio of the quantities of the two elements found in minerals. The constancy of this ratio, which has been principally affirmed by the experiments of Boltwood, is readily explained if we assume that radium is produced from uranium, and that the destruction of radium is much more rapid than that of uranium. The ratio permits of calculating the mean life of uranium.

Attempts to demonstrate directly the formation of radium from uranium have shown that this transformation is certainly not immediate, and that there ought to exist at least one substance intermediate between uranium and radium. This has been confirmed by Rutherford and Boltwood's discovery of a new substance capable of producing radium. This new substance has been named ionium. The mean life of ionium being probably long, there is hope that this substance will be isolated without much difficulty.

The question of the relationship between uranium and radium seemed to be definitly settled, when recently Mlle. Gleditsch announced that the ratio of the quantities of uranium and radium was *not* the same in all minerals, contradicting the earlier results of Boltwood. While the ratios found by Mlle. Gleditsch are of the same order of magnitude, they nevertheless differ very materially from one another. The hypothesis of the formation of radium from uranium furnishes so simple an explanation of the presence of radium in minerals that one can hardly abandon it. As a matter of fact, however, the conditions of formation of radium appear to be complex and not yet completely elucidated. Unquestionably, further study of the relative quantities of the different active substances in minerals will yield new and important results. Such study will also be of great usefulness in geology.

If the phenomena of radioactivity indicate atomic transformation, one expects to find radioactive energy, corresponding to the transformation of atoms, to be far greater than the energy changes generally accompanying the transformation of molecules. That this is true is shown by Pierre Curie and Laborde's discovery of the enormous quantity of energy given off by radium. One gram of radium in radioactive equilibrium would produce about 120 calories of heat in an hour. The quantity of heat that would be set free by the complete transformation of one gram of radium is nearly the same as that produced by the combustion of a ton of coal. Most of this heat has been shown to come from the kinetic energy of the $\alpha$ particles. Heat has also been shown to be developed by actinium, thorium, and polonium. Radioactivity thus constitutes an extremely important source of energy. A very slight proportion of radium in the sun (about 1 gram per cubic meter) would be sufficient to account for all the energy radiated by it. The energy radiated by our own planet seems to be more than compensated for by the radium contained in its crust, so that the progressive cooling of the earth, once generally accepted, now seems to be problematic. It seems legitimate to assume that radioactivity constitutes one of the principal sources of the energy radiated in the universe. No other hypothesis is based on an equally serious experimental foundation.

The atomic transformation of radioactivity takes place under very peculiar conditions. As already stated, the phenomenon is spontaneous, apparently causeless. Moreover, no method is as yet known by which such transformations might be brought about or stopped, or even in the least degree hastened or slowed up. Elevation of temperature, which is so sure to increase the velocity of chemical reactions, seems to have no effect whatever on radioactive transformations. Thus, the characteristic constant of the destruction of radium emanation is the same at high temperatures as at the temperature of liquid air. Neither does the nature of an inactive chemical element combined with the radioactive atom seem to have any influence upon the velocity of its destruction. As yet, we are mere spectators, observing the transformation of atoms, but unable to interfere with it in any way.

The transformation follows a probability law identical with the law of mass action followed by chemical reactions: the number of atoms transformed per unit of time is at any instant proportional to the total number of atoms present. No simple and satisfactory hypothesis, however, has been advanced explaining this fact. In the case of mono-molecular chemical reactions, the fact that the transformation takes place gradually is explained on the assumption that all the molecules present are not in the same condition, either owing to collisions between the molecules or because of differences in whatever motion may be going on within the molecules themselves. The transformation of a given molecule is instantaneous, but the molecule will not undergo transformation unless it happens to get into a certain condition necessary for it. The probability law must then remain the same as long as the number of molecules remains very great and the external conditions of the reaction remain the same. In the case of radioactive transformations, external conditions (*e. g.*, of temperature) and intermolecular collisions ought to have no effect. Therefore, only the motion within the interior of the atom can be invoked in an effort to explain why, in one and the same substance, some atoms break down immediately after being formed, while others are destined to live hundreds or even thousands of years before undergoing transformation.

