

*The Average Energy of Disintegration of Radium E.*

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The problem of the velocity of the particles emitted from the nuclei of disintegrating radioactive atoms has always attracted considerable attention. It was early established that in the case of the  $\alpha$ -rays all the particles from one substance were emitted with the same velocity, and the latest experiments of Briggs\* have emphasised the high degree of homogeneity attained. This result, showing that each disintegration involves exactly the same emission of energy, is easily reconcilable with our general ideas of the radioactive processes, and, as is well known, there is undoubtedly some connection between the characteristic energy and the mean life of the body.

The behaviour of the  $\beta$ -ray bodies is in sharp contrast to this. In place of the  $\alpha$ -particles all emitted with the same energy, we find that the disintegration electrons coming from the nucleus have energies distributed over a wide range. For example, in the case of radium E this continuous energy spectrum formed by the disintegration electrons has an upper limit at 1,050,000 volts, rises to a maximum at 300,000 volts, and continues certainly as low as 40,000 volts, and similar results have been obtained for other  $\beta$ -ray bodies. If this result is interpreted as showing that different disintegrating nuclei of the same substance emit their disintegration electron with different energies, we must deduce that in this case the energy of disintegration is not a characteristic constant of the body, but can vary between wide limits. Many workers have considered this to be so contrary both to the ideas of the quantum theory and the definiteness shown by radioactive disintegration that they have asserted the inhomogeneity must be a result of some secondary process, such as collision with the extra-nuclear electrons or emission of general  $\gamma$ -radiation, and that although we cannot observe them before they become inhomogeneous, the disintegration electrons are actually emitted from the nucleus with a definite characteristic energy as in the case of the  $\alpha$ -particles.

Such views are plausible and deserve careful consideration, but they meet with the great difficulty that it has up till now proved impossible to discover any evidence of the secondary effects which are presumed to produce the

\* *Roy. Soc. Proc., A*, vol. 114, p. 313 (1927).

observed inhomogeneity. On a previous occasion\* we have discussed the secondary effects that might reasonably be expected to occur, and we showed that were these effects to be present with sufficient intensity to account for the inhomogeneity, then simple experiments would already have given direct evidence of their occurrence. It was on these grounds that we concluded that the disintegration electrons **must be emitted** from the nucleus with varying energies, however contrary **at first sight** this might appear to be to the general principles of the quantum theory.

This conclusion is so fundamental for the whole subject of  $\beta$ -ray disintegration, and has been the occasion of so much controversy, that it is highly important to have more direct proof. As will be described in the next section, it is possible to subject the two alternatives to a direct experimental test, and it may be stated at once that the result is such as to confirm our previous opinion and to show that the energy liberated at different disintegrations of atoms of the same kind varies within wide limits.

#### *General Principle of the Experiment.*

For the purpose of testing whether in a  $\beta$ -ray body every atom gives out the same energy on disintegration, it is desirable to employ a radioactive body emitting  $\beta$ -rays alone. Such an example is found in radium E, and the following work was therefore performed on this element.

The  $\beta$ -ray emission from radium E can be analysed by means of a magnetic field and the intensity of the rays of various energies determined by means of an ionisation chamber. The result of such measurements is shown by the curve in fig. 1. There are no groups of discrete energy as in the ordinary magnetic spectra owing to the absence of  $\gamma$ -rays, and it will be seen that the electrons may be said to form a continuous energy spectrum extending from an upper limit of 1,050,000 volts to values as low as 40,000 volts. It has been established by Emeléus† that the number of electrons in this spectrum corresponds closely with the number of atoms disintegrating, and since at each disintegration one electron **must be emitted** from the nucleus, we can interpret this curve as showing the distribution of energy among the disintegration electrons when they have escaped from the parent atoms. Up to the present time no other process by which radium E emits energy has been detected, so that there are *a priori* grounds to believe this represents the total energy of disintegration. Since we must assume **each** disintegration to be independent

\* 'Proc. Camb. Phil. Soc.,' vol. 22, p. 849 (1925).

