practically all of the emanation comes off very suddenly at a temperature not much more than one degree above that at which only 2 per cent. has volatilized. The general indication of all the experiments, considered together, is to show that the condensed emanation possesses a true vapour-pressure, and that the emanation commences to volatilize slowly two or three degrees below the temperature of rapid volatilization even when the process occurs in a stationary atmosphere. The emanations therefore possess the usual properties possessed by ordinary gaseous matter, in so far as the phenomena of volatilization and condensation are concerned. It was shown in a recent paper that they also possess the property possessed by gases of being occluded by solids under certain conditions. These new properties, taken in conjunction with the earlier discovered diffusion phenomena, characteristic of the radioactive emanations, leave no doubt that the latter must consist of matter in the gaseous state.

McGill University, Montreal,
March 9, 1903.

LX. *Radioactive Change.* *By* E. RUTHERFORD, *M.A.*, *D.Sc.*, *Macdonald Professor of Physics, McGill University, and* F. SODDY, *M.A.* (*Oxon.*).

CONTENTS.

§ 1. *The Products of Radioactive Change and their Specific Material Nature.*

IN previous papers it has been shown that the radioactivity of the elements radium, thorium, and uranium is maintained by the continuous production of new kinds of matter which possess temporary activity. In some cases the new product exhibits well-defined chemical differences from the element producing it, and can be separated by chemical processes. Examples of this are to be found in the removal of thorium X from thorium and uranium X from uranium. In other cases the new products are gaseous in character, and

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[*] Communicated by the Authors.

so separate themselves by the mere process of diffusion, giving rise to the radioactive emanations which are produced by compounds of thorium and radium. These emanations can be condensed by cold and again volatilized ; although they do not appear to possess positive chemical affinities, they are frequently occluded by the substances producing them when in the solid state, and are liberated by solution; they diffuse rapidly into the atmosphere and through porous partitions, and in general exhibit the behaviour of inert gases of fairly high molecular weight. In other cases again the new matter is itself non-volatile, but is produced by the further change of the gaseous emanation; so that the latter acts as the intermediary in the process of its separation from the radioactive element. This is the case with the two different kinds of excited activity produced on objects in the neighbourhood of compounds of thorium and radium respectively, which in turn possess well-defined and characteristic material properties. For example, the thorium excited activity is volatilized at a definite high temperature, and redeposited in the neighbourhood, and can be dissolved in some reagents and not in others.

These various new bodies differ from ordinary matter, therefore, only in one point, namely, that their quantity is far below the limit that can be reached by the ordinary methods of chemical and spectroscopic analysis. As an example that this is no argument against their specific material existence, it may be mentioned that the same is true of radium itself as it occurs in nature. No chemical or spectroscopic test is sufficiently delicate to detect radium in pitchblende, and it is not until the quantity present is increased many times by concentration that the characteristic spectrum begins to make its appearance. Mme. Curie and also Giesel have succeeded in obtaining quite considerable quantities of pure radium compounds by working up many tons of pitchblende, and the results go to show that radium is in reality one of the best defined and most characteristic of the chemical elements. So, also, the various new bodies, whose existence has been discovered by the aid of their radioactivity, would no doubt, like radium, be brought within the range of the older methods of investigation if it were possible to increase the quantity of material employed indefinitely.

