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## THE NUMBER OF $\gamma$-RAYS EMITTED PER SECOND FROM RADIUM B AND C IN EQUILIBRIUM WITH A GRAM OF RADIUM AND THE NUMBER EMITTED PER ATOM DISINTEGRATING

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Abstract

**Number of $\gamma$ rays emitted by RaB and RaC per atom disintegrating.**—$\gamma$-rays entering a metal produce $\beta$-ray emissions. By a $\beta$-ray emission is meant the simultaneous emission of one or more $\beta$-rays, initially in the general direction of the exciting $\gamma$-rays. Those $\beta$-ray emissions which passed through the metal window front of a counting chamber were counted, using an automatic registering device previously described. Different thicknesses of various metals were used as fronts. Corrections for scattered $\gamma$-rays and for $\beta$-rays from the walls of the chamber were determined experimentally. A standard 1.305 mg of radium was used, placed between the poles of an electromagnet. The coefficient of absorption of the $\gamma$-rays was determined from corrected counts with different thicknesses of absorbing metal placed between the source and the counting chamber but nearer the source, and the coefficient of absorption of the $\beta$-rays from a determination of the thickness of the metal cover which gave the maximum number of counts. From these coefficients and the geometrical constants, the total number of emissions which would have been produced if all the $\gamma$-rays from RaB and RaC had been absorbed in the metal was determined for Al, Cu, Sn, Pt, and Pb and found the same for all within a mean variation of $\pm 3$ per cent, viz. $7.28 \times 10^{10}$ per gm Ra per sec. equal, within experimental error, to twice $3.57 \times 10^{10}$ which is the number of atoms of each disintegrating per second. Evidently this proves that each radioactive transformation results in the emission of a $\gamma$-ray entity which sooner or later produces a $\beta$-ray emission from a single atom. For the hard $\gamma$-rays, capable of penetrating 1.55 cm of lead, the number of counts, corrected for absorption and scattering, came out 76 per cent of the total. Ionisation experiments, repeated by the author, give about 73 per cent, the smaller figure being due to the smaller relative ionising power of the fast $\beta$-rays. Since $\gamma$-rays are entities, the counts seem to be more significant.

**Coefficient of absorption of $\gamma$-rays from RaB and RaC and for secondary $\beta$-rays, determined from counts.**—For all the $\gamma$-rays the values found for Al, Cu, Sn, Pt, and Pb, are 0.121, 0.38, 0.36, 1.40 and 0.78 per cm, and for the hard $\gamma$-rays 0.11, 0.32, 0.29, 0.81 and 0.47 respectively. For the $\beta$-rays in the metal in which they were produced (1) by all the $\gamma$-rays: 38.6, 160, 84.3, 374 and 200 per cm, (2) by hard $\gamma$-rays: 16.2, 58.1, 52.3, 215 and 104.

## INTRODUCTION

THE $\gamma$-rays from radioactive substances and x-rays have been looked upon as entities from the earliest days when attempts were made to explain them either as electromagnetic phenomena or later as corpuscular phenomena. That $\gamma$-rays are continuous waves has no experimental basis. From all experimental work one is forced to conclude that $\gamma$-rays, if electromagnetic waves, are discrete trains of waves, and therefore definite entities. Whether the $\gamma$-rays are the result of the expulsion of a $\beta$-particle from the nucleus or whether the expulsion of $\beta$-particles is due to $\gamma$-rays as is suggested by the recent work of Ellis,[1] the fact remains that between $\beta$-ray magnetic spectra and $\gamma$-ray spectra certain quantum relations hold. That $\gamma$-rays may be detected as entities was pointed out by Kovarik and McKeehan[2] in their statistical work on $\beta$-particles in considering the corrections due to natural causes and $\gamma$-rays.