† 'Proc. Camb. Phil. Soc.,' vol. 22, p. 400 (1924).

of the other atoms present, we conclude that the energy of disintegration is not a fixed characteristic quantity. To take the extreme cases, there are a few

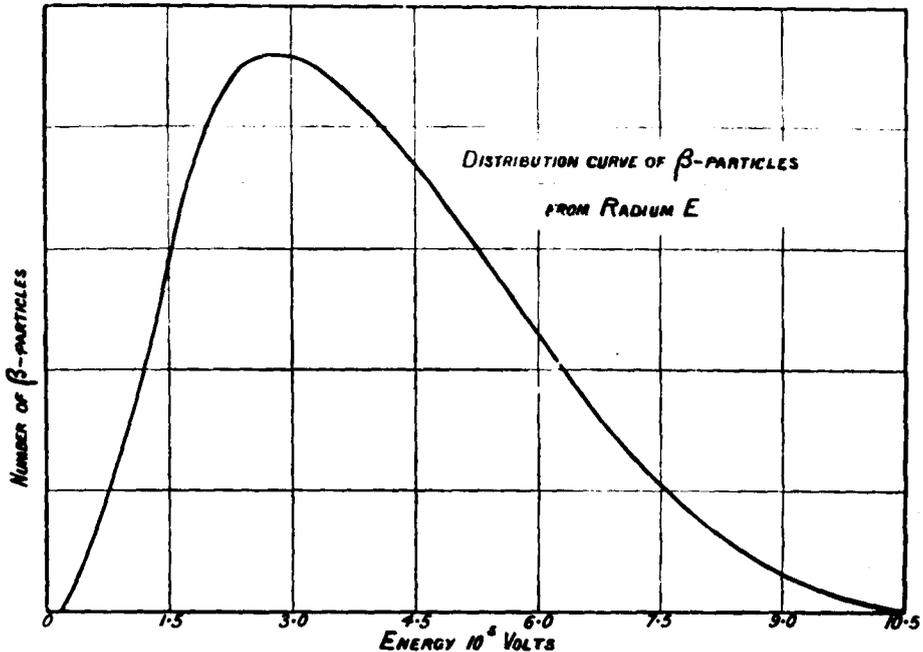


FIG. 1.

atoms emitting as much as 1,000,000 volts, whereas at the other end of the spectrum there are a few emitting only 4 per cent. of this. From this curve we can, following out this hypothesis, deduce the average energy of disintegration, and we obtain a figure about 390,000 volts. Now the average energy of disintegration can be measured by another method entirely free from any hypothesis, namely, the heating effect of the  $\beta$ -rays. This is most simply done by enclosing a source of radium E in a calorimeter whose walls are sufficiently thick to absorb completely the  $\beta$ -radiation. If the heating effect is now measured and divided by the number of atoms disintegrating per unit time, we obtain the average energy given out on disintegration. If this figure agrees with the value estimated from the distribution curve, 390,000 volts, then it is clear that the observed  $\beta$ -radiation accounts for the entire energy emission, and we deduce the corollary that the energy of disintegration varies from atom to atom.

There is a sharp distinction between this result and that to be anticipated on the view that the energy of disintegration is a characteristic constant of the atom. On this latter view, since electrons are emitted with energies as high as 1,000,000 volts, the characteristic energy cannot be less than this figure, and

atoms which emit the slower electrons must get rid of their surplus energy in some other form. It is well known that no large amount of penetrating radiation is emitted by radium E, so that if this hypothetical surplus energy really does exist, it must be absorbed inside the calorimeter and will contribute to the heating effect. In this case the heating effect would be 2.6 times as great and would correspond to 1,000,000 volts per atom.

It will be seen that a measurement of the heating effect provides a unique distinction between the two hypotheses, since one predicts a value of 390,000 and the other 1,000,000 volts per atom.

The experiment is difficult to carry out because large sources of radium E are not available and the heating effect is small, but owing to the great differences predicted by the rival hypotheses, it is possible to obtain a definite result. A further difficulty lies in determining the number of atoms disintegrating per second, and we obviated the necessity of knowing it by observing how the combined heat emission of the radium E and polonium varied with time. From this we deduced the ratio of the mean energies liberated by the radium E and polonium and calculated the polonium energy from the energy of the  $\alpha$ -rays. We were never able to prepare a source entirely free from polonium, but this method could still be employed provided the amount of polonium initially present was found. This was done by an ordinary  $\alpha$ -ray ionisation measurement. Although the polonium was separated in the preparation of the radium E, yet we can consider it to have been grown from a pure radium E source provided we antedate the moment of preparation by an appropriate number of days. If the  $\alpha$ -ray activities of the source initially and about 20 to 25 days later be found, it is clear that since the growth curve of the  $\alpha$ -ray activity depends only on the decay constants of radium E and polonium, we can calculate the time at which the source would have been pure radium E. It is not necessary to know the absolute number of  $\alpha$ -rays emitted, as only a ratio of  $\alpha$ -activities is involved.

