XXXVII. The Connexion between the $\beta$ and $\gamma$ Ray Spectra.

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THE problem of the nature of emission and absorption of radiation has occupied a very prominent position in modern Physics, both on account of its outstanding importance and of the great difficulties involved. It is clear that the question of the excitation of X rays and their conversion into $\beta$ rays, and also the spontaneous emission of $\beta$ and $\gamma$ rays from radioactive substances, must be included in any general theory of radiation. A study of the $\beta$ and $\gamma$ rays from radioactive matter is of especial interest in this connexion, since the $\beta$ rays are expelled with a very high velocity and a considerable fraction of the energy is emitted in the form of $\gamma$ rays of very short wave-length. It is to be anticipated that a close study of the emission of these radiations from radioactive bodies should throw light of a fundamental character on the radiation problem on the high frequency side.

During the last few years a number of careful investigations have been made in this Laboratory bearing on this problem, and it may prove of interest to discuss briefly the evidence that has so far been obtained and to indicate the general conclusions that can be drawn from it. The problem is much too large and involved to hope for an

* Communicated by the Author.

immediate and definite solution, but the experimental results are sufficiently complete to afford some data for drawing some tentative conclusions.

In a paper published two years ago* I discussed the possible connexion between $\beta$ and $\gamma$ rays emitted from radioactive substances and outlined a general theory in explanation of the magnetic "spectrum" observed when the $\beta$ rays are analysed by their passage through a magnetic field. It was pointed out that the emission of a large number of groups of the $\beta$ rays of definite velocity from a single substance could be most simply explained by supposing that it is a statistical effect due to a large number of atoms each of which gave rise to a few only of the groups of $\beta$ rays observed.

In a transformation where primary $\beta$ and $\gamma$ rays appear, it was supposed that each atom broke up with the emission of a $\beta$ particle of definite speed. The latter in passing through the external electronic system set it into vibration, and energy was abstracted from the $\beta$ particle in definite integral units depending on the vibrating system. If, for example, the $\beta$ particle passed through two distinct vibrating systems $A_1$ and $A_2$, the final energy of the escaping $\beta$ particle was given by $E_0 - (pE_1 + qE_2)$, where $E_0$ was the initial energy of the $\beta$ particle, $p$ and $q$ whole numbers which might have any values 0, 1, 2, 3, etc., and $E_1$, $E_2$ the units of energy abstracted in passing through $A$ and $B$ respectively. It was supposed that the energy $pE_1 + qE_2$ which was abstracted from the $\beta$ particle appeared in the form of $p$ gamma rays each of energy $E_1$, and of $q$ gamma rays each of energy $E_2$. It was suggested that the $\gamma$ rays so excited corresponded to one or more of the types of characteristic radiations brought to light by the experiments of Prof. Barkla on X rays. This theory has formed a starting point for a number of subsequent researches. In the first place, in order to test the theory, it was necessary to know the energy of the $\beta$ particles comprising the different groups with the greatest possible accuracy. The initial experiments made by Baeyer, Hahn and Meitner, and by Danysz on the groups of $\beta$ rays emitted from radium B and radium C were repeated with great care by Mr. H. Robinson and myself †. By the adoption of a modified method, the magnetic spectra due to radium B and radium C were separately determined. The spectrum of radium C was greatly extended and found

* Phil. Mag. xxiv. p. 453 (1912).
† The particular point of view of which this formula is an expression has been modified subsequently.
to consist of a great number of lines, about 50 of which were measured. It was pointed out that there appeared to be certain simple numerical relations between a number of the groups of β rays from radium C. In the meantime, the problem had been attacked from another direction. According to the theory, the γ rays emitted from a radioactive substance should consist of types of characteristic X radiations which should be exponentially absorbed by a light substance like aluminium. This question has been examined in detail by Mr. H. Richardson and myself *, and the results obtained have fully confirmed this point of view. The γ rays from each radioactive substance can be analysed into a number of distinct groups. Some of these groups undoubtedly correspond to the characteristic radiations to be expected from elements of their atomic weight; but attention was drawn to the evidence of the existence of other types of characteristic radiation not previously observed by workers with X rays. It was found that the different radioactive substances showed great variety in the types of γ rays emitted, but they could be classified by their power of penetration as belonging to certain general types of characteristic radiations. Mr. H. Richardson has continued these investigations and has recently obtained evidence of the excitation of characteristic radiations in a large number of elements when the β rays of active matter fall upon them.