§ 2. *The Synchronism between the Change and the Radiation.*

In the present paper the nature of the changes in which these new bodies are produced remains to be considered. The experimental evidence that has been accumulated is now sufficiently complete to enable a general theory of the nature of the process to be established with a considerable degree of certainty and definiteness. It soon became apparent from this evidence that a much more intimate connexion exists between the radioactivity and the changes that maintain it than is expressed in the idea of the production of active matter. It will be recalled that all cases of radioactive change that have been studied can be resolved into the production by one substance of one other (disregarding for the present the expelled rays). When several changes occur together these are not simultaneous but successive. Thus thorium produces thorium X, the thorium X produces the thorium emanation, and the latter produces the excited activity. Now the radioactivity of each of these substances can be shown to be connected, not with the change in which it was itself produced, but with the change in which it in turn produces the next new type. Thus after thorium X has been separated from the thorium producing it, the radiations of the thorium X are proportional to the amount of emanation that it produces, and both the radioactivity and the emanating power of thorium X decay according to the same law *and at the same rate*. In the next stage the emanation goes on to produce the excited activity. The activity of the emanation falls to half-value in one minute, and the amount of excited activity produced by it on the negative electrode in an electric field falls off in like ratio. These results are fully borne out in the case of radium. The activity of the radium emanation decays to half-value in four days, and so also does its power of producing the excited activity.

Hence it is not possible to regard radioactivity as a *consequence* of changes that have already taken place. The rays emitted must be an *accompaniment* of the change of the radiating system into the one next produced.

Non-separable activity.—This point of view at once accounts for the existence of a constant radioactivity, non-separable by chemical processes, in each of the three radio-elements. This non-separable activity consists of the radiations that accompany the primary change of the radio-element itself into the first new product that is produced. Thus in thorium about 25 per cent. of the α radiation accompanies the first change of the thorium into thorium X. In uranium the whole of the α radiation is non-separable and accompanies the change of the uranium into uranium X.

Several important consequences follow from the conclusion that the radiations accompany the change. A body that is radioactive must *ipso facto* be changing, and hence it is not possible that any of the new types of radioactive matter—*e. g.*, uranium X, thorium X, the two emanations, &c.—can be identical with any of the known elements. For they remain in existence only a short time, and the decay of their radioactivity is the expression of their continuously diminishing quantity. On the other hand, since the ultimate products of the changes cannot be radioactive, there must always exist at least one stage in the process beyond the range of the methods of experiment. For this reason the ultimate products that result from the changes remain unknown, the quantities involved being unrecognizable, except by the methods of radioactivity. In the naturally occurring minerals containing the radio-elements these changes must have been proceeding steadily over very long periods, and, unless they succeed in escaping, the ultimate products should have accumulated in sufficient quantity to be detected, and therefore should appear in nature as the invariable companions of the radio-elements. We have already suggested on these and other grounds that possibly helium may be such an ultimate product, although, of course, the suggestion is at present a purely speculative one. But a closer study of the radioactive minerals would in all probability afford further evidence on this important question.

§ 3. *The Material Nature of the Radiations.*

The view that the ray or rays from any system are produced at the moment the system changes has received strong confirmation by the discovery of the electric and magnetic deviability of the α ray. The deviation is in the opposite sense to the β or cathode-ray, and the rays thus consist of positively charged bodies projected with great velocity (Rutherford, Phil. Mag., Feb. 1903). The latter was shown to be of the order of $2{\cdot}5\ 10^9$ cms. per second. The value of e/m, the ratio of the charge of the carrier to its mass, is of the order $6\ 10^3$. Now the value of e/m for the cathode-ray is about 10^7. Assuming that the value of the charge is the same in each case, the apparent mass of the positive projected particle is over 1000 times as great as for the cathode-ray. Now $e/m = 10^4$ for the hydrogen atom in the electrolysis of water. The particle that constitutes the α ray thus behaves as if its mass were of the same order as that of the hydrogen atom. The α rays from all the radio-elements, and from the various radioactive bodies which they produce, possess analogous properties, and differ only to a slight extent in penetrating power. There are thus strong reasons for the belief that the α rays generally are projections and that the mass of the particle is of the same order as that of the hydrogen atom, and very large compared with the mass of the projected particle which constitutes the β or easily deviable ray from the same element.

With regard to the part played in radioactivity by the two types of radiation, there can be no doubt that the α rays are by far the more important. In all cases they represent over 99 per cent. of the energy radiated *, and although the β rays on account of their penetrating power and marked photographic action have been more often studied, they are comparatively of much less significance.