There are thus two types of measurement in this experiment, one of a small heating effect and the other of a fairly large  $\alpha$ -ray activity. The details of the apparatus used are described in the next two sections.

#### *Experimental Details.*

*Heating Measurement.* The problem of measuring the heating due to the complete absorption of the  $\beta$ -ray of radium E presents difficulties. The rate of evolution is very small, and it is necessary to have a considerable thickness of material round the source. In these experiments a thickness of approximately 1 mm. of lead was used and the heat capacity of the calorimeter was large

compared to the rate of heat evolution. If the thermal insulation had been made very good, a considerable rise in temperature might have been obtained, but only after a long time. It was felt that the accuracy depended more on being able to repeat experiments quickly than on any other feature, and as will be seen no special precaution was taken to reduce the heat loss but only to define the conditions so as to make it constant. That it did remain constant was verified by repeated calibrations with a small glass tube containing a known amount of radium emanation. The heat evolution in any experiment was then determined by measuring the steady temperature reached when the heat loss equalled the heat supply. This steady temperature was reached in about 3 minutes, and the small rise of temperature (of the order of  $1/1000^{\circ}$  C.) was measured by a system of thermocouples attached to a low-resistance sensitive Paschen galvanometer.

After several trials the calorimeter which was finally used consisted of two lead tubes, 13 mm. long and 3.5 mm. diameter, each with a central hole of rather more than 1 mm. diameter. Each calorimeter fitted exactly into a thin outer sheath of silver, and were supported as shown in fig. 2 (a) by two discs of mica A and B, which in turn were carried by the brass screw C fitting into an ebonite base DE. The thermocouples were insulated by the thinnest mica possible, a sheet of the latter being attached to the calorimeter tubes by a very small quantity of soft wax. The thermocouples were laid on this sheet of mica with a little wax at the junctions, and then another piece of mica laid on top and the whole pressed together with a hot iron.\* The two lead calorimeters were made as nearly alike as possible so as to minimise the effect of external variations of temperature on the difference of temperature between them. In order still further to reduce these externally induced temperature differences, the whole calorimeter system was placed in a small cavity in a copper block, as

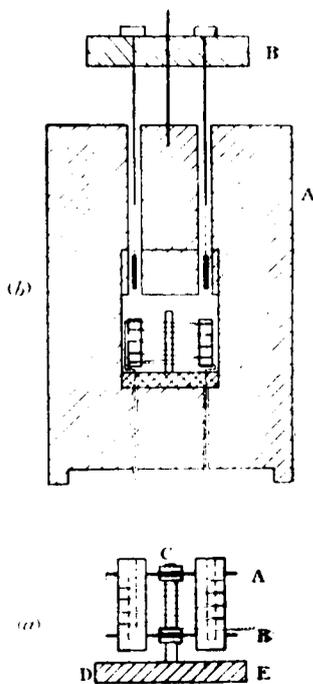


FIG. 2.

\* The temperature of the thermocouples may have been different to that of the lead tubes, but this is of no importance, since we do not require the absolute temperature rise but only to have a reproducible deflection of some instrument which registers a deflection when the calorimeters are heated, proportional to the temperature rise. That this was the case was shown by following the decay of radium emanation enclosed in a small tube.

shown in fig. 2 (b). The top portion A of this block had two small holes of diameter just greater than the internal diameter of the lead tubes and at such a distance apart that two small brass tubes of nearly the same diameter could slide smoothly from the holes in the copper block into the lead tubes. One of these brass tubes contained the source of radium E and the other an inactive wire of the same thermal capacity. These brass tubes were attached by means of two short lengths of thin glass rod to threads attached to brass rods fixed into the ebonite block B. By this means the brass tubes could be removed from the calorimeters and kept in the upper copper block without introducing thermal disturbances. The function of the small glass rods was to eliminate any possible variation in the conduction down the threads owing to their touching the sides of the copper block at different points in different experiments. The composite copper block, which was half an inch thick at its thinnest part, was housed in a wooden box lined with felt, and the system afforded good protections against external variations in temperature.