The discovery of Laue of the diffraction of X rays and the subsequent work of W. H. and W. L. Bragg and of Moseley and Darwin and others, have placed into our hands a powerful and simple method for determining the wave-lengths of the X rays. If the γ rays from radioactive matter consisted of groups of characteristic rays, it was to be anticipated that the rays would show a line spectrum when reflected from a crystal surface. This point of view has been completely confirmed by subsequent researches of Dr. Andrade and myself. In the first paper † we gave an account of the examination of the spectrum of the soft γ rays from radium B, and adduced evidence that the strong lines of the spectrum of this substance were identical with the characteristic "L" spectrum of lead. In a subsequent research ‡ we have determined the wave-lengths of the penetrating γ rays from radium B and radium C and verified the results by the adoption of a new experimental method.

† Rutherford and Andrade, Phil. Mag. xxvii. p. 854 (1914).
‡ Rutherford and Andrade, Phil. Mag. August 1914.
Distribution of energy between $\beta$ and $\gamma$ rays.

It was initially supposed that a large fraction of the $\beta$ radiation from substances like radium B and radium C, which give a marked $\beta$-ray spectrum, appeared in the form of the homogeneous groups of $\beta$ rays observed. J. Chadwick * has shown, however, in a recent paper that even the intense lines in the magnetic spectrum of radium B represent only a small fraction of the total number of $\beta$ rays emitted. This result was obtained by direct counting of the $\beta$ particles and confirmed by showing that an increase of intensity of only a few per cent. of the $\beta$ radiation falling at a given part of the photographic plate gave the impression on development of a strongly marked band.

We may conclude from these results that the magnetic spectrum of the $\beta$ rays from radium B or radium C consists of a continuous spectrum of $\beta$ rays on which is superimposed a line spectrum corresponding to groups of rays expelled at definite speeds. A satisfactory explanation of these results and also of other marked differences in the distribution of $\beta$ and $\gamma$ rays from radioactive substances can, I think, be given on the following lines. Suppose—as seems probable—that the disintegration of the atom leads to an expulsion of a high speed $\beta$ particle from or near the nucleus. This $\beta$ particle in passing through the outer distribution of electrons will, on the average, suffer several collisions of an ordinary type with the electrons, and will share its energy with them. As a statistical result of a large number of atoms, the velocity of the escaping $\beta$ particles will, on the average, be continuously distributed within certain limits of velocity. This would give rise to the continuous spectrum of $\beta$ rays which is most typically illustrated by the $\beta$ rays from radium E. Next suppose that there are certain well-defined regions in the electronic distribution which can be set into definite vibration by the escaping $\beta$ particle. These regions are to be identified as containing the particular structures which give rise to the "characteristic" $\gamma$ radiations from the atom. If some of the $\beta$ particles in escaping from the atom pass through one or more of these regions, they give rise to a line-spectrum of $\gamma$ rays and at the same time to one or more groups of $\beta$ rays of definite speed. The connexion between the energy of the $\gamma$ ray and of the $\beta$ ray will be discussed later.

On this view, the appearance of homogeneous groups of $\beta$ rays and the line-spectrum of $\gamma$ rays are to be ascribed to certain definite regions of vibration within the atom. It is

to be anticipated that characteristic $\gamma$ rays will always accompany a line-spectrum of $\beta$ rays. This seems to be in harmony with radioactive data. Radium E, which gives rise to a continuous $\beta$-ray spectrum, emits exceedingly little $\gamma$ radiation in comparison with typical $\beta$ and $\gamma$ ray products like radium B and radium C, which give well marked spectra for both $\beta$ and $\gamma$ rays.

While it would appear probable that the greater part of the $\gamma$ radiation from radium B and radium C is composed of several groups of rays of definite frequencies, no doubt a small part of the $\gamma$ radiation gives a continuous spectrum. Such a result is to be anticipated from analogy with X rays. This general radiation probably has its origin in the electronic collisions of an ordinary type when the $\beta$ particle is escaping from the atom or to the passage of the $\beta$ particle close to the nucleus.

Importance of direction of escape of a $\beta$ particle.