It has been shown that the non-separable activity of all three radio-elements, the activity of the two emanations, and the first stage of the excited activity of radium, comprise only α rays. It is not until the processes near completion in so far as their progress can be experimentally traced that the β or cathode-ray makes its appearance †.

In light of this evidence there is every reason to suppose, not merely that the expulsion of a charged particle accompanies the change, but that this expulsion actually *is* the change.

§ 4. *The Law of Radioactive Change.*

The view that the radiation from an active substance accompanies the change gives a very definite physical meaning to the law of decay of radioactivity. In all cases where one of the radioactive products has been separated, and its activity examined independently of the active substance which gives rise to it, or which it in turn produces, it has been found that the activity under all conditions investigated falls off in a geometrical progression with the time. This is expressed by the equation

$$\frac{I_t}{I_o} = \epsilon^{-\lambda t}$$

where I_o is the initial ionization current due to the radiations, I_t that after the time t, and λ is a constant. Each ray or

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* In the paper in which this is deduced (Phil. Mag. Sept. 1902, p. 329) there is an obvious slip of calculation. The number should be 100 instead of 1000.

† In addition to the a and β rays the radio-elements also give out a third type of radiation which is extremely penetrating. Thorium as well as radium (Rutherford, *Phys. Zeit.* 1902) gives out these penetrating rays, and it has since been found that uranium possesses the same property. These rays have not yet been sufficiently examined to make any discussion possible of the part they play in radioactive processes.

projected particle will in general produce a certain definite number of ions in its path, and the ionization current is therefore proportional to the number of such particles projected per second. Thus

$$\frac{n_t}{n_o} = \epsilon^{-\lambda t},$$

where n_t is the number projected in unit of time for the time t and n_o the number initially.

If each changing system gives rise to one ray, the number of systems N_t which remain unchanged at the time t is given by

$$N_t = \int_t^\infty n_t \,.\, dt = \frac{n_o}{\lambda}\epsilon^{-\lambda t}.$$

The number N_o initially present is given by putting $t=0$.

$$N_o = \frac{n_o}{\lambda}$$

and

$$\frac{N_t}{N_o} = \epsilon^{-\lambda t}.$$

The same law holds if each changing system produces two or any definite number of rays.

Differentiating

$$\frac{dN}{dt} = -\lambda N_t,$$

or, the rate of change of the system at any time is always proportional to the amount remaining unchanged.

The law of radioactive change may therefore be expressed in the one statement—the proportional amount of radioactive matter that changes in unit time is a constant. When the total amount does not vary (a condition nearly fulfilled at the equilibrium point where the rate of supply is equal to the rate of change) the proportion of the whole which changes in unit time is represented by the constant λ, which possesses for each type of active matter a fixed and characteristic value. λ may therefore be suitably called the "radioactive constant." The complexity of the phenomena of radioactivity is due to the existence as a general rule of several different types of matter changing at the same time into one another, each type possessing a different radioactive constant.

§ 5. *The Conservation of Radioactivity.*

The law of radioactive change that has been deduced holds for each stage that has been examined, and therefore holds for the phenomenon generally. The radioactive constant λ has been investigated under very widely varied conditions of temperature, and under the influence of the most powerful chemical and physical agencies, and no alteration of its value has been observed. The law forms in fact the mathematical expression of a general principle to which we have been led as the result of our investigations as a whole. Radioactivity, according to present knowledge, must be regarded as the result of a process which lies wholly outside the sphere of known controllable forces, and cannot be created, altered, or destroyed. Like gravitation, it is proportional only to the quantity of matter involved, and in this restricted sense it is therefore true to speak of the principle as the conservation of radioactivity*. Radioactivity differs of course from gravitation in being a special and not necessarily a universal property of matter, which is possessed by different kinds in widely different degree. In the processes of radioactivity these different kinds change into one another and into inactive matter, producing corresponding changes in the radioactivity. Thus the decay of radioactivity is to be ascribed to the disappearance of the active matter, and the recovery of radioactivity to its production. When the two processes balance—a condition very nearly fulfilled in the case of the radio-elements in a closed space—the activity remains constant. But here the apparent constancy is merely the expression of the slow rate of change of the radio-element itself. Over sufficiently long periods its radioactivity must also decay according to the law of radioactive change, for otherwise it would be necessary to look upon radioactive change as involving the creation of matter. In the universe therefore the total radioactivity must, according to our present knowledge, be growing less and tending to disappear.