Whilst the  $\alpha$ -rays of polonium are completely absorbed in the brass tube, the  $\beta$ -rays escape through it and are chiefly absorbed in the lead tube. If this fact were to make the heating of the  $\alpha$ - and  $\beta$ -rays not truly comparable, it would make the  $\beta$ -rays appear to have a greater heating effect relative to the  $\alpha$ -rays than they actually have. We have looked into this point carefully and it seems very unlikely that any error is caused, since each part, including the sources, were made to fit very closely one in another, and the brass tubes were so thin as to give up their heat almost instantly to the lead tubes.

To avoid thermoelectric effects elsewhere in the circuit, a reversing key of special construction was placed immediately behind the calorimeter and the deflection measured was the difference in the galvanometer readings with the key in the two positions. It was necessary to use a Paschen galvanometer of 12 ohms resistance, working at a sensitivity as high as 30,000 divisions per microampere, and the sensitivity was measured several times in the course of each experiment by incorporating in the reversing key an arrangement for switching in a known small standardising current.\*

*$\alpha$ -Ray Measurement.*— It has been mentioned that only a ratio of  $\alpha$ -ray activities was required, and we used a simple ionisation chamber connected to a high-resistance leak. The wire source was mounted with its length parallel to the

\* A greatly enhanced accuracy was obtained both in the galvanometer readings and in the electrometer readings of the  $\alpha$ -ray activity by use of a Cambridge Instrument Company curve-tracer bought with a grant from the Government Grant Committee of the Royal Society.

plane of two gauzes forming a shallow ionisation chamber, the latter being screened by an earthed gauze. The source was capable of rotation about its axis, and measurements were always made for four orientations at  $90^\circ$  to one another, and the mean taken, in this way correcting for unevenness of distribution of the active material on the wire. The source was placed farther from the ionisation chamber than the range in air at atmospheric pressure of the  $\alpha$ -rays, and to measure the activity the pressure was reduced, and a series of deflections of the electrometer at different pressures were observed, and a measure of the activity was obtained by taking the deflections corresponding to a fixed stopping power. To be independent of the sensitivity of the electrometer and the value of the high-resistance leak, this activity was expressed as a ratio to a standard polonium source. This process was repeated after the radium E had nearly all decayed, and the ratio of the two activities enabled the time to be calculated at which the source consisted entirely of radium E. With this arrangement, saturation of the ionisation was not attained; however, small changes of the applied voltage did not alter the ratio, and in any case any error due to this cause would tend to give finally too large a value for the heating effect of radium E.

#### *Experimental Procedure.*

The source of radium E was prepared by electrolysis on to platinum or nickel wires 1 mm. in diameter and 9 mm. long, and immediately afterwards the  $\alpha$ -ray activity of the polonium separated with it was measured. It was then put into one of the small brass tubes of the heating apparatus and a similar inactive wire in the other. These small brass tubes were then placed in the heating apparatus and held up in the waiting position in the copper block. After 3 hours the disturbances due to manipulation had died away and the first heating measurement could be taken. On any one day four measurements were taken, each in the following manner: First, the sensitivity of the galvanometer was determined, and then, with the brass tubes still lifted, the thermocouples were connected to the galvanometer and the residual difference of temperature determined. The tubes were then lowered and the temperature difference, which after 3 minutes became steady, was measured. On raising the brass tubes into the copper block the calorimeters cooled down, and in 3 minutes another measurement of the residual effect could be made. The sensitivity of the galvanometer was then checked, and this whole procedure repeated for each of the four measurements made on any one day. For a period of about 20 days the source was left in the brass tubes in the calorimeter and not touched in any way, and, during this time, a suitable number of heating determinations were made.

After these were finished, the source was removed and the  $\alpha$ -ray activity again measured to find the growth of polonium.

### Experimental Results.

The heating measurements obtained in our best experiment are shown plotted against the time in fig. 3A. The radium E was in this case deposited on platinum.