It is imaginable that there exists in space a special field of force which influences intra-atomic motion and is therefore capable of causing the disintegration of atoms. The action of such a force must then be independent of any translatory motion of the atoms. There is, however, at present absolutely no indication of the existence of such a force in space.

If the transformation is *not* brought about by an external force, and if external conditions of pressure, temperature, etc., have really no influence upon the progress of radioactive changes, one is led to assume that the destiny of a given atom is completely determined at the very moment of its formation, that at that moment it is already in such a state that its transformation must take place after exactly a certain interval of time. In that case a radioactive element must be considered as made up of atoms of different nature, some destined to very speedy destruction, others to a more or less prolonged existence. It is not unthinkable that these different atoms of one and the same radioactive element may some day be separated.

In order to account for the exponential law of spontaneous destruction, it is necessary, in that case, to assume that the distribution of life durations among the atoms at the moment of their formation is represented by a simple exponential function, the atoms of short life being much more numerous than those of long life. It is, however, difficult to imagine what can possibly be the cause of such a law of distribution, and considerations like the above only show that while the laws of radioactive transformations have been determined with precision and are well known, the initial cause of the phenomena is as yet altogether obscure.

In concluding this summary, I will mention the attempts that have been made with a view to artificially bringing about atomic transformations with the aid of radioactive energy. Some results in this connection have been published by Ramsay and Cameron. They believed that by the action of radium emanation upon water they had succeeded in producing neon. They further believed that by the action of the emanation upon a salt of copper they had produced alkali metals: the formation of lithium appeared to have been especially well demonstrated.

These results have, unfortunately, been shown to be erroneous. Mme. Curie and Mlle. Gleditsch repeated the experiments on the formation of lithium and found that when no other than platinum vessels were used, the appearance of lithium could not be detected; in Ramsay and Cameron's experiments the lithium came from the glass of the apparatus employed. Similarly, Rutherford and Royds have re-investigated the effect of emanation upon water and have failed to obtain any neon. I, too, have failed to find neon in the gases evolved by a solution of radium. The neon found by Ramsay and Cameron must have come from a small quantity of air introduced by accident.

So it may be said that up to the present time no atomic transmutation has been produced artificially. All we can do is to subject to inquiry spontaneous transmutations which we cannot control. A long step, therefore, remains to be taken before the dream of the alchemists has been realized.[1]

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## NOTES.

*An Electrically Heated Sealed Tube Furnace.*—A sealed tube furnace must, frequently, be allowed to run over night and, at the same time, admit of being easily moved from place to place. The danger from fire, involved when heated by the ordinary burner, as well as the impossibility of keeping a uniform temperature without a temperature regulator, in many cases, makes the use of electricity very convenient as a means of heating.

This is very readily accomplished by means of nichrome resistance wire covered with asbestos (this wire can be obtained from the Driver-Harris Wire Co., of Harrison, N. J.). With this wire it is possible to make the windings directly on the iron tubes of the furnace without danger of short circuit at the temperature customarily used in these furnaces.

The furnace in question was made by covering each of the two tubes, in an ordinary sealed tube furnace, with one layer of thin absestos paper (an advisable precaution) and then winding with 55 feet of No. 22 B. S. asbestos covered, nichrome resistance wire. The wire was wound somewhat closer at each end than in the center of the tube, this making an even distribution of heat throughout the length of the tube. Under these conditions about 2 amperes were used when connected in parallel to a 110 volt circuit and 1 ampere when connected in series. This gave temperatures of 150° and 250° within the tubes. When the space within the box around the iron tubes was filled with asbestos fiber and magnesium oxide, temperatures of 240° and 440° were obtained. If checked occasionally a resistance box marked with the temperatures corresponding to the different steps will give a very satisfactory means of regulating the temperature. RAYMOND C. BENNER.

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*A Handy Buret-Holder.*—Being obliged, on an occasion three years ago, to work with a small traveling laboratory forty miles from the base of supplies, it became necessary to improvize a compact support for a

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[1] New results have been published by Ramsay and Gray. According to these investigators, carbon dioxide may be produced by the action of radium emanation upon compounds of thorium, zirconium, silicon, etc. But inasmuch as carbon compounds may easily find their way into apparatus by accident, it is difficult to establish beyond doubt a transformation of the elements thorium or zirconium into carbon. The authors themselves admit that their experiments are not conclusive.