There is another very interesting point that arises in consideration of this question. Why does radium E, which emits $\beta$ rays of great intensity and over a wide range of velocity, not emit $\gamma$ rays at all, or at any rate in very small amount compared with radium B or radium C? There appears to be no reason to suppose that radium E would not give rise to characteristic radiations of a frequency corresponding to its atomic weight or atomic number when bombarded by cathode rays of suitable speed. In order to explain this anomaly, it appears necessary to assume that the primary $\beta$ particle from a given radioelement is always expelled in a fixed position with regard to the structure of the atom itself. Considering the remarkably definite way in which the atom of the same substance disintegrates, this assumption does not seem improbable. On this view, the absence of $\gamma$ rays from radium E is due to the fact that the direction of escape of the $\beta$ particle does not pass near or through the definite regions where characteristic radiations are set up, and in consequence only a continuous spectrum of $\beta$ rays is observed. An explanation may be given on similar lines of many remarkable anomalies in the types and relative intensities of $\gamma$ rays emitted from radioactive substances. This is well illustrated by a comparison of the $\gamma$ rays from radium B and radium C which are nearly of the same atomic weight. Radium B emits a very soft radiation which is almost entirely absent in radium C, while radium B does not emit the very penetrating radiation observed from radium C. We must suppose that the $\beta$ particle from radium B passes
through one or more distinct regions which give rise to the corresponding characteristic radiations, while the \( \beta \) particle from radium C escapes in such a direction that it does not pass through the corresponding regions but does pass through a new region not involved in the case of the expulsion of the \( \beta \) particle from radium B.

The general evidence available indicates that radium B and radium D have identical general physical and chemical properties with those of lead, although differing from the latter in atomic weight. If this be correct, we should anticipate that these elements should give identical \( X \) ray spectra when bombarded by cathode rays. On the other hand, from the work of Rutherford and Richardson, radium B and radium D are known to emit types of \( \gamma \) rays which are widely different in relative amount and penetrating power. Such results are, however, at once intelligible if it be supposed that the \( \beta \) particles from these two elements are expelled in different directions with regard to the atomic structure.

It is to be anticipated that some of the lines of the \( \gamma \)-ray spectra of these two radioactive elements should be coincident, but some may be absent or very faint in one spectrum and strong in another. In fact, the relative intensities of the spectral lines of the \( \gamma \) rays from radioactive substances may in all cases be very different from those which would be observed when the element is bombarded by cathode rays. In the latter case, all types of characteristic radiation have a chance of excitation—supposing of course account is taken of the speed of the incident cathode rays—since the \( \beta \) particles enter the atom on an average equally in all directions.

Theory of the origin of the \( \beta \) and \( \gamma \) rays.

One fundamental fact that has to be taken into account in considering the origin of the \( \beta \) and \( \gamma \) rays is the conversion of the energy of a \( \gamma \) ray into the form of a high speed electron or \( \beta \) ray, and vice versa. This point has been emphasized by Bragg in his papers on the nature of X rays. He supposed that the energy of a single X ray could be converted by its passage through matter into the energy of a single \( \beta \) ray of appropriate speed, and that no loss of energy occurred in the process. It would appear, however, necessary to generalize this conception, for it will be seen later that there is considerable evidence from a study of the \( \beta \) and \( \gamma \) rays from radioactive matter that a train of X rays of the same frequency may be given out each of definite energy, and that the whole energy of this train of waves may, under suitable conditions,
appear in the form of a swift $\beta$ ray. There is now strong evidence from a variety of directions that the energy emitted by a source of radiation of frequency $\nu$ is in definite quanta $E$ when $E=\hbar \nu$, $\hbar$ being Planck's constant. The general idea that the energy of the $\gamma$ rays is emitted in definite units or quanta appears to be necessary to explain the origin of homogeneous groups of $\beta$ rays expelled from radioactive matter. We shall first assume that the energy in a single $\gamma$ ray of frequency $\nu$ is given by Planck's formula, and then discuss how far this particular relation is supported by the experimental evidence.

We shall suppose certain regions in the atom are set in vibration by the escape of the $\beta$ particle during the atomic explosion. If $\nu_1$, $\nu_2$... are the frequencies of vibration, the energy emitted in the form of $\gamma$ rays is $p\hbar \nu_1$, $q\hbar \nu_2$ ..., where $p$ and $q$ may have any integral values. For example, one atom may emit one $\gamma$ ray of frequency $\nu$ and energy $\hbar \nu$, another may emit a train of two $\gamma$ rays of the same frequency but of energy $2\hbar \nu$, another three, and so on. There is no method at present of deciding the most probable value of $p$ for a single atom, nor to fix an upper limit to its value. This may depend on the intensity of the disturbance communicated to a vibrating system by the escaping $\beta$ particle. The energy of these $\gamma$ rays is supposed to be partially or wholly converted into the $\beta$ ray form in their escape from the radioactive atom. Unfortunately there is no evidence available at present of how this conversion occurs or whether any energy is absorbed in the process. If the conversion takes place without loss of energy, a train of $\gamma$ rays of frequency $\nu_1$ will give rise to a $\beta$ particle of energy given by $E=p\hbar \nu_1$.