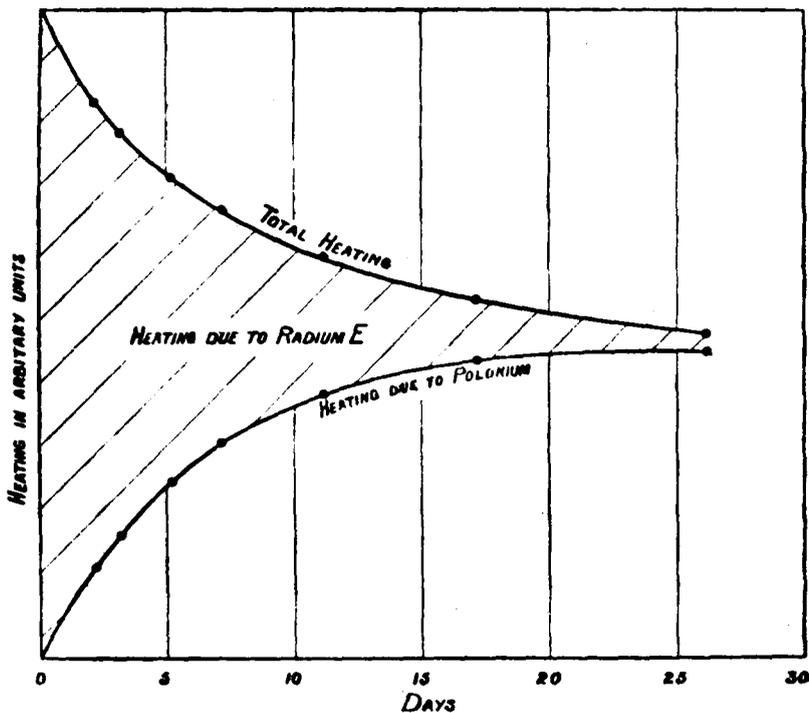


FIG. 3A.

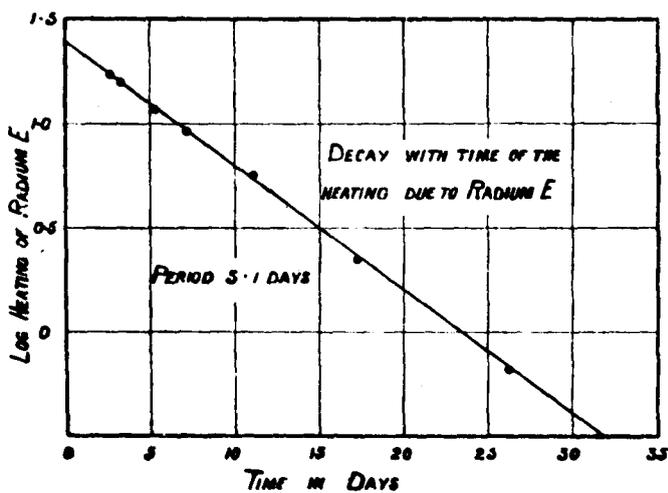


FIG. 3B.

The time is measured from the moment when the source would have consisted of pure radium E, which, by the  $\alpha$ -ray measurements, was found to be 2 days before the first  $\alpha$ -ray measurement was made. The heating effects\* are expressed in terms of the galvanometer deflection at a standard sensitivity of 10,000 mm. per microampere; the actual deflections were about three times as great. From the graph (fig. 3A) it can be seen that the measurements extend over 26 days, by which time the radium E will have fallen to 0.027 of its initial value. It is easy to estimate the initial value to be about 25 mm., and so it can have been at the end only 0.67 mm. (see Table I *infra*). If we subtract this small quantity from the measured heating of 12.85 mm., we obtain the heating due to the polonium formed. Extrapolating this backwards, using periods of 5.0 days and 139 days† respectively for radium E and polonium, we obtain the lower curve, showing the heating due to the polonium. The difference between the two curves must show the heating effect due to radium E, and it is a most important confirmation of the accuracy of our experiments that this difference shows an exponential decay with a period of about 5.1 days. This result is shown in fig. 3B.

To deduce the heating effect of radium E we proceed as follows:—

If at zero time there are  $N_E$  radium E atoms and no polonium, then after time  $t$  there will be  $N_E \lambda_E e^{-\lambda_E t}$  radium E disintegrations, per second and  $N_E \lambda_E \lambda_P (e^{-\lambda_P t} - e^{-\lambda_E t}) / (\lambda_E - \lambda_P)$  polonium disintegrations per second.

If  $x$  denotes the ratio of the energy given out at a polonium disintegration to the average energy given out at a radium E disintegration, then at time  $t$  the ratio of the heating effect of radium E to that of polonium is

$$e^{-\lambda_E t} (\lambda_E - \lambda_P) / x \lambda_P (e^{-\lambda_P t} - e^{-\lambda_E t}).$$

The curves in fig. 3A enable  $x$  to be calculated by this expression, and then division of this quantity into  $5.22 \times 10^6$  volts, the energy of disintegration of polonium, gives the heating effect of radium E. The results of analysing this experiment in this way are shown in the next table.

\* The figures from which the curves of fig. 3A have been drawn are given in Table I.

