THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[SIXTH SERIES.]

OCTOBER 1912.

XLIII. *The Origin of β and γ Rays from Radioactive Substances.* *By* E. RUTHERFORD, *F.R.S., Professor of Physics in the University of Manchester* *.

FROM a study of the α radiations from active matter, it has been found that each atom of a substance in disintegrating emits one α particle which is expelled with a definite velocity and with a range in air characteristic of that substance. The only exception is the product thorium C, which emits two distinct groups of α rays, each of definite but different range in air. In this case, the atom appears to break up in two distinct ways.

In many transformations β and γ rays are emitted, and, from analogy with the α ray transformations, it would be expected that one β particle of definite speed would be emitted for the disintegration of each atom. The experiments, however, of v. Baeyer, Hahn and Miss Meitner †, and later of Danysz ‡, have shown that the emission of β rays from a radioactive substance is in most cases a very complicated phenomenon. The complexity of the radiation is most simply shown by observing the deflexion of a narrow pencil of β rays by a magnetic field in a vacuum. If the rays fall on

* Communicated by the Author. A preliminary paper on this subject was read before the Manchester Literary and Philosophical Society, 1912.

† v. Baeyer and Hahn, *Phys. Zeit.* xi. p. 488 (1910); v. Baeyer, Hahn and Meitner, *Phys. Zeit.* xii. pp. 273, 378 (1911); xiii. p. 264 (1912).

‡ Danysz, *C. R.* cliii. pp. 339, 1066 (1911); *Le Radium*, ix. p. 1 (1912).

a photographic plate, a number of sharply marked bands are observed, indicating that the rays are complex and consist of a number of homogeneous groups of rays, each of which is characterized by a definite velocity.

This complexity of the radiation is best shown by those products which emit penetrating β rays and intense γ rays; for example, each of the products thorium D and mesothorium 2 emits a number of well defined groups of β rays and penetrating γ rays. The complexity of the β rays is, however, most markedly exhibited in the case of the products radium B and radium C, when a very strong source of radiation is employed. Using as a β ray source a thin-walled glass tube containing a large quantity of radium emanation, Danysz found that radium B and radium C together emitted about 30 groups of homogeneous rays.

Notwithstanding this great complexity of the β rays from these products, general experiment has shown that the number of β particles emitted by them is about that to be expected if each atom in breaking up emitted only one β particle. This important point has been carefully examined by H. Moseley *, who has shown that not more than 2·13 β particles are emitted during the disintegration of one atom of radium B and one atom of radium C. By separating these two products, Moseley found that the atom of each product contributes about half of this number. It thus seems clear that on an average one atom in disintegrating emits about one β particle.

In addition to the well-known β ray products, Baeyer, Hahn and Meitner have shown by the photographic method that radium itself and radium D emit a weak β radiation which consists in each case of two definite groups of β rays. In these cases, no evidence of the emission of a γ radiation has yet been observed.

There appears to be no doubt that the γ rays from active matter are closely connected with the β rays, and that both types of rays arise in the transformation of the same atom. Investigation, however, has shown that there is not any obvious relation between the relative intensity of the β and γ rays which are emitted from a given product. The products radium C, thorium D, and mesothorium 2 emit β and γ rays of about the same penetrating power and in about the same relative proportion. On the other hand, uranium X, which emits penetrating β rays, gives relatively few γ rays. A still more striking instance is the β ray

* Moseley, "The number of β particles emitted in the transformation of radium." Read Roy. Soc. June 13, 1912.

product radium E, which, as Gray * has shown, emits relatively an exceedingly weak γ radiation. It may prove significant that only those products which emit well-defined groups of β rays emit also a strong γ radiation; for, as far as observation has gone, the β rays from uranium X and radium E give a continuous spectrum in a magnetic field.

In order to account for the emission of groups of homogeneous rays from a single product, it is necessary to suppose either that the atom breaks up in a number of distinct ways, each of which is characterized by the emission of β particles of definite velocity, or that the β rays are altered in velocity in some definite way during their escape from the disintegrating atom. On the first hypothesis, it might be anticipated that the different modes of transformation of a β ray product would give rise to a series of new products, but only one is observed. In addition, the energy emitted during the transformation from one type of matter into another would vary widely for different atoms of the same substance, and this seems improbable. On the second hypothesis, it is supposed that the disintegration of each atom takes place in exactly the same way with the emission of the same amount of energy, but that the energy of the β particle may be decreased by definite but different amounts due to transformations of its energy in its passage through the atomic system from which it originates. Since it is known that β rays in escaping from an atom give rise to γ rays, it is natural to suppose that the loss of energy of the β particle in escaping from the atomic system is connected in some way with the excitation of γ rays.