It has been of interest from the very beginning to know the number of $\gamma$-ray entities emitted from an atom when it disintegrates. Eve[3] concluded from his experiments on ionisation by $\gamma$-rays from radium C that the $\gamma$-radiation contains twice as much energy as the $\beta$-radiation. Moseley[4] measuring secondary $\beta$-radiation due to $\gamma$-rays concluded on the basis of Bragg's corpuscular theory that the nearest whole number expressing the $\gamma$-rays per atom disintegrating is two. Rutherford and Robinson's[5] determination of the heating effects of the various radiations from radium and its products in equilibrium is 4.7 calories per hour per gram of radium for the $\beta$-rays of radium B and C and 6.4 for the $\gamma$-rays, or 1.36 times as much energy in the $\gamma$-rays as in the $\beta$-rays of radium B and C. In the preliminary results of the writer[6] using the counting method the value obtained for $\gamma$-rays from radium B and C per second per gram of radium was $7\times10^{10}$. The work of Hess and Lawson[7] then came (belatedly owing to the war) to the notice of the writer and stopped further work temporarily. The results obtained by Hess and Lawson are for radium C $1.43\times10^{10}$ and for radium B $1.49\times10^{10}$ per second per gram of radium. These values are so much below those obtained by the author and below what one might expect if a whole number of entities is associated with one disintegrating atom that the work was recently resumed and a record of this work is reported in this paper. It was

[1] Ellis, C. D., Proc.Roy. Soc. A **101,** 1 (1922)
[2] Kovarik and McKeehan, Phys. Zeits. **15,** 1 (1914)
[3] Eve, Phil. Mag. **22,** 551 (1911)
[4] Moseley, Proc. Roy. Soc. A **87,** 250 (1912)
[5] Rutherford and Robinson, Phil. Mag. **25,** 312 (1913)
[6] Kovarik, Proc. Nat. Acad. Sci. **6,** 105 (1920)
[7] Hess and Lawson, Sitzb. Akad. Wien. **125,** 585 (1916)

thought important to determine experimentally all of the constants used in the calculations and this was done except for the coefficient of absorption in air. The value obtained is $7.28\times10^{10}$ $\gamma$-rays per second from radium B and radium C in equilibrium with one gram of radium, or one $\gamma$-ray per atom disintegrating.

## Theory

Let us suppose that a beam of $\gamma$-rays is incident on a plate of matter. The $\beta$-rays which are produced are produced at the expense of the absorbed $\gamma$-ray energy. Let us look at a $\gamma$-ray entity as a train of waves whose energy is a definite quantum. This energy may be all used up in the substance into which the $\gamma$-ray enters either to produce (a) one $\beta$-particle or (b) several simultaneously from one atom or (c) several at intervals of time from different atoms. In the first two cases the ionisation produced by the $\beta$-particle or $\beta$-particles may be looked upon as if produced by one $\beta$-ray at one instant, and statistically, as one event due to one $\gamma$-ray. In the third case the number of $\beta$-ray events produced by one $\gamma$-ray would be greater than one. From the experiments of C. T. R. Wilson[8] on x-rays and $\gamma$-rays, it would appear that both of the first cases are possible. There seems to be no experimental evidence for the third case; and from the results of these experiments it would appear that such a condition does not exist, i.e. that the energy of a $\gamma$-ray is really all used up to produce one $\beta$-particle or several $\beta$-particles simultaneously or so nearly simultaneously at one place that they may be regarded as such. It is on this hypothesis as a basis that the calculations are made. In the method used in these experiments the phenomenon of the production of a single $\beta$-particle or several $\beta$-particles simultaneously can be detected as a single event and, therefore, corresponds to the absorption of one $\gamma$-ray entity. If the initially produced $\beta$-particles are supposed to have the direction of the $\gamma$-rays,[9] the laws of absorption of the $\beta$-particles would be the same as for normal rays passing through the matter. If there is any deviation from this supposition it will not affect the calculations provided the coefficient of absorption of the $\beta$-rays produced by the $\gamma$-rays is determined.* This was done in these experiments.

[8] C. T. R. Wilson, Proc. Roy. Soc. A **104**, 1 and 192 (1923)

[9] Rutherford, Radioactive Substances etc., p. 276

*If any of the $\beta$-rays are scattered, as they are, or if the $\gamma$-rays produce $\beta$-rays, initially, in the opposite direction, as very likely they do, the coefficient of absorption will not be that of true absorption but of all the effects which cause a diminution of the number of emergent $\beta$-rays and, therefore, of the events counted.