† There is some doubt about the value of the period of polonium, but this is of no importance in this experiment, owing to the short duration and the final accuracy which is claimed.

Table I.—Heating Effect of Radium E deduced from Curves of fig. 3.

| True age. | Total heating. | Portion due to Po. | Portion due to Radium E. | $\alpha$ | Disintegration energy of Radium E in volts. |
|-----------|----------------|--------------------|--------------------------|----------|---------------------------------------------|
| days.     | mm.            |                    |                          |          |                                             |
| 2·25      | 22·0           | 3·68               | 18·3                     | 15·4     | 339000                                      |
| 3·20      | 20·8           | 4·91               | 15·9                     | 15·5     | 337000                                      |
| 5·20      | 19·0           | 6·99               | 12·0                     | 15·5     | 337000                                      |
| 7·20      | 17·8           | 8·64               | 9·2                      | 15·6     | 335000                                      |
| 11·20     | 16·1           | 10·53              | 5·6                      | 14·5     | 360000                                      |
| 17·20     | 14·2           | 11·83              | 2·4                      | 14·7     | 355000                                      |
| 26·20     | 12·85          | 12·18              | 0·67                     | 15·1     | 346000                                      |

Considering the nature of the experiment, the agreement is excellent and shows that the energy of disintegration of radium E cannot be much different from 344,000 volts.

Table II summarises our results with four different sources of radium E, the experiment already quoted in detail appearing as the fourth entry. The object of columns I, II and III is to provide a basis for comparing the different experiments. Column I expresses the amount of radium E present in "equivalent milligrammes," by which is meant the amount of radium E which gives  $3.72 \times 10^7$  disintegrations per second. It will be seen from the amount of material and the amount of polonium initially present that the accuracy in experiments 1, 2 and 3 was not as high as in experiment 4. We estimate the accuracy of the first three experiments to be about 15 per cent. and of the fourth about 5 per cent. We think it best to take the value from experiment 4 as the final result, with an overall accuracy of at least 10 per cent.

Table II.—Mean Energy of Disintegration of Radium E.

| Source. | I                                     | II.           | III.                                    | IV.                                     |
|---------|---------------------------------------|---------------|-----------------------------------------|-----------------------------------------|
|         | Amount of Radium E                    | Age of source | Ratio of Radium E heating to Po heating | Mean disintegration energy of Radium E. |
|         | at time of first heating measurement. |               |                                         |                                         |
|         | mg.                                   | days.         |                                         |                                         |
| 1       | 0·13                                  | 11·3          | 0·50                                    | 320000                                  |
| 2       | 0·17                                  | 3·3           | 3·15                                    | 420000                                  |
| 3       | 0·22                                  | 12            | 0·43                                    | 320000                                  |
| 4       | 1·02                                  | 2·25          | 5·1                                     | 344000                                  |

The decay of the radium E sources were followed with an ordinary  $\beta$ -ray electroscopes, and in each case it was found to be correct within 1 per cent., and it was not possible to obtain greater accuracy owing to the necessity of keeping the source in the calorimeter. However, a short consideration will show that this accuracy, while showing the purity of the source to a per cent. or so, might still leave room for serious errors in the heating measurements. If there is any radium D present, then we may imagine the equilibrium amount of radium E and polonium as separated from the rest of the material\* and constant both in heating and  $\alpha$ -ray activity, and these constant amounts will have to be subtracted from all measurements. Now supposing 1 per cent. of the radium E is kept constant in amount by growth from this radium D, the equivalent heating correction will be only 1 per cent., since the energy of the radium D disintegration is virtually negligible, but the heating correction for the corresponding amount of polonium will be about 15 per cent., as will be seen from the value of the factor  $x$  in Table I.

We determined the amount of radium D present by measuring the residual  $\beta$ -ray activity after all the free radium E had decayed. For example, in the case of the last experiment which has been quoted in detail, the source, measured 65 and 96 days after its preparation, showed a residual activity of about 1/400. The corresponding constant correction to the heating turns out to be about 4 per cent. and to the age of the source of a little more than half a day. These corrections have been applied to the results given.