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* Apart from the considerations that follow, this nomenclature is a convenient expression of the observed facts that the total radioactivity (measured by the radiations peculiar to the radio-elements) is for any given mass of radio-element a constant under all conditions investigated. The radioactive equilibrium may be disturbed and the activity distributed among one or more active products capable of separation from the original element. But the sum total throughout these operations is at all times the same.

For practical purposes the expression "conservation," applied to the radioactivity of the three radio-elements, is justified by the extremely minute proportion that can change in any interval over which it is possible to extend actual observations. But *rigidly* the term "conservation" applies only with reference to the radioactivity of any definite quantity of radioactive matter, whereas in nature this quantity must be changing spontaneously and continually growing less. To avoid possible misunderstanding, therefore, it is necessary to use the expression only in this restricted sense.

Hence the energy liberated in radioactive processes does not disobey the law of the conservation of energy.

It is not implied in this view that radioactivity, considered with reference to the quantity of matter involved, is conserved under all conceivable conditions, or that it will not ultimately be found possible to control the processes that give rise to it. The principle enunciated applies of course only to our present state of experimental knowledge, which is satisfactorily interpreted by its aid.

The general evidence on which the principle is based embraces the whole field of radioactivity. The experiments of Becquerel and Curie have shown that the radiations from uranium and radium respectively remain constant over long intervals of time. Mme. Curie put forward the view that radioactivity was a specific property of the element in question, and the successful separation of the element radium from pitchblende was a direct result of this method of regarding the property. The possibility of separating from a radio-element an intensely active constituent, although at first sight contradictory, has afforded under closer examination nothing but confirmation of this view. In all cases only a part of the activity is removed, and this part is recovered spontaneously by the radio-element in the course of time. Mme. Curie's original position, that radioactivity is a specific property of the element, must be considered to be beyond question. Even if it should ultimately be found that uranium and thorium are admixtures of these elements with a small *constant* proportion of new radio-elements with correspondingly intense activity, the general method of regarding the subject is quite unaffected.

In the next place, throughout the course of our investigations we have not observed a single instance in which radioactivity has been created in an element not radioactive, or destroyed or altered in one that is, and there is no case at present on record in which such a creation or destruction can be considered as established. It will be shown later that radioactive change can only be of the nature of an atomic disintegration, and hence this result is to be expected, from the universal experience of chemistry in failing to transform the elements. For the same reason it is not to be expected that the rate of radioactive change would be affected by known physical or chemical influences. Lastly, the principle of the conservation of radioactivity is in agreement with the energy relations of radioactive change. These will be considered more fully in § 7, where it is shown that the energy changes involved are of a much higher order of magnitude than is the case in molecular change.

It is necessary to consider briefly some of the apparent exceptions to this principle of the conservation of radioactivity. In the first place it will be recalled that the emanating power of the various compounds of thorium and radium respectively differ widely among themselves, and are greatly influenced by alterations of physical state. It was recently proved (Phil. Mag. April 1903, p. 453) that these variations are caused by alterations in the rate at which the emanations escape into the surrounding atmosphere. The emanation is produced at the same rate both in de-emanated and in highly emanating thorium and radium compounds, but is in the former stored up or occluded in the compound. By comparing the amount stored up with the amount produced per second by the same compound dissolved, it was found possible to put the matter to a very sharp experimental test which completely established the law of the conservation of radioactivity in these cases. Another exception is the apparent destruction of the thorium excited activity deposited on a platinum wire by ignition to a white heat. This has recently been examined in this laboratory by Miss Gates, and it was found that the excited activity is not destroyed, but is volatilized at a definite temperature and redeposited in unchanged amount on the neighbouring surfaces.