Let $N \equiv$ the number of $\gamma$-ray entities from a given source $S$ that are incident on the plate of matter per second;

$S \equiv$ the strength of the source;

$a \equiv$ the area of the plate of matter on which the $\gamma$-rays are incident;

$r \equiv$ the distance of the source from the plate of matter, this distance being great enough to consider the rays normal to the plate;

$d \equiv$ the thickness of the plate;

$\mu_1 \equiv$ the coefficient of absorption of the $\gamma$-rays in the material of the plate;

$\mu_2 \equiv$ the coefficient of absorption in the material of the plate of the $\beta$-particles produced by the $\gamma$-rays in the same material;

$n \equiv$ number of events detected beyond the plate caused by emergent single $\beta$-particles or several simultaneously produced $\beta$-particles due to $N$ $\gamma$-rays.

Consider an element $dx$ of the plate at a distance $x$ from the incident side. Then the $\gamma$-rays entering $dx$ (assuming the exponential law of absorption) $\equiv N' = N\epsilon^{-\mu_1 x}$ and $dN' = -N\mu_1\epsilon^{-\mu_1 x}\,dx$, so that the $\gamma$-rays absorbed in $dx$ are $N\mu_1\epsilon^{-\mu_1 x}\,dx$ and these give rise to, say, $dn'$ $\beta$-rays. The $\beta$-particles are absorbed exponentially and therefore the emergent $\beta$-particles $\equiv dn = \epsilon^{-\mu_2(d-x)}\,dn' = \epsilon^{-\mu_2(d-x)} N\,\mu_1\,\epsilon^{-\mu_1 x}\,dx$

$$\text{Hence} \quad n = N\mu_1\,\epsilon^{-\mu_2 d}\int_0^d \epsilon^{(\mu_2-\mu_1)x}\,dx = \frac{\mu_1}{\mu_2-\mu_1} N\,(\epsilon^{-\mu_1 d} - \epsilon^{-\mu_2 d}) \qquad (1)$$

and

$$N = n\,\frac{\mu_2-\mu_1}{\mu_1}\,\frac{1}{\epsilon^{-\mu_1 d} - \epsilon^{-\mu_2 d}}.$$

Since $N$ represents the $\gamma$-rays per second from a given source $S$ incident on a plate of area $a$ which is situated at a distance $r$ from the source, then if $\Gamma_1 \equiv$ total $\gamma$-rays per second from a unit source at a distance $r$, uncorrected for absorption by air and walls of vessel containing the source,

$$\Gamma_1 = n\frac{\mu_2-\mu_1}{\mu_1}\,\frac{1}{\epsilon^{-\mu_1 d} - \epsilon^{-\mu_2 d}}\,\frac{4\pi r^2}{aS} \qquad (2)$$

and if $\Gamma_0 \equiv$ total $\gamma$-rays emitted per second by a unit source,

then $\Gamma_0 = \Gamma_1 \times$ reciprocal exponentials, correcting for absorption by the air and walls of the vessel containing $S$. (3)

Eq. (1) on the right hand side shows a difference of two exponentials. With an increase in $d$ there is an increase in the production of $\beta$-particles but also a rapid decrease of $n$ due to the absorption of the $\beta$-particles. The relation between $n$ and $d$ shows a maximum for $n$ for a certain value of $d$. If $D \equiv$ the thickness of the plate for maximum value of $n$, the condition for this maximum is found from Eq. (1) to be

$$\mu_1\,\epsilon^{-\mu_1 D} = \mu_2\,\epsilon^{-\mu_2 D} \qquad (4)$$

The Eq. (2) then becomes

$$\Gamma_1 = n\frac{1}{\epsilon^{-\mu_2 D}}\frac{4\pi r^2}{aS} = n\frac{\mu_2}{\mu_1\epsilon^{-\mu_1 D}}\frac{4\pi r^2}{aS} \qquad (2')$$

In the experimental arrangement we may either use any thickness $d$ of the plate and solve for $\Gamma_1$ by Eq. (2) or we may use the definite thickness $D$ and solve by the simpler equation (2').