It is possible the conversion may occur in one of the regions of the atom which give rise to characteristic radiations, and is accompanied by the appearance of a new type of $\gamma$ rays of frequency $\nu_2$ etc. In such a case, we should anticipate that the energy of the escaping $\beta$ particle is given by $E=p\hbar \nu_1 - q\hbar \nu_2$, where $p$ and $q$ are whole numbers which may have all possible values consistent with $p\nu_1$ being greater than $q\nu_2$.

The value of $E$ here refers to the energy of the $\beta$ particle at the point in the atom where the conversion of energy occurs. It seems possible that there may be a further change of the energy of the $\beta$ particle in escaping from the atom. In this case, the energy of the $\beta$ particle after it has escaped from the atom is given by $p\hbar \nu_1 - q\hbar \nu_2 - \Lambda$, where $\Lambda$ may have a negative value and is at present indeterminate.

It will be seen that the present theory of the origin of the
β rays differs somewhat from that advanced in the earlier papers (loc. cit.). I there supposed that homogeneous groups of β rays were due to the decrease of energy in definite units of the primary β particle in exciting the vibrations in the atom. The present theory supposes that the homogeneous groups of β rays arise from the conversion of the energy of the γ rays into the β ray form. In other words, the primary effect in the atom is the excitation of γ rays by the escape of the β particle from the nucleus. The appearance of groups of homogeneous β rays is a secondary effect due to the partial conversion of the γ rays into β rays in their passage through the radioactive atom. On the other hand, the continuous β radiation is ascribed mainly to the effect of the primary β particles escaping from the nucleus which have lost energy, though not in definite quanta, in setting the electronic system of the atom into vibration.

Consideration of the experimental evidence.

We shall now consider briefly some recent experimental evidence which has thrown light on this question. Robinson, Rawlinson, and the writer* have shown that the β rays excited by the γ rays in their passage through matter consist of definite groups which, no doubt, would be homogeneous if the layer of matter in which the β rays were excited was exceedingly thin. As far as experiment has gone, the velocities of these groups of "excited" β rays are in close if not complete agreement with the velocities of the stronger groups of primary β particles from the source of radiation. The velocities of the corresponding groups appear to vary slightly when the β rays are excited in different metals, but the differences, though no doubt real, are not very marked. We may conclude from these results that the primary β particles, for example from radium B, like the β rays excited by the γ rays in traversing absorbing material, are due to the conversion of γ rays into β rays in their escape from the radioactive atom. The observed variations of velocity between the primary groups of β rays from the radioactive atom and the β rays excited by the γ rays in different substances, may be due to the variation of the part \(-(qv_2+A)\) in the expression for the energy \(E=phv_2-qpv_2-A\). The experiments, however, show that the variation due to this cause is small for the swift groups of β rays excited by γ rays in different kinds of matter, and for simplicity it may be assumed as a first approximation.

* Phil. Mag. August 1914.
that the value of $qhv_2 + A$ is very small compared with $phv_1$
for the actual groups of swift $\beta$ rays under consideration.

We shall now consider whether the experimental evidence
supports the view that the energy of the homogeneous
groups of $\beta$ rays from radium B and radium C are connected
with the values of $hv$, where $v$ is the frequency of one or
more of the stronger lines in the $\beta$ ray spectrum.

For convenience of discussion, the frequencies of the
stronger lines of the $\gamma$ ray spectrum of the penetrating
$\gamma$ rays from radium B and radium C are included in the
following table. The value of $hv$ is calculated from the
observed frequency, assuming $h = 6.55 \times 10^{-27}$, and expressed
in the same form as the energies of the groups of $\beta$ rays
from radium B and radium C in the previous paper of
Rutherford and Robinson. The value of $e$ is taken as
$4.69 \times 10^{-10}$ e.s. units—the value deduced directly by Planck
from his theory of radiation. The energy $hv$ of the strong
line, which is reflected at $1^\circ$ from rocksalt, is $1.25 \times 10^{13} e$,
where $e$ is in electromagnetic units. If Millikan's value of
$e$ is taken, viz. $4.77 \times 10^{-10}$, the corresponding value of $hv$
is $1.23 \times 10^{13} e$.

Angles of reflexion and energies of lines in $\gamma$-ray spectra
of radium B and radium C.