Radioactive "Induction."—Various workers in this subject have explained the results they have obtained on the idea of radioactive "induction," in which a radioactive substance has been attributed the power of inducing activity in bodies mixed with it, or in its neighbourhood, which are not otherwise radioactive. This theory was put forward by Becquerel to explain the fact that certain precipitates (notably barium sulphate) formed in solutions of radioactive salts are themselves radioactive. The explanation has been of great utility in accounting for the numerous examples of the presence of radioactivity in non-active elements, without the necessity of assuming in each case the existence of a new radio-element therein, but our own results do not allow us to accept it.

In the great majority of instances that have been recorded the results seem to be due simply to the *mixture of active matter with the inactive element.* In some cases the effect is due to the presence of a small quantity of the original radio-element, in which case the "induced" activity is permanent. In other cases, one of the disintegration products, like uranium X or thorium X, has been dragged down by the precipitate, producing temporary, or, as it is sometimes termed, "false" activity. In neither case is the original character of the radiation at all affected. It is probable that a re-examination of some of the effects that have been attributed to radioactive induction would lead to new disintegration products of the known radio-elements being recognized.

Other Results.—A number of cases remain for consideration, where, by working with very large quantities of material, there have been separated from minerals possible new radio-elements, *i. e.* substances possessing apparently permanent radioactivity with chemical properties different from those of the three known radio-elements. In most of these cases, unfortunately, the real criteria that are of value, viz., the nature of the radiations and the presence or absence of distinctive emanations, have not been investigated. The chemical properties are of less service, for even if a new element were present, it is not at all necessary that it should be in sufficient quantity to be detected by chemical or spectroscopic analysis. Thus the radio-lead described by Hoffmann and Strauss and by Giesel cannot be regarded as a new element until it is shown that it has permanent activity of a distinctive character.

In this connexion the question whether polonium (radio-bismuth) is a new element is of great interest. The polonium discovered by Mme. Curie is not a permanent radioactive substance, its activity decaying slowly with the time. On the view put forward in these papers, polonium must be regarded as a disintegration product of one of the radio-elements present in pitchblende. Recently, however, Marckwald (*Ber. der D. Chem. Gesel.* 1902, pp. 2285 & 4239), by the electrolysis of pitchblende solutions, has obtained an intensely radioactive substance very analogous to the polonium of Curie. But he states that the activity of his preparation does not decay with time, and this, if confirmed, is sufficient to warrant the conclusion that he is not dealing with the same substance as Mme. Curie. On the other hand, both preparations give only α rays, and in this they are quite distinct from the other radio-elements. Marckwald has succeeded in separating his substance from bismuth, thus showing it to possess different chemical properties, and in his latest paper states that the bismuth-free product is indistinguishable chemically from tellurium. If the permanence of the radioactivity is established, the existence of a new radio-element must be inferred.

If elements heavier than uranium exist it is probable that they will be radioactive. The extreme delicacy of radioactivity as a means of chemical analysis would enable such elements to be recognized even if present in infinitesimal quantity. It is therefore to be expected that the number of radio-elements will be augmented in the future, and that considerably more than the three at present recognized exist in minute quantity. In the first stage of the search for such elements a purely chemical examination is of little service. The main criteria are the permanence of the radiations, their distinctive character, and the existence or absence of distinctive emanations or other disintegration products.