The work of Barkla and others on the X rays have brought out clearly that under suitable conditions of excitation, each element emits one or more definite types of X radiation which are characteristic of the element. Barkla † has determined the coefficient of absorption μ in aluminium of the characteristic X rays for elements up to atomic weight 140. The value of μ/D for aluminium, where D is the density, decreases rapidly with the atomic weight and varies between 435 for calcium of atomic weight 40·1 to 0·6 for cerium of atomic weight 140·25. Plotting the logarithms of the values of μ/D against the logarithm of the corresponding atomic weights, the points for the heavier elements are found to lie nearly on a straight line. If this

* Gray, Proc. Roy. Soc. A. lxxxv. p. 131 (1911); lxxxvi. p. 513 (1912).

† Barkla, Phil. Mag. xxii. p. 396 (1911).

straight line be produced, it can be shown by extrapolation that an element of atomic weight 214 should emit a characteristic radiation whose value of $\mu/D = \cdot 04$ about for aluminium. This is in good accord with the value $\mu/D = \cdot 0406$ for aluminium found by Soddy and Russell for the penetrating γ rays from radium C. It would thus appear probable that the penetrating γ radiation from radium C is to be regarded as the characteristic radiation of that element excited by the escape of β particles from the atomic system.

Whiddington * has shown that the β or cathode particle incident on matter must have a definite minimum speed for each element before the characteristic radiation of the latter is excited. Over the range examined, this velocity is directly equal to $A \times 10^8$ cm. per second, where A is the atomic weight of the element. If it be supposed that this law holds generally for all the elements, the velocity of the β particle required to excite the characteristic radiation of radium C of atomic weight 214 should be 0·71 of the velocity of light. It is not improbable, however, that the energy $\frac{1}{2}mu^2$ rather than the velocity u is the determining factor for high-speed β particles. Taking this into consideration, the velocity required to excite the characteristic radiation is given by $u = 10^8 A \sqrt{m_0/m}$, where m_0 is the mass of the β particle for slow speeds. On this hypothesis, $u = \cdot 63$ of the velocity of light. The mean value for the two methods of calculation gives $u = \cdot 67$. The corresponding energy of the β particle for the mean value of u is $1 \cdot 5 \times 10^{13} e$ ergs, where e is the charge carried by the β particle. If it be supposed that the whole energy of the β particle is converted into γ radiation, the energy absorbed in exciting the characteristic γ ray should be $1 \cdot 5 \times 10^{13} e$ ergs.

If the complexity of the β radiation is connected with the emission of γ rays, it is to be expected that some definite relation should exist between the energies of the β particles in each of the groups emitted. From this point of view, it is of interest to examine whether there is any evidence of such a relation for the β rays emitted by radium B and C. The results given by Danysz are included in the table on the opposite page.

The various groups differ widely in photographic intensity. This is designated in column 1 by the symbols s = strong, m = mean, f = feeble, vf = very feeble. Each group is defined by a number given in the second column; for the sake of completeness, two groups of rays of low velocity A and B

* Whiddington, Proc. Roy. Soc. A. lxxxv. p. 323 (1911).

Intensity.	No.	$H\rho$.	β.	Energy.	Intensity.	No.	$H\rho$.	β.	Energy.
	A	Hahn	·36	$0{\cdot}353 \times 10^{13} e$.	f	11	2190	·790	$2{\cdot}595 \times 10^{13} e$.
	B	Hahn	·41	0·468 ,,	s	12	2870	·862	3·711 ,,
s	1	1320	·615	1·218 ,,	f	13	3140	·882	4·155 ,,
f	2	1390	·634	1·322 ,,	f	14	3420	·897	4·60 ,,
vf	3	1490	·660	1·475 ,,	f	15	4000	·920	5·52 ,,
s	4	1580	·682	1·616 ,,	s	16	4670	·940	6·585 ,,
f	5	1680	·703	1·771 ,,	f	17	4800	·943	6·79 ,,
vf	6	1750	·718	1·885 ,,	f	18	4980	·946	7·07 ,,
s	7	1830	·735	2·017 ,,	m	19	5100	·949	7·26 ,,
m	8	1900	·748	2·132 ,,	s	20	5700	·957	8·18 ,,
f	9	1970	·760	2·246 ,,	f	21	5990	·962	8·63 ,,
s	10	2150	·786	2·535 ,,	complex	22	11200	·988	16·6 ,,
					complex	23	18100	·996	27·0 ,,