## Apparatus

The apparatus used for the detection and counting of the $\beta$-particles has been described in previous papers[10] on $\alpha$, $\beta$ and $\gamma$-rays. The events to be counted were automatically registered by a device described in this journal.[11] The counting chamber in most of the experiments was a cylinder 5.5 cm long and 0.81 cm in radius. The axis of the chamber was in the direction of the source. The circular front of the chamber was a plate of the material in which the $\gamma$-rays were absorbed and $\beta$-particles produced. In the early experiments the entire chamber was of the same material and thickness as the front, but in the final experiments the chamber cylinder was of paper (d = .0384 cm), India inked on the inside, or of aluminium (d = .0365 cm), and the front was a circular plate made of different material in different experiments. In some experiments, particularly those in which the chamber used was of the same material and thickness as the front, the counting chamber was in the open air; in the final experiments, it was in a lead block cast to house the chamber. The protective walls were 3 to 4 cm thick and the cylindrical opening for the chamber was about 3.4 cm in diameter and was lined with thick paper. The metals used for the fronts were Al, Cu, Sn, Pt, Pb, each in several thicknesses.

The source of $\gamma$-rays was radium B and radium C in equilibrium with radium which was enclosed in a glass tube. Radium of strength from 0.15 mg to 5.002 mg was used but in the final experiments the laboratory standard of 1.305 mg was the source of $\gamma$-rays. When the hard $\gamma$-rays were studied the radium tube enclosed in a brass tube was placed in a lead cylinder of 1.55 cm thickness which was provided with lead caps at the two ends. The radium tube was set up vertically between the poles of a large Pye magnet to deflect the direct $\beta$-radiation coming from the source in case of the total radiation, and the $\beta$-radiation from the lead in case of the hard radiation.

[10] Geiger, Verh. d. D. Phys. Ges. 15, 534, 1913
Kovarik and McKeehan, Phys. ZS. 15, 434, 1914; Phys. Rev. **6**, 426, 1915 and **8**, 574, 1916.

[11] Kovarik, Phys. Rev. **13**, 272, 1919

## Procedure and Precautions

The quantities to be determined experimentally are $n$, $\mu_1$, $\mu_2$, $d$ and $r$. The thickness of the plate $d$ and the distance $r$ were easily measured. The coefficients of absorption and $n$ depend on counting the $\beta$-ray events under the various necessary conditions.

The precautions and corrective measures to be taken to obtain correct results for the counts are of great consequence. The $\gamma$-rays passing from the source in all directions are scattered not only by the air but by all objects in the neighborhood. This scattering effect is very appreciable. If the counting chamber is left in the open, not only do direct rays enter through the front, but also scattered $\gamma$-rays, both through the front and through the cylindrical sides of the chamber. The latter effect of the scattered rays can be minimized by housing the chamber in a block of lead having walls of considerable thickness. The rest of the effect due to scattered radiation along with any natural effect such as natural discharges from the point or effects due to penetrating radiation from any source other than that used, was corrected for in the following way. Lead plates aggregating 19 cm in thickness were placed in the path of the direct rays at a position such that the scattered radiation effect was a maximum. There is a range of positions for which the scattered effect has about the same (maximum) value. The position nearest to the source was used for reasons given below. If the lead plates are next to the chamber then on account of their size the scattered radiation coming to the chamber from a considerable solid angle is cut out in this observation while this scattered radiation will enter when counts are taken for the direct plus the scattered radiation effect without the use of the lead plates. If the lead plates are next to the source, then radiation from the source in directions other than that toward the counting chamber is also absorbed and therefore cannot be scattered as is the case when counts are taken without the lead plates. In both of these instances, therefore, the correction for scattered radiation would be too small. In a position between the source and the counting chamber both of these difficulties are obviated unless the plates are very large or the distance of the source from the counting chamber (when a weak source is used) is small. For the final experiments the source was 310 cm from the chamber and the lead plates, about 12 cm$\times$12 cm, were placed at 90 cm from the source for this correction reading, For a distance of 310 cm between the source and the counting chamber the lead plates could be placed as much as 100 cm nearer the counting chamber than they were and a correction reading still be obtained of about the same maximum value. Now, in experiments on absorption of $\gamma$-rays, absorbing

plates of various thicknesses are used and if placed near the counting chamber, the β-particles produced in them and passing in the direction of the γ-rays would enter the counting chamber and produce records similar to those for the γ-rays and the effect counted would not be due alone to γ-rays which are not absorbed, but also partly to these β-particles. For this reason the same position was used for the lead plates and for the absorbing plates in absorption experiments, and this position was as far away from the counting chamber as possible. In this way reliable correction readings for the scattered radiation and for the count of the γ-rays passing through the absorbing plates in absorption experiments were obtained.