<table>
<thead>
<tr>
<th>Angle of reflexion from rocksalt</th>
<th>$\gamma$</th>
<th>$\gamma$</th>
<th>$\gamma$</th>
<th>$\gamma$</th>
<th>$\gamma$</th>
<th>$\gamma$</th>
<th>$\gamma$</th>
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<th>$\gamma$</th>
<th>$\gamma$</th>
<th>$\gamma$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>43</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>24</td>
<td>37</td>
<td>43</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$(E = hv) \times 10^{13} e$</td>
<td>1.74</td>
<td>1.25</td>
<td>1.07</td>
<td>0.893</td>
<td>0.773</td>
<td>0.728</td>
<td>0.625</td>
<td>0.537</td>
<td>0.507</td>
<td>0.469</td>
<td>0.417</td>
<td>0.379</td>
</tr>
</tbody>
</table>

$\beta$-ray spectrum of radium C.

In the previous paper by Rutherford and Robinson (loc.
cit.), it was shown that the energy of the lines of the $\beta$-ray
spectrum of radium C from No. 1 to No. 29 could be expressed
approximately by an integral multiple of a unit of energy
$E = 4384 \times 10^{13} e$. It was pointed out, however, that in
several cases the adjacent lines appeared to be closer together
than would be indicated by this difference relation. Since
one of the strong lines of the $\gamma$ ray spectrum of radium C,
reflected at $1^\circ$, has an energy of $1.25 \times 10^{15} e$ on Planck's
relation, it is to be anticipated on the theory that the energy
of a number of lines should show differences of this unit or
integral multiples of it. As a special case, the energy of the
$\beta$ particle itself might be expected to be integral multiples
of this unit. The original difference unit \( \cdot4284 \times 10^{13} \, e \), when multiplied by three gives \( 1\cdot285 \times 10^{13} \, e \), which does not differ from \( 1\cdot25 \times 10^{13} \, e \) by more than the experimental error. It will be seen in the table below that a number of the lines, including some of the stronger lines, can be expressed very closely as integral multiples of the unit \( E = 1\cdot285 \times 10^{13} \, e \).

The numbers of the lines refer to those given in the previous paper by Rutherford and Robinson.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Index number of line} & \text{Intensity} & \text{Velocity as a fraction of light} & \text{Observed energy} & \text{Energy} \\
\hline
\text{M 45} & \text{m.} & 7\cdot50 & 2\cdot59 & 2\cdot015 \\
\text{K 38} & \text{s.} & 8\cdot88 & 5\cdot16 & 4\cdot016 \\
\text{32} & \text{m.f.} & 9\cdot17 & 7\cdot68 & 5\cdot98 \\
\text{G 29} & \text{m.s.} & 9\cdot46 & 10\cdot31 & 8\cdot62 \\
\text{F 26} & \text{m.} & 9\cdot52 & 11\cdot49 & 8\cdot94 \\
\text{23} & \text{f.} & 9\cdot59 & 12\cdot82 & 9\cdot97 \\
\text{D 20} & \text{m.} & 9\cdot643 & 14\cdot09 & 10\cdot96 \\
\text{17} & \text{f.} & 9\cdot687 & 15\cdot42 & 12\cdot00 \\
\text{C 14} & \text{m.} & 9\cdot724 & 16\cdot71 & 13\cdot01 \\
\text{11} & \text{f.} & 9\cdot754 & 17\cdot96 & 13\cdot97 \\
\hline
\end{array}
\]

Of the twelve strong lines in the table marked with index letters, six are seen to be expressed very nearly as integral multiples of \( E_1 \). In picking out possible other units, it appears significant that another series of lines can be expressed as a multiple of \( E_2 = \cdot74 \times 10^{13} \, e \). This is seen in the following table.

\[
\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
\text{Multiple} & 2 & 4 & 6 & 8 & 9 & 12 & 14 & 15 & 16 & 18 & 19 & 22 & 23 \\
\hline
\text{Calculated energy} & 1\cdot48 & 2\cdot96 & 4\cdot44 & 5\cdot92 & 6\cdot76 & 8\cdot88 & 10\cdot36 & 11\cdot10 & 11\cdot84 & 13\cdot32 & 14\cdot06 & 16\cdot28 & 17\cdot02 \\
\hline
\text{Observed energy} & 1\cdot49 & 2\cdot96 & 4\cdot48 & 5\cdot94 & 6\cdot74 & 8\cdot91 & 10\cdot31 & 11\cdot07 & 11\cdot86 & 13\cdot28 & 14\cdot09 & 16\cdot28 & 17\cdot11 \\
\hline
\text{Intensity} & f. & m. & m.f. & m.s. & m.f. & m.s. & f. & v.f. & m.s. & m. & f. & f. \\
\hline
\end{array}
\]

Only two of these lines, viz. of energies 10\cdot31 and 14\cdot09, are included in the first table. These lines may possibly be close doubles.