observed by Hahn are added to those given by Danysz. The third column gives the value of $H\rho$ experimentally observed ; the fourth column β the ratio of the velocity of the β particle to the velocity of light, calculated from the Lorentz-Einstein formula. In the fifth column I have added the value of the energy of the β particle. The value of e/m for the β particle is taken as $1{\cdot}772 \times 10^7$ e.m. units.

Starting from group No. 21, the differences between the energies of the individual β particles comprising the different groups are shown in column 2 of the following table:—

Number of group.	Observed difference in energy.	pE_1+qE_2.	Calculated difference in energy.
(21)−(20)	$\cdot 45 \times 10^{13} e$.	E_1	$\cdot 456 \times 10^{13} e$.
,, −(19)	1·37 ,,	$3E_1$	1·37 ,,
,, −(18)	1·56 ,,	E_2	1·56 ,,
,, −(17)	1·84 ,,	$4E_1$	1·82 ,,
,, −(16)	2·05 ,,	E_1+E_2	2·01 ,,
,, −(15)	3·11 ,,	$2E_2$	3·11 ,,
,, −(14)	4·03 ,,	$2E_1+2E_2$	4·02 ,,
,, −(13)	4·48 ,,	$3E_1+2E_2$	4·48 ,,
,, −(12)	4·92 ,,	$4E_1+2E_2$	4·94 ,,
,, −(11)	6·03 ,,	$3E_1+3E_2$	6·03 ,,

On examining these differences, it is seen that they can be expressed closely by the relation pE_1+qE_2, where $E_1=0{\cdot}456 \times 10^{13} e$, $E_2=1{\cdot}556 \times 10^{13} e$, and p and q are whole numbers which may have any values 0, 1, 2, 3, &c. The differences calculated on this hypothesis are shown in the last column, and are observed to be in close agreement for the whole series of lines from No. 21 to No. 11. This relation does not hold below line No. 11, but in all probability most of the lines, Nos. 1 to 10, belong to radium B and not to radium C. The energy of the β particle for group No. 21 is $8{\cdot}63\times10^{13}\,e$, while its velocity is ·962 of the velocity of light. Groups 22 and 23 are not included in the calculation, for Danysz states that No. 22 includes from 3 to 5 groups of β rays, of which only the average velocity is given; similarly No. 23 is considered to be a complex group.

The values of the velocity of the β particles will require to be known with great accuracy before such a relation as is indicated can be definitely established; but it does not appear likely that the connexion observed is accidental. It is of interest to note that the value of $E_2=1{\cdot}556\times10^{13}e$ is in fair accord with the calculated energy of the β particle, viz., $1{\cdot}5\times10^{13}e$, which would be required to excite the characteristic radiation from radium C. The value of E_1 may in a similar way be connected with the energy required to excite the second type of characteristic X radiation which has been observed in a number of elements by Barkla.

It is possible that some of the groups from Nos. 10 to 1 may also belong to radium C. For example, No. 8 fits in well with a difference $4E_1+3E_2$ from No. 21. Hahn has determined the velocity of the stronger groups of rays from radium B and radium C separately. For radium B, the values $\beta=\cdot36, \cdot41, \cdot63, \cdot69, \cdot74$ are given. The last three no doubt correspond to groups Nos. 1, 4, and 7 respectively given by Danysz. A group for which $\beta=\cdot80$, which appears to correspond to No. 10, is ascribed to radium C. Group No. 10, however, does not fit in at all with the relation found between Nos. 11 to 21. It would be of great value to determine definitely the division of the groups of β rays observed between radium B and radium C.