Since the counting chamber is a cylinder of some length and the discharge point cannot readily be placed in a position so that the intense electric field exists only between the point and the front but extends usually to the walls of the chamber as well, and moreover since some β-particles are produced in the cylindrical wall of the chamber itself, it is necessary to standardize the position of the point and to make a correction for those β-particles that do not come from the front. On varying the distance between the point and the front of the chamber and thereby varying the surface of the chamber to which the intense field from the point spreads, the counts obtained are different. When the point is near the front the count is small but as the point is moved farther back the count rapidly increases until the surface includes the whole of the front, and then increases less rapidly as the surface includes more and more of the cylindrical surface of the chamber. It is essential, therefore, to have the point always in the same position with respect to the front and to make corrections for effects due to β-particles which do not come from the front. If the point is well to the rear of the chamber, one would expect that the strong field lies mainly between the point and the side-walls of the chamber, and that by separating the front from the chamber electrically one would obtain the same counts as when the front was a part of the chamber. This was tested experimentally. The point was set 4 cm from the front of a copper counting chamber and records made for a given radiation. The front was then set a millimeter in front of the chamber, and was earthed, the chamber being at about 2000 volts. The reading in the second case was only 0.3 per cent smaller than in the first case. It was, therefore, decided that a record taken with the front removed corrects for all β-particles produced elsewhere in the chamber than in the front. A further test on the effect of the modified field, with the front removed, was carried out as follows. Wire gauze fronts were made with 5, 10, and 15 fine copper wires uniformly arranged and

crossing at right angles and records were taken with each of them and the curve obtained was extrapolated to a condition with no wire front. The effect, of course, increased with an increase in the number of wires, due (a) to any increase of field to the front and (b) to $\beta$-particles produced by the $\gamma$-rays in the wires. The increase, as shown by the first test, is undoubtedly due mainly to the second cause. The extrapolated value corresponded to the count made with no front. In all the experiments from which data were collected, records were also made for "no fronts" for the hard rays alone and for all the rays from the source. This correction reading involved observations made throughout the series of experiments and in aggregate took several hours.

In taking records of counts, therefore, records were taken for (1) the primary and scattered radiation together, for (2) the scattered radiation alone (including natural effects of the point, etc.) and for (3) "no front" on the chamber. The second was always taken along with the first and ultimately the difference of the two readings was corrected for the mean value of the third. The net result represents the effect due to $\gamma$-rays acting on the front alone.

Two distinct sets of observations were made involving separate determinations of all the quantities involved, namely, for all $\gamma$-rays emerging from the glass tube containing the radium, which are designated as total or *heterogeneous $\gamma$-rays*, and for the $\gamma$-rays passing through the glass tube, a protecting brass tube and a lead cylinder 1.55 cm thick, which are designated as *hard $\gamma$-rays*.

The inverse square law assumed in the calculations was tested by obtaining records of counts when the radium was placed at various distances, 200 cm to 450 cm from the counting chamber. The net count of the $\beta$-ray events produced by the $\gamma$-rays incident on the front multiplied by the square of the distance gave substantially the same value for these distances. At 450 cm two radium specimens, 1.305 mg and 5.002 mg, gave net counts proportional to the strengths of the radium specimens. It may be assumed, from these tests, that the application of the inverse square law and the proportionality of net counts to the strength of the material is justifiable.

The effect of the area of the front on the net count of the phenomena registered was tested in two ways. In the first method three chambers of areas in the ratio of 1:1.91:4.1 were used and the registered counts corrected for scattered radiation and for "no front" effects were in the ratio of the areas. In the second method one chamber enclosed in a lead house was used. Two blocks of lead were placed so as to form a slit. The net counts obtained for different widths of slits were plotted

against the exposed areas of the front as the two blocks of lead were separated. The resulting curve was a straight line.

It was therefore concluded that the corrections as applied must give sensibly the correct readings for any position of the source and for the size of the chamber. Consequently, in the final experiments, only one distance $r$ corresponding to a convenient position of the source relative to the chamber was used and the chamber was also selected of a convenient size having a fixed area of the front.