It has been pointed out in the paper of Rutherford and Andrade that the strong \( \gamma \) ray line reflected at 1\(^\circ\) 40' is
probably a close double which it is difficult to separate under the experimental conditions. One component is believed to belong to radium B and the other to radium C. This appears very probable, for Richardson has found recently that radium C emits some γ radiation which has about the same absorption in lead as the soft γ rays from radium B. We should consequently anticipate that radium C should give a strong line near 1° 40' of energy about \( 0.75 \times 10^{13} \) e—in good agreement with the unit found above.

Only two strong lines remain which are not included as multiples of these two units \( 0.74 \) and \( 1.29 \times 10^{13} \) e. These are the two lines A and B of energies 21.02 and 17.5 \( \times 10^{13} \) e. These can be expressed as \( 12E \) and \( 10E \) where \( E = 1.75 \times 10^{13} \) e. It appears more than a coincidence that this value is very close to the energy of the shortest wave-length observed for the γ rays from radium C, viz. 43' of energy \( 1.74 \times 10^{13} \) e.

It was also found that several lines in the spectrum were multiples of the energy of the strong β-ray line of energy \( 1.81 \times 10^{13} \) e. This corresponds nearly twice the energy of the line 1° 24' of energy \( 0.89 \times 10^{13} \) e.

There are a number of other faint lines not included in the above tables. It is probable these may owe their origin to other frequencies not observed in the γ-ray experiments.

It is seen from the above that there is strong evidence that the energies of many of the lines in the β-ray spectrum may be expressed as integral values of certain definite units which correspond with the frequencies of vibration of the γ rays, assuming Planck's relation between frequency and energy. It hardly seems possible that the numerous close agreements observed are accidental; for it must be remembered that the units are chosen to fit in with three strong lines of comparatively slow velocity observed in the β-ray spectrum of radium C, whose energies are 1.81, 2.59, 2.96 \( \times 10^{13} \) e, where the multiple is 2 for the first two units and 4 for the last.

If these deductions are correct, it follows that not a single γ ray but a train of γ rays of definite frequency can be emitted from each vibrating centre of the atom. The number of waves composing the train varies for different atoms and for the different frequencies, but evidence is obtained that the number of complete waves may in some cases be ten or more. The train of waves on passing through matter may under suitable conditions give all its energy to a single electron, and thus give rise to the high speed electrons when γ rays pass through matter. We have already drawn attention to the fact that the primary β rays emitted from a
Sir E. Rutherford on the radioactive atom have a very similar spectrum to that observed for the \( \beta \) rays excited by \( \gamma \) rays, indicating that both have a similar origin.

\[ \textit{\beta-ray spectrum from radium B.} \]

We shall now consider the \( \beta \)-ray spectrum of radium B for which the energies of the groups of \( \beta \) rays have been carefully determined by Rutherford and Robinson. The results are included in the following table. Column I. gives the number of the line, II. the intensity, III. the ratio \( \beta \) of velocity of the \( \beta \) particle to the velocity of light, IV. the energy of the \( \beta \) particle composing each group, and V. the suggested unit and its multiple.