§ 6. *The Relation of Radioactive Change to Chemical Change.*

The law of radioactive change, that the rate of change is proportional to the quantity of changing substance, is also the law of monomolecular chemical reaction. Radioactive change, therefore, must be of such a kind as to involve one system only, for if it were anything of the nature of a combination, where the mutual action of two systems was involved, the rate of change would be dependent on the concentration, and the law would involve a volume-factor. This is not the case. Since radioactivity is a specific property of the element, the changing system must be the chemical atom, and since only one system is involved in the production of a new system and, in addition, heavy charged particles, in radioactive change the chemical atom must suffer disintegration.

The radio-elements possess of all elements the heaviest atomic weight. This is indeed their sole common chemical characteristic. The disintegration of the atom and the expulsion of heavy charged particles of the same order of mass as the hydrogen atom leaves behind a new system lighter than before, and possessing chemical and physical properties quite different from those of the original element. The disintegration process, once started, proceeds from stage to stage with definite measurable velocities in each case. At each stage one or more α "rays" are projected, until the last stages are reached, when the β "ray" or electron is expelled. It seems advisable to possess a special name for these now numerous atom-fragments, or new atoms, which result from the original atom after the ray has been expelled, and which remain in existence only a limited time, continually undergoing further change. Their instability is their chief characteristic. On the one hand, it prevents the quantity accumulating, and in consequence it is hardly likely that they can ever be investigated by the ordinary methods. On the other, the instability and consequent ray-expulsion furnishes the means whereby they can be investigated. We would therefore suggest the term *metabolon* for this purpose.

Thus in the following table the metabolons at present known to result from the disintegration of the three radio-elements have been arranged in order.

Uranium.	Thorium.	Radium.
↓	↓	↓
Uranium X.	Thorium X.	Radium Emanation.
↓	↓	↓
?	Thorium Emanation.	Radium-Excited Activity I.
	↓	↓
	Thorium-Excited Activity I.	ditto II.
	↓	↓
	ditto II.	ditto III.
	↓	↓
	?	?

The three queries represent the three unknown ultimate products. The atoms of the radio-elements themselves form, so to speak, the common ground between metabolons and atoms, possessing the properties of both. Thus, although they are disintegrating, the rate is so slow that sufficient quantity can be accumulated to be investigated chemically. Since the rate of disintegration is probably a million times faster for radium than it is for thorium or uranium, we have an explanation of the excessively minute proportion of radium in the natural minerals. Indeed, every consideration points to the conclusion that the radium atom is also a metabolon in the full sense of having been formed by disintegration of one of the other elements present in the mineral. For example, an estimation of its "life," goes to show that the latter can hardly be more than a few thousand years (see § 7). The point is under experimental investigation by one of us, and a fuller discussion is reserved until later.

There is at present no evidence that a single atom or metabolon ever produces more than one new kind of metabolon at each change, and there are no means at present of finding, for example, either how many metabolons of thorium X, or how many projected particles, or "rays," are produced from each atom of thorium. The simplest plan therefore, since it involves no possibility of serious error if the nature of the convention is understood, is to assume that each atom or metabolon produces one new metabolon or atom and one "ray."

§ 7. *The Energy of Radioactive Change, and the Internal Energy of the Chemical Atom.*

The position of the chemical atom as a very definite stage in the complexity of matter, although not the lowest of which it is now possible to obtain experimental knowledge, is brought out most clearly by a comparison of the respective energy relations of radioactive and chemical change. It is possible to calculate the order of the quantity of energy radiated from a given quantity of radio-element during its complete change, by several independent methods, the conclusions of which agree very well among themselves. The most direct way is from the energy of the particle projected, and the total number of atoms. For each atom cannot produce less than one "ray" for each change it undergoes, and we therefore arrive in this manner at a minimum estimate of the total energy radiated. On the other hand, one atom of a radio-element, if completely resolved into projected particles, could not produce more than about 200 such particles at most, assuming that the mass of the products is equal to the mass of the atom. This consideration enables us to set a maximum limit to the estimate. The α rays represent so large a proportion of the total energy of radiation that they alone need be considered.