If the groups Nos. 10 to 1 supposed to belong to radium B be analysed in a similar way to the groups for radium C, the differences may be approximately expressed by the relation pE_1+qE_2 where $E_1=\cdot114\times10^{13}e$ and $E_2=\cdot144\times10^{13}e$. The agreement, however, between calculation and theory is not nearly so good as for the case previously considered, and it is doubtful whether any weight can be attached to it. For the slow velocity β rays here considered, the reduction of velocity in passing through the glass walls of the emanation tube is quite appreciable, and the correction is different for each group. Until this correction is made, it does not seem possible to draw any definite conclusions.

The simplest way of regarding this relation between the groups of β rays is to suppose that the same total energy is emitted during the disintegration of each atom, but that the energy is divided between β and γ rays in varying proportions for different atoms. For some atoms most, if not all, of the energy is emitted in the form of a high-speed β particle; in others the energy of the β particle is reduced by definite but different amounts by the conversion of part of its energy into γ rays. Suppose, for example, the total energy liberated in the form of β and γ rays during the transformation of one atom is E_0. If the β particle before it escapes from the atom passes through two regions where the energy required to excite a γ ray is E_1 and E_2 respectively, the resulting energy of the β particle is $E_0-(pE_1+qE_2)$, where p and q are whole numbers corresponding to the number of γ rays excited in each region. The energy emitted in the form of γ rays is pE_1+qE_2, and p γ rays of energy E_1 and q of energy E_2 appear.

According to this view, the transformation of one atom gives rise to only one β ray, but to p γ rays of one kind and q of another. The groups of homogeneous β rays observed are the statistical effect due to a large number of disintegrating atoms. The relative distribution of β particles amongst the numerous groups of homogeneous rays will depend on the probability that 0, 1, 2, &c. of the units of energy E_1 and E_2 are abstracted from the β particle in traversing the atom.

This mode of regarding the connexion between β and γ rays suggests that the number of γ rays emitted from radium C is considerably greater than the number of β rays. Assuming that each γ ray from radium C was converted into one β ray, Moseley (*loc. cit.*) found that at least two γ rays appeared for the transformation of one atom of radium C. There is reason to believe that this is a minimum estimate, and that the actual number is two or three times greater.

From the results already considered, it does not necessarily follow that group No. 21 is to be regarded as the head of the β ray series. Evidence on this point can be obtained by calculating the energy E_0 liberated per atom in the form of β and γ rays during the transformation of radium C. In same recent experiments the results of which have been communicated to the Vienna Academy, the writer and Mr. H. Robinson conclude that the heating effect of the β and γ rays from 1 gram of radium is 10·8 gram calories, of which about 4·3 is due to the β rays and 6·5 to the γ rays. An uncertain part of this energy arises from the β and γ rays emitted by radium B; but there will not be much error if it be supposed that the energy of the β and γ rays from radium C in one gram of radium is about 8 gram calories per hour. Supposing, as Moseley found, that one β ray is on the average expelled from each atom of radium C, the energy emitted per atom of radium C in the form of β and γ rays is $17 \cdot 8 \times 10^{13}\, e$ ergs, assuming that $3 \cdot 4 \times 10^{10}$ β particles per second are emitted from radium C in equilibrium with one gram of radium. This approximately corresponds with the average energy of the β particle included in group No. 22, viz. $16 \cdot 6 \times 10^{13}\, e$.

Danysz states that No. 22 consists of 3 to 5 groups of β rays, for which only the average velocity of the group is given. In the absence of any definite information of the velocity of the components, it is impossible to ascertain whether any relationship exists between this complex group and the rest of the radium C series. The wide difference between the energies of the β rays included under No. 21 and No. 22 indicates that possibly a third region exists within the atom for which the energy required to excite γ rays is much greater than that for the other two regions considered.

Unless the energy of the β and γ rays from radium determined by experiment has been much underestimated, it does not seem possible to suppose that the swiftest β ray given by Danysz, which has the energy $27 \times 10^{13} e$, can be the head of the β ray series. The existence of such a swift group of β rays is, however, open to some doubt, as Danysz expressly states in his paper. The photographic effect of such swift β rays is very difficult to detect in the presence of a strong photographic action due to the γ rays.

We have so far confined our discussion to the connexion between the β and γ rays emitted from radium C, for in this case the necessary data are far more definite and complete than for any other product. It seems probable, however, that the same general explanation will apply to the emission of β and γ rays from mesothorium 2 and thorium D, both of which emit a number of groups of homogeneous β rays and also penetrating γ rays. In each of these products, the energy emitted in the form of γ rays is of about the same order of magnitude as the energy emitted in the form of β rays.