The heating effect we have measured is that due to the radiations stopped by an equivalent of 1.2 mm. of lead. This is sufficient to absorb completely all the  $\beta$ -rays, but it is well known that radium E, in addition, emits a small amount of  $\gamma$ -radiation. To complete the measurement of the total energy given out at a disintegration, it is necessary to know the energy escaping from the calorimeters. This was carried out for us by Mr. Aston, and his results will be published in full very soon. His method was as follows: From our heating measurements we calibrated an ordinary  $\beta$ -ray electroscopes in terms of "milligrams" of radium E ( $3.72 \times 10^7$  atoms disintegrating per second), so that he was able to compare directly the ionisation penetrating 1.2 mm. of lead from the same number of disintegrating atoms of radium E, and of radium B and radium C respectively. Since the penetrating power of the radium E  $\gamma$ -rays is intermediate between that of radium B and radium C, the ratio of the ionisation to radium B will give a lower limit and to radium C an upper limit of the

\* This clearly depends on the presence of a sufficient quantity of polonium when the source was prepared, a condition which was always fulfilled.

ratio of energies emitted. Approximate figures for the  $\gamma$ -ray energies of radium B and radium C are known, and in this way Mr. Aston obtained a figure of 5,000 volts per atom for radium E for the energy penetrating 1.2 mm. lead. As was to be expected, this amount of energy is virtually negligible in this connection, and no further discussion of the accuracy of this experiment is necessary, although it has, of course, a very important bearing on our view of the  $\beta$ -ray disintegration.

#### *Discussion.*

The experiments described in this paper show that the average energy of disintegration of radium E is about 350,000 volts, and this energy is liberated in such a form that the major portion, 344,000 volts, is stopped by 1.2 mm. lead and the remainder has an absorption coefficient in lead of 5.9 cm.<sup>-1</sup>. The interpretation of this result is simple. The main energy is due to the disintegration electrons, and the small extra radiation is probably continuous  $\gamma$ -radiation of a relatively hard type, emitted by a few of the disintegration electrons which suffer close collisions with the planetary electrons in their escape from the atom.

It is not necessary to repeat in detail the argument given in the introduction to show that this means that the same amount of energy cannot be given out at each disintegration; it is only necessary to refer again to fig. 1, which shows the energy distribution among the electrons emitted by radium E. The curve extends from 1,000,000 volts downwards, and if the same energy were emitted at each disintegration, then we must have found by the heating experiment a value close to 1,000,000 volts, that is, 2.8 times the experimental figure. The final accuracy has been estimated as being about 10 per cent. owing to inherent difficulties in the experiment, but this is quite sufficient to decide the point and, in fact, it justifies a closer comparison between the heating result and the distribution curve, which we shall now proceed to describe.

The curve shown in fig. 1 is taken from some experiments of Mr. Madgwick carried out in the Cavendish Laboratory, and while there can be no doubt about the substantial correctness of the curve, leading as it does to the accepted absorption coefficient of the total  $\beta$ -rays from radium E, there is yet room for criticism in some details. In the first place, the curve was obtained by the ionisation method, and to deduce the number of electrons emitted within a given range of energy it was necessary to make a correction for the variation of ionisation with energy. This was carried out by multiplication of the results by  $\beta^2$ , where  $\beta$  is the velocity in terms of the velocity of light. This correction is rough, but is in the right direction. No account has been taken of reflection

of the  $\beta$ -particles inside the ionisation chamber, an effect which would tend to over-emphasise the faster particles. Again, owing to the necessity of covering the opening of the ionisation chamber with mica, slow electrons, if present, will not have been measured. The final conclusion is that the curve of fig. 1, leading to an average energy of 395,000 volts, is likely to be in error by giving too high a value for the average energy. But there is another effect not concerned with the measurement which will work in the opposite direction. We have assumed so far that only one electron comes from each disintegrating atom, but it is possible that the number may be slightly greater owing to occasional close collisions with a planetary electron, leading also to the ejection of the latter with a considerable energy. This effect will not be large, although possibly of the order of 10 per cent., since a direct count of the number of electrons by Émiléus\* gave a number  $1.1 \pm 0.1$  electrons from each disintegrating atom, and again, the weak  $\gamma$ -radiation which could be assigned to this cause is small in amount but yet penetrating, indicating a very small number of close collisions.

While an effect of this kind has no influence at all on the heating method of finding the mean disintegration energy, it will affect the deduction of this quantity from the distribution curve. If this curve really contains  $1 + \delta$  electrons on the average from each disintegrating atom, then the true average energy of the electrons emitted from the nucleus will be the average energy from the curve multiplied by  $1 + \delta$ . We see that there is here a possibility of a correction of about 10 per cent. However, even if the counting measurements were carried out with great care, it would still be a doubtful procedure to apply this correction directly owing to the uncertainty, both in the counting and ionisation methods, of determining the number of slow electrons.