## Coefficients of Absorption

The coefficient of absorption of the $\gamma$-rays was obtained from counts, corrected for scattering by air and objects and for natural effects, for different thicknesses of absorbing material, by plotting the logarithm of the number against the thickness. The values obtained are given in the table below under $\mu_1$ and $\mu_1'$, for "hard" and "heterogeneous" $\gamma$-rays. The coefficients on the whole indicate harder rays than do values found by ionisation methods, which can readily be explained by the fact that in ionisation measurements the values depend not only on the number of $\gamma$-rays but also on the ionisation per cm of the $\beta$-particles produced by them and this increases with the decrease of velocity of the $\beta$-particles.

The coefficient of absorption of the $\beta$-particles produced by the $\gamma$-rays might be obtained in a manner similar to that followed by Bragg and Madsen[12] or by determining the thickness of the material giving maximum effect, i.e. the quantity $D$, and with the knowledge of $D$ and $\mu_1$ solving Eq. (4). It must be admitted that the experimental determination of $D$ introduces the greatest experimental error into the calculations, but the calculation of $\mu_2$ involves no approximations. It was this second method that was used. Determinations of $D$ from three types of experiments were made, (1) using chambers of different thicknesses in open air and plotting the count against thickness; (2) housing a standard counting chamber in the lead block and using fronts of the chamber of different thicknesses; and (3) repeating Bragg and Madsen's experiments, with some modification in the measuring instruments, by the measurement of the ionisation current. These last experiments were repeated to find if the maximum appeared materially different from that obtained by the counting method inasmuch as the $\mu_2$ seemed to come higher in value than that reported by Bragg and Madsen. The values of $D$ so obtained were not materially different from those obtained by the counting method. The average of all values by all methods for

[12] Bragg and Madsen, Phil. Mag. **16**, 918 (1908)

each metal was used. The value of $\mu_2$ was obtained from Eq. (4) by trial after changing the equation in the following way: $\mu_1\epsilon^{-\mu_1 D} = \mu_2\epsilon^{-\mu_2 D} = A$ and $\log_{10}\mu_2 - \log_{10}A - \mu_2 D\log_{10}\epsilon = \phi$ and giving values to $\mu_2$ until $\phi = 0$, $A$ being determined from $\mu_1$ and $D$. Table I gives the values

TABLE I

*The coefficient of absorption of $\gamma$-rays, $\mu_1$, and the coefficient of absorption in a metal of the $\beta$-particles produced in the metal by $\gamma$-rays, $\mu_2$*

| Metal | $\mu_1$ | $D$ | $\mu_2$ | $\mu_1/\rho$ | $M\mu_1/\rho$ | $\mu_2/\rho$ | $M\mu_2/\rho$ |
|---|---|---|---|---|---|---|---|
| | | | Hard $\gamma$-rays | | | | |
| Pb | 0.47 cm | 0.052 cm | 104.3 cm | 0.041 | 8.56 | 9.17 | 1900 |
| Pt | 0.81 | 0.026 | 215.5 | .038 | 7.36 | 10.02 | 1960 |
| Sn | 0.29 | 0.10 | 52.3 | .040 | 4.72 | 7.20 | 855 |
| Cu | 0.32 | 0.09 | 58.1 | .036 | 2.28 | 6.51 | 414 |
| Al | 0.11 | 0.31 | 16.2 | .041 | 1.10 | 6.00 | 163 |
| | | | Heterogeneous $\gamma$-rays | | | | |
| Pb | 0.78 | 0.029 | 200 | .069 | 14.2 | 17.6 | 3640 |
| Pt | 1.40 | 0.015 | 374 | .065 | 12.7 | 17.4 | 3400 |
| Sn | 0.36 | 0.065 | 84.3 | .049 | 5.86 | 11.6 | 1373 |
| Cu | 0.38 | 0.038 | 160 | .043 | 2.71 | 17.9 | 1140 |
| Al | 0.121 | 0.15 | 38.6 | .046 | 1.21 | 14.3 | 388 |

of $\mu_1$, $D$, and $\mu_2$. The values of $\mu_2$ are higher than the values for corresponding primary $\beta$-particles from the same source, which would indicate a softer $\beta$-radiation than the primary. If all the energy of the $\gamma$-ray goes to the ejection of a $\beta$-particle, the $\beta$-particle will not have the total energy because some of the energy must be used to eject the electron from some inner ring of the atom. Although the primary $\beta$-rays and the $\gamma$-rays are undoubtedly connected by some relation, the secondary $\beta$-radiation produced in metals, coming as a later transformation, should be softer than the primary radiation.