Let m = mass of the projected particle,
v = the velocity,
e = charge.

Now for the α ray of radium

$$v=2{\cdot}5\ 10^9,$$

$$\frac{e}{m}=6\ 10^3.$$

The kinetic energy of each particle

$$\tfrac{1}{2}mv^2=\frac{1}{2}\frac{m}{e}v^2e=5\ 10^{14}e.$$

J. J. Thomson has shown that

$e=6\ 10^{-10}$ E.S. Units $=2\ 10^{-20}$ Electromagnetic Units.

Therefore the kinetic energy of each projected particle $=10^{-5}$ erg. Taking 10^{20} as the probable number of atoms in one gram of radium, the total energy of the rays from the latter $=10^{15}$ ergs $=2{\cdot}4\ 10^7$ gram-calories, on the assumption that each atom projects one ray. Five successive stages in the disintegration are known, and each stage corresponds to the projection of at least one ray. It may therefore be stated that the total energy of radiation during the disintegration of one gram of radium cannot be less than 10^8 gram-calories, and may be between 10^9 and 10^{10} gram-calories. The energy radiated does not necessarily involve the whole of the energy of disintegration and may be only a small part of it. 10^8 gram-calories per gram may therefore be safely accepted as the least possible estimate of the energy of radioactive change in radium. The union of hydrogen and oxygen liberates approximately $4\ 10^3$ gram-calories per gram of water produced, and this reaction sets free more energy for a given weight than any other chemical change known. The energy of radioactive change must therefore be at least twenty-thousand times, and may be a million times, as great as the energy of any molecular change.

The rate at which this store of energy is radiated, and in consequence the life of a radio-element, can now be considered. The order of the total quantity of energy liberated per second in the form of rays from 1 gram of radium may be calculated from the total number of ions produced and the energy required to produce an ion. In the solid salt a great proportion of the radiation is absorbed in the material, but the difficulty may be to a large extent avoided by determining the number of ions produced by the radiation of the emanation, and the proportionate amount of the total radiation of radium due to the emanation. In this case most of the rays are absorbed in producing ions from the air. It was experimentally found that the maximum current due to the emanation from 1 gram of radium, of activity 1000 compared with uranium, in a large cylinder filled with air, was $1{\cdot}65\ 10^{-8}$ electromagnetic units. Taking $e = 2\ 10^{-20}$, the number of ions produced per second $= 8{\cdot}2\ 10^{11}$. These ions result from the collision of the projected particles with the gas in their path. Townsend (Phil. Mag. 1901, vol. i.), from experiments on the production of ions by collision, has found that the minimum energy required to produce an ion is 10^{-11} ergs. Taking the activity of pure radium as a million times that of uranium, the total energy radiated per second by the emanation from 1 gram of pure radium $= 8200$ ergs. In radium compounds in the solid state, this amount is about ·4 of the total energy of radiation, which therefore is about

$2\ 10^4$ ergs per second,
$6{\cdot}3\ 10^{11}$ ergs per year,
15,000 gram-calories per year.

This again is an under-estimate, for only the energy employed in producing ions has been considered, and this may be only a small fraction of the total energy of the rays.

Since the α radiation of all the radio-elements is extremely similar in character, it appears reasonable to assume that the feebler radiations of thorium and uranium are due to these elements disintegrating less rapidly than radium. The energy radiated in these cases is about 10^{-6} that from radium, and is therefore about ·015 gram-calorie per year. Dividing this quantity by the total energy of radiation, 2·4 10^7 gram-calories, we obtain the number 6 10^{-10} as a maximum estimate for the proportionate amount of uranium or thorium undergoing change per year. Hence in one gram of these elements less than a milligram would change in a million years. In the case of radium, however, the same amount must be changing per gram *per year*. The "life" of the radium cannot be in consequence more than a few thousand years on this minimum estimate, based on the assumption that each particle produces one ray at each change. If more are produced the life becomes correspondingly longer, but as a maximum the estimate can hardly be increased more than 50 times. So that it appears certain that the radium present in a mineral has not been in existence as long as the mineral itself, but is being continually produced by radioactive change.