The above considerations clearly indicate that the electrical methods show that the average energy per disintegration of the emitted particles is 400,000 volts to within 15 per cent., and this is in good agreement with the average total energy of disintegration found by the heating method of 350,000 volts  $\pm$  40,000 volts.

We may safely generalise this result obtained for radium E to all  $\beta$ -ray bodies, and the long controversy about the origin of the continuous spectrum of  $\beta$ -rays appears to be settled.

We must conclude that in a  $\beta$ -ray disintegration the nucleus can break up with emission of an amount of energy that varies within wide limits. This is a curious conclusion and one which has frequently been questioned when it was put forward on less secure evidence on the grounds that the law of

\* *Loc. cit.*

radioactive disintegration, the homogeneity of the  $\alpha$ -rays and of the  $\gamma$ -rays showed a definiteness in the nucleus quite at variance with this indefiniteness of the energy of the emitted  $\beta$ -particles. There is, however, a simple hypothesis by which these facts can be reconciled.

The structure of the nucleus has been discussed by Rutherford on several occasions, and recently\* he suggested that there was "a concentrated inner nucleus carrying a positive charge surrounded at a distance by a number of electrons and then at a distance a number of neutral satellites circulating round the system." The neutral satellites are considered to consist of an  $\alpha$ -particle with two electrons bound very closely and are held in equilibrium by the attractive forces either due to the polarisation of the neutral particle by the electric field from the charged central nucleus, or due to magnetic forces arising from the nucleus, or to a combination of both types of force. To a first approximation we may consider these three regions as distinct, and there is no reason why the outer satellite region should not be quantised, and so give the possibility of ejection of  $\alpha$ -particles of definite energy, but yet the electronic region unquantised in the sense that the electrons have energies varying continuously over a wide range. We must, however, conclude that the  $\gamma$ -rays cannot be emitted from this unquantised electron region. The varying energy of the disintegration electrons and the high degree of homogeneity of the  $\gamma$ -rays appear to make it quite impossible for the same system to be responsible for both emissions, whatever picture be made of the structure of the nucleus. This is one of the most important results of this work, because although previously wherever it was necessary we have for simplicity spoken of the  $\gamma$ -rays being emitted by electrons, yet on several occasions we have pointed out that there was no evidence to decide this point. It appears now that what we have called the electronic region of the nucleus cannot emit the  $\gamma$ -rays, so that by exclusion they must be emitted by what have been termed the positive regions of the nucleus. There is good reason to believe the neutralised  $\alpha$ -particles are in quantised states, so that homogeneous  $\gamma$ -rays could be emitted by them. There are, of course, other possibilities, but at this stage it would be premature to discuss them.†

It is interesting to enquire whether this picture of the free electrons in the nucleus existing in unquantised states is contrary to modern views. At first

\* Rutherford, Guthrie Lecture, 'Phys. Soc. Proc.', vol. 39, p. 371 (1927).

† Rutherford ('Phil. Mag.', vol. 4, p. 580, 1927) has pointed out that some recent theoretical work of Kuhn ('Zeit. f. Physik,' xliii, p. 56, 1927; xliv, p. 32, 1927) indicates that the homogeneity of the  $\gamma$ -rays is incompatible with their being emitted by electrons.

sight it would certainly appear to be so, but this is not necessarily the case. For example, if we employed the orbit picture we might say that for a particle to be quantised it must be able to describe many complete orbits without disturbance, and in the confined region of the nucleus this is scarcely to be expected. The heavier positive particles will be little affected by the proximity of the electrons, but the converse will not be true. If the outer neutral  $\alpha$ -particle shell were distributed continuously, we might perhaps still expect the inner electrons to be quantised, but with discrete particles, even if they move in regular paths, we can scarcely expect undisturbed electronic orbits close to them. This view of the unquantised electronic region is not contrary to the definiteness of the law of radioactive decay. When we measure the decay of a substance we are concerned with time intervals immensely long compared to those involved in the frequencies of rotation or movement of the component parts of the nucleus, and the final statistical result can well follow regular laws, whether the real life of the nucleus is entirely ordered or not. We would go farther and suggest that in the region of  $\beta$ -ray disintegration there seems to be now more hope of understanding why disintegration should ever occur. The energy resident in the electronic part will fluctuate among the electrons, and occasionally at intervals, long compared with the ordinary time scale, the energy may heap up in one electron and lead to an explosion.

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