A difficulty arises in connexion with the β ray products like radium E and uranium X, which emit penetrating β rays but relatively weak γ rays. In the case of uranium X, some penetrating γ rays are observed, but they are weak in relative intensity compared with the γ rays from radium C. It is possible that the atomic structure of uranium X is such that only an occasional β particle loses energy by conversion into γ rays in its escape from the atom. In the case of radium E where the γ rays are very weak in intensity and of slight penetrating power, it seems probable that the β rays originate near the surface of the atom, and consequently do not traverse the regions where penetrating γ rays can be set up. There still remains the difficulty, however, of accounting for the heterogeneity of the β rays which are emitted, to which attention has been drawn by Gray and by Gray and Wilson.

There is one point of interest which has so far not been considered. Bragg has given strong evidence for believing that a β and a γ ray are mutually convertible forms of energy. The energy of a γ ray incident on matter is transformed into the energy of a β ray, and *vice versa*. On this view, it has generally been supposed that the whole of the energy of one γ ray is converted into the energy of one β ray, so that the γ ray disappears and the β particle takes its place. From the point of view outlined in this paper, it is supposed that the β ray originating in the transformation of an atom loses only part of its energy which is abstracted from it in definite units, depending on the region of the atom through which the β particle passes. A swift β ray may consequently give rise to several γ rays in escaping from the atom and yet retain a part of its initial energy.

In a previous paper* I have given reasons for believing that the atom consists of a positively charged nucleus of very small dimensions, surrounded by a distribution of electrons in rapid motion, possibly of rings of electrons rotating in one plane. The instability of the atom which leads to its disintegration may be conveniently considered to be due to two causes, although these are not mutually independent, viz., the instability of the central nucleus and the instability of the electronic distribution. The former type of instability leads to the expulsion of an α particle, the latter to the appearance of β and γ rays. The instability which leads to the expulsion of a β ray may be mainly confined to one of the rings of concentric electrons, and leads to the escape of a β particle from this ring with great velocity. The β particle in escaping from the atom passes through the electronic distribution external to it, and in traversing each ring may lose part of its energy in exciting one or more γ rays which have a definite energy, which is characteristic for each ring.

At present we have no definite information of the mode in which the transformation of a β into a γ ray or a γ ray into a β ray takes place, but it is no doubt connected with the

* Rutherford, Phil. Mag. xxi. p. 669 (1911).

structure of the ring of electrons, and possibly with its period of free vibration. The general evidence indicates strongly that the transformation of energy from the γ ray form to the β ray form or *vice versa* takes place in definite units which are characteristic for a given ring of electrons but vary from one to the other. The transformation of energy of the β ray form into the γ ray form appears to take place far more efficiently during the disintegration of an atom than when β rays fall on the atoms of ordinary matter. This is not unexpected, for the conditions in the former case are eminently favourable to the conversion, since the β particle passes directly through the electronic distribution of the atom. It is at the same time to be expected that some of the energy of the γ rays which are formed within the atom should also be converted, in part at least, into β rays again, and should thus give rise to one or more groups of homogeneous rays. It is possible that two groups of slow velocity β rays which appear during the transformation of radium itself may arise in consequence of such a transformation of the γ rays set up by the escape of the α particles from the atom. J. Chadwick, working in the laboratory of the writer, has recently obtained evidence that α rays are able to excite γ rays in falling on ordinary matter.

If this be the case, it is to be expected that all α ray products should emit some β rays and γ rays, though probably of very weak intensity in both cases. The excitation of γ rays by α rays is not improbable if the energy of the charged particle rather than its velocity is the determining factor; for although the velocity of the α particle is small compared with that of the ordinary β particle, its energy of motion is much greater.

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Aug. 16, 1912.

XLIV. *On the Emission of Electrons by Metals under the Influence of Alpha Rays.* *By* H. A. Bumstead *and* A. G. McGougan, *Yale University* *.

Introduction.

IN a previous paper under the same title by one of the present authors †, an account was given of some experiments upon the so-called δ-rays which are emitted by

* Communicated by the Authors.

† Amer. Journ. Sci. xxxii. p. 403 (1911); Phil. Mag. xxii. p. 907 (1911).