The columns $\mu/\rho$ and $M\mu/\rho$ give respectively the mass coefficient of absorption and the coefficient of absorption per gram atom for the $\gamma$-rays and for the $\beta$-rays produced by the $\gamma$-rays in the metal, where $\rho$ is the density of the metal and $M$ its atomic weight. If the values of $M\mu/\rho$ are plotted against the atomic number (Fig. 1), it will be found that the relation is not a linear one and that the relative increase in $M\mu/\rho$ with the atomic number is greater for the heterogeneous radiation, whether it be the $\gamma$-rays or the $\beta$-rays.

## FINAL DISPOSITION OF THE APPARATUS AND OBSERVATIONS

Although several specimens of radium were at the disposal of the writer it was deemed advisable to use the laboratory standard whose radium content was separately determined with consistent results by Professor B. B. Boltwood and by the U. S. Bureau of Standards. It was considered best to place this specimen at such a distance so that

the counts obtained would be most convenient in number both for the hard γ-rays and for the total or heterogeneous γ-rays.

The standard 1.305 mg in its glass tube was placed between the poles of a strong magnet to deflect the primary β-rays and at a distance of 310 cm from the front of the counting chamber. The counting chamber n some experiments, made of paper India-inked on the inside, and in other experiments, made of thin aluminium, was enclosed in a lead block described above. The fronts used were of various metals and thicknesses given. The plates of lead (19 cm) to obstruct direct γ-rays were set at 90 cm from the source when counts were taken to correct for scattering and natural effects. Since this last count besides scattering involved also the natural effect due to the points used and these differed in sharpness, symmetry, etc. and therefore in their discharges, it was necessary to take a reading for this effect after each reading for the direct and

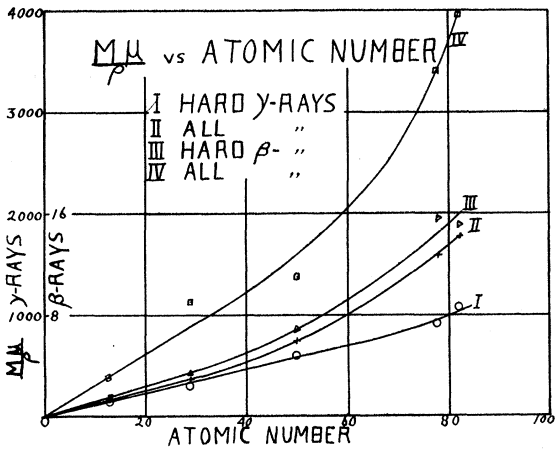


Fig. 1. Coefficients of absorption per gram atom for γ-rays and for the secondary β-rays.

scattered rays, etc; and the differences were finally averaged. The readings for any front used covered in total several hours of actual counts. Counts with the front removed were taken frequently during the whole time of the experiments. The correction so obtained was corrected by 0.3 per cent for the effect noted above when the front plate was earthed and set a millimeter in front of the chamber. For the heterogeneous rays this correction for "no front" amounted to 39.0 counts per minute and for the hard rays to 21.0 per minute. In the experiments with the hard γ-rays the radium tube was placed in a brass (protective) cylinder and a lead cylinder of 1.55 cm thickness and the whole was also

placed between the poles of the magnet deflecting the $\beta$-particles produced in the lead cylinder.

The final results are given in Table II. The third column gives the average of the difference in counts per minute when the direct and scattered $\gamma$-rays and natural effects were recorded and when the lead plates were set up to stop the direct $\gamma$-rays. The fourth column gives the net count per minute for the $\gamma$-ray effect produced in the metal of the front of the chamber, i.e. the value of the third column less the