Lastly, the number of "rays" produced per second from 1 gram of a radio-element may be estimated. Since the energy of each "ray" $=10^{-5}$ ergs $=2·4\ 10^{-13}$ gram-calories, 6 10^{10} rays are projected every year from 1 gram of uranium. This is approximately 2000 per second. The α radiation of 1 milligram of uranium in one second is probably within the range of detection by the electrical method. The methods of experiment are therefore almost equal to the investigation of a single atom disintegrating, whereas not less than 10^4 atoms of uranium could be detected by the balance.

It has been pointed out that these estimates are concerned with the energy of radiation, and not with the total energy of radioactive change. The latter, in turn, can only be a portion of the internal energy of the atom, for the internal energy of the resulting products remains unknown. All these considerations point to the conclusion that the energy latent in the atom must be enormous compared with that rendered free in ordinary chemical change. Now the radio-elements differ in no way from the other elements in their chemical and physical behaviour. On the one hand they resemble chemically their inactive prototypes in the periodic system very closely, and on the other they possess no common chemical characteristic which could be associated with their radioactivity. Hence there is no reason to assume that this enormous store of energy is possessed by the radio-elements alone. It seems probable that atomic energy in general is of a similar, high order of magnitude, although the absence of change prevents its existence being manifested. The existence of this energy accounts for the stability of the chemical elements as well as for the conservation of radioactivity under the influence of the most varied conditions. It must be taken into account in cosmical physics. The maintenance of solar energy, for example, no longer presents any fundamental difficulty if the internal energy of the component elements is considered to be available, *i. e.* if processes of sub-atomic change are going on. It is interesting to note that Sir Norman Lockyer has interpreted the results of his spectroscopic researches on the latter view (Inorganic Evolution, 1900) although he regards the temperature as the cause rather than the effect of the process.

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LXI. *Removal of the Voltaic Potential-Difference by Heating in Oil.* *By* J. BROWN, *F.R.S.*[*]

IN 1879, at an early stage of my investigations on voltaic action[†], it was suggested that the difference of potential observed near the surfaces of dissimilar bodies in contact is due to chemical action of films condensed on their surfaces from the atmosphere or gas surrounding such bodies.

It was pointed out[‡] that such a condition of things is quite analogous to that of an ordinary voltaic cell divided by a non-conductor through its electrolyte, *e. g.*, copper | electrolyte | air | electrolyte | zinc, the copper and zinc being in contact and the difference of potential being taken between the two air | electrolyte surfaces. The film is therefore probably of an electrolytic nature, thus falling in with Faraday's view[§] that "in considering this oxidation, or other direct action upon the METAL itself as the cause and source of the electric current, it is of the utmost importance to observe that the oxygen or other body must be in a peculiar condition, namely in the state of *combination* and not only so, but limited still further to such a state of combination and in such proportions as will constitute an *electrolyte.*" In 1886 I explained[||] the important difference between my view and that of De La Rive, which latter included the formation of non-conducting oxide films on the metal surfaces as necessary to maintain the electrification. I showed[¶] experimentally that if the surfaces of the zinc and copper plates, arranged as in Volta's condenser, be nearly true planes and be brought sufficiently close together to allow their films to come in contact, but not the metals

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[*] Communicated by the Author.

[†] Phil. Mag. vii. p. 111 (1879).

[‡] *Ibid.* p. 110.

[§] Experimental Researches, i. p. 273

[||] Proc. Roy. Soc. lxi. p. 295 (1886).

[¶] *Ibid.* p. 307.