<table>
<thead>
<tr>
<th>I.</th>
<th>II.</th>
<th>III.</th>
<th>IV. ( \div 10^{15} ) e.</th>
<th>V. ( \div 10^{15} ) e.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>f.</td>
<td>.823</td>
<td>3.852</td>
<td>5 \times 770</td>
</tr>
<tr>
<td>2</td>
<td>m.s.</td>
<td>.805</td>
<td>3.489</td>
<td>4 \times 870</td>
</tr>
<tr>
<td>3</td>
<td>s.</td>
<td>.797</td>
<td>3.332</td>
<td>7 \times 476 or 6 \times 555</td>
</tr>
<tr>
<td>4</td>
<td>v.f.</td>
<td>.787</td>
<td>3.190</td>
<td>5 \times 632</td>
</tr>
<tr>
<td>5</td>
<td>m.s.</td>
<td>.762</td>
<td>2.758</td>
<td>5 \times 552</td>
</tr>
<tr>
<td>6</td>
<td>v.s.</td>
<td>.751</td>
<td>2.610</td>
<td>3 \times 870</td>
</tr>
<tr>
<td>7</td>
<td>m.</td>
<td>.731</td>
<td>2.365</td>
<td>5 \times 473</td>
</tr>
<tr>
<td>8</td>
<td>m.s.</td>
<td>.719</td>
<td>2.228</td>
<td>3 \times 743 or 4 \times 557</td>
</tr>
<tr>
<td>9</td>
<td>v.s.</td>
<td>.700</td>
<td>2.039</td>
<td>4 \times 510 or 6 \times 373</td>
</tr>
<tr>
<td>10</td>
<td>m.s.</td>
<td>.696</td>
<td>1.850</td>
<td>4 \times 412 or 3 \times 350</td>
</tr>
<tr>
<td>11</td>
<td>v.s.</td>
<td>.685</td>
<td>1.619</td>
<td>2 \times 760 or 3 \times 506</td>
</tr>
<tr>
<td>12</td>
<td>m.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>m.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>m.s.</td>
<td>.426</td>
<td>.339</td>
<td>1 \times 539</td>
</tr>
<tr>
<td>15</td>
<td>s.</td>
<td>.414</td>
<td>.503</td>
<td>1 \times 503</td>
</tr>
<tr>
<td>16</td>
<td>v.s.</td>
<td>.355</td>
<td>.376</td>
<td>1 \times 376</td>
</tr>
</tbody>
</table>

It is certainly striking that the energies of the three strong groups of \( \beta \) rays 14–16 agree very closely with the calculated values for the reflexion angles of the \( \gamma \) rays for the lines at 2° 20', 2° 28', and 3° 18', which gave energies .537, .507, .379 \( \times 10^{15} \) e respectively. When there are so many lines as in the \( \gamma \)-ray spectrum of radium B, and uncertainty as to whether some of the lines are to be ascribed to radium B or to radium C, it is obvious that it is difficult to fix with certainty the unit in which to express the energies of the groups. It is noticeable, however, that the strong lines 2 and 6 are expressed by small integral multiples of .870 \( \times 10^{15} \) e, which agrees fairly well with the energy to be
expected for the \( \gamma \) radiation reflected at \( 1^\circ 24' \). With the exception of lines 1 and 11, there appears very little evidence of the unit of energy corresponding to the strong reflection line at about \( 1^\circ 40' \), the energy of which should be about \( \cdot750 \). There is another unit, however, \( \cdot553 \) which agrees fairly well with a number of lines. The observed \( \gamma \)-ray line nearest to this value is reflected at \( 2^\circ 20' \) of energy \( \cdot537 \), but the difference in the observed and calculated energies is more than two per cent. Possibly the unit may be \( 1^\circ 10' \) corresponding to the \( 1^\circ 10' \) line.

It will be observed that several of the lines are in approximate accord with multiples of different units calculated from the frequencies of observed lines. This will be seen by comparison of the above table with the energies for frequencies given on p. 313.

Apart from the group of slow velocity lines and lines 2 and 6, the agreement between observed and calculated energies is fair, but is not sufficiently definite to draw certain deductions as to the origin of the individual lines in the spectrum.

There is one interesting point which should be mentioned here. Danysz * determined the velocities of the slow velocity groups of \( \beta \) rays from radium D, and found them to be quite different from the corresponding groups of \( \beta \) rays (14–16) in the spectrum of radium B, although the actual numerical differences between the energies of the corresponding lines were approximately the same for the two substances. Now the general evidence indicates that radium B and radium D, although of different atomic weights, have identical general chemical properties, and would be expected to give the same \( \gamma \)-ray spectra, and also the same type of primary \( \beta \) rays. It has been pointed out earlier in this paper that the observed differences in \( \beta \) and \( \gamma \) ray spectra may possibly be ascribed to the different conditions of excitation of the \( \gamma \) rays in the atom in the two cases due to the expulsion of the \( \beta \) particle from the nucleus in a different direction with regard to the structure of the atom. If the latter point of view is correct, we should anticipate that the energies of the groups of \( \beta \) rays from radium D should be expressed in terms of some of the frequencies in the \( \gamma \) rays of radium B.

The energies observed by Danysz are \( \cdot309, \cdot311, \cdot435, \cdot468 \times 10^{13} \varepsilon \). Two of these agree well with the values of the energies \( \cdot312, \cdot469 \times 10^{13} \varepsilon \), calculated for the lines of radium B reflected from rocksalt at angles of \( 4^\circ \) and \( 2^\circ 40' \). The line \( 2^\circ 51' \) of energy \( \cdot438 \) was observed on one or two

* Le Radium, x. p. 5 (1913).
plates but was not recorded in the list of lines published by Rutherford and Andrade. The corresponding lines involved in the radium B spectrum are at 3° 18', 2° 28', and 2° 20'.

It is of interest to note that the soft $\gamma$ rays of radium B which give two strong spectral lines reflected at 10° or 12° from rocksalt and have values $h\nu$, 2° 125, 1° 104 x 10° e, respectively, do not appear to be responsible for any of the observed $\beta$-ray lines in radium B. The fact that the energy of the slowest group of $\beta$ rays 3° 76 is about 3 x 1° 125 is probably merely a coincidence.

Some recent measurements of Miss Szmidt in this Laboratory have brought out the surprisingly small amount of energy emitted in the form of these soft $\gamma$ rays, the amount being only about 2 per cent. of the energy of the more penetrating $\gamma$ rays from radium B and only about 0° 14 per cent. of the total energy of the $\gamma$ radiation from radium B and radium C together. Although the energy of these soft rays is only about 1/1000 of the total $\gamma$-ray energy emitted from an emanation tube, they yet give the most intense spectrum lines under the experimental conditions.

The small relative amount of energy from the soft $\gamma$ rays shows that either these rays are emitted from only a small fraction of the disintegrating atoms, or, what is more probable, that they do not consist of trains of waves but mostly of single waves.

The general comparison of the soft $\beta$ and $\gamma$ ray spectra of radium B with radium C indicates that the higher the frequency of the radiation, the greater the tendency to excite long trains of waves. It does not seem possible at this stage to decide whether this is a definite property of the vibrating systems, or whether it is due to the violence of the disturbance in the case of the higher frequencies of vibration.

Excitation of $\beta$-ray spectra by characteristic $X$ rays.

It is known that when a comparatively light element like nickel is bombarded by cathode rays, the $X$ rays initially emitted consist mainly of the "K" characteristic radiation of that element. Rawlinson* has found that with increasing voltage, more and more penetrating types of radiation appear in addition, but no certain evidence has been found that these penetrating rays give a line spectrum on reflexion from crystals. Moseley showed that the characteristic radiation of nickel consists mainly of two strong lines reflected from

* Phil. Mag. August 1914.
Connexion between $\beta$ and $\gamma$ Ray Spectra.

rocksalt at angles of $15^\circ.5$ and $17^\circ.15$. From analogy with the case of $\beta$ rays from a radio-element, it is to be anticipated that with a high voltage discharge, the nickel radiation would consist of a train of one or more waves each of energy $h\nu$ corresponding to the frequency $\nu$ of each of the strong lines of nickel. When this radiation falls on another element, it is absorbed and partially converted into $\beta$ rays. For a given frequency $\nu_1$, we may suppose as before that the excited $\beta$ rays would fall into groups of energy $ph\nu_1 - qh\nu_2 - A$, where $q$ is an integer and $\nu_2$ is the frequency of the characteristic radiations excited by the $X$ rays in the element in question. The general evidence indicates that the constant $A$ is negligible. If no characteristic radiation is excited, it is to be expected that the energy of the groups of $\beta$ rays should be given by $ph\nu_1$, where $p$ is an integer. If the conversion of the $X$ rays into $\beta$ rays is accompanied by the characteristic radiation of the element, another series of lines should make their appearance of energy given by $ph\nu_1 - qh\nu_2$. At the same time, the characteristic radiation of the frequency $\nu_2$ would be partially converted into $\beta$ rays in escaping from the substance and would thus be expected to give rise to groups of $\beta$ rays of energy $qh\nu_2$, where $q$ is an integer, and so on.

It is obvious, that on these views, the spectrum of the $\beta$ rays excited by the passage of only one frequency of $X$ radiation through matter may show a very complex $\beta$-ray spectrum, consisting of a number of distinct groups of $\beta$ rays. If the primary radiation consists of a number of frequencies, the resulting $\beta$-ray spectrum will probably prove as complex as the $\beta$-ray spectrum of radium $B$ or radium $C$.

A preliminary examination of the $\beta$-ray spectra excited in different elements by the characteristic radiation of nickel has been made by Robinson and Rawlinson*. They have found that the magnetic spectrum of the $\beta$ rays does show the presence of a number of well-marked groups of $\beta$ rays, but the experimental evidence is not yet complete enough to test the correctness of the above point of view.

University of Manchester,
June 30, 1914.

* Phil. Mag. August 1914.