TABLE II

| Front of chamber | Thickness in cm | Total count less scattering per min. | Net count per min. | $n$ Net per second | $K$ per gm | $\epsilon^{-\mu_1 d} - \epsilon^{-\mu_2 d}$ | $\Gamma_1$ per gm per sec. | Aver. $\Gamma_1$ |
|---|---|---|---|---|---|---|---|---|
| | | | | Total $\gamma$-radiation | | | | |
| Pb | 0.0324 | 75.2 | 36.2 | 0.603 | $11.47\times10^{10}$ | 0.973 | $7.10\times10^{10}$ | |
| | .065 | 73.2 | 34.2 | .570 | | .950 | 6.88 | |
| | | | | | | | | $6.99\times10^{10}$ |
| Pt | 0.0040 | 64.5 | 25.5 | 0.425 | 11.95 | 0.747 | 6.80 | |
| | .020 | 70.7 | 31.7 | .528 | | .971 | 6.50 | |
| | | | | | | | | 6.65 |
| Sn | 0.0238 | 75.0 | 36.0 | 0.600 | 10.47 | 0.857 | 7.33 | |
| | .051 | 75.4 | 36.4 | .607 | | .968 | 6.57 | |
| | | | | | | | | 6.95 |
| Cu | 0.0248 | 61.7 | 22.7 | 0.378 | 18.85 | 0.972 | 7.33 | |
| | .052 | 61.4 | 22.4 | .373 | | .980 | 7.17 | |
| | | | | | | | | 7.25 |
| Al | 0.0365 | 60.2 | 21.2 | 0.353 | 14.28 | 0.751 | 6.71 | |
| | .1095 | 67.5 | 28.5 | .475 | | .972 | 6.98 | |
| | | | | | | | | 6.85 |
| | | | | | | | | Mean $6.94\times10^{10}$ |
| | | | | Hard $\gamma$-radiation | | | | |
| Pb | 0.0324 | 35.0 | 14.0 | 0.233 | 9.93 | 0.951 | 2.43 | |
| | .065 | 36.6 | 15.6 | .260 | | .969 | 2.67 | |
| | .084 | 35.9 | 14.9 | .248 | | .961 | 2.56 | |
| | | | | | | | | 2.55 |
| Pt | 0.0040 | 28.8 | 7.8 | 0.130 | 11.90 | 0.575 | 2.69 | |
| | .020 | 33.9 | 12.9 | .215 | | .971 | 2.64 | |
| | | | | | | | | 2.67 |
| Sn | 0.0238 | 35.7 | 14.7 | 0.245 | 8.05 | 0.705 | 2.73 | |
| | .051 | 38.5 | 17.5 | .292 | | .915 | 2.57 | |
| | | | | | | | | 2.65 |
| Cu | 0.052 | 37.0 | 16.0 | 0.267 | 8.11 | 0.937 | 2.31 | |
| | | | | | | | | 2.31 |
| Al | 0.0365 | 31.4 | 10.4 | 0.173 | 6.57 | 0.443 | 2.56 | |
| | .1095 | 40.1 | 19.1 | 0.318 | | .818 | 2.56 | |
| | .1042* | 42.0 | 21.0 | 0.350 | 5.88 | .806 | 2.56 | |
| | | | | | | | | 2.56 |
| | | | | | | | | Mean $2.55\times10^{10}$ |

For total radiation: $\Gamma = \Gamma_1 \times \frac{1}{0.972} \times \frac{1}{0.981}$

$= 7.28\times10^{10}$ per gram per second

For hard rays: $\Gamma' = \Gamma_1' \times \frac{1}{0.482} \times \frac{1}{0.981} \times \frac{1}{0.988} \times \frac{1}{0.981}$

$= 5.56\times10^{10}$ per gram per second

* Thick Al chamber and $a = 2.30$ cm$^2$

"no front" correction; and the fifth column gives this count per second. Since it was thought best to have readings for at least two thicknesses of each material, Eq. (2) was used for calculating the number of $\gamma$-rays and was written in the form

$$\Gamma_1 = nK\frac{1}{\epsilon^{-\mu_1 d} - \epsilon^{-\mu_2 d}}$$

where $$K = \frac{\mu_2 - \mu_1}{\mu_1}\frac{4\pi r^2}{aS} = \frac{\mu_2 - \mu_1}{\mu_1} 4.49 \times 10^8/\text{gram},$$

since $a = \pi$ (0.81 cm)$^2$ = 2.06 cm$^2$, $r = 310$ cm and $S = 1.305$ mg. This value of $K$ is given in the sixth column. In the last Al record, the value of $K$ was obtained by taking $a = 2.30$ cm$^2$ since a different chamber was used made of thicker aluminium and with a larger window. The seventh column gives the difference $(\epsilon^{-\mu_1 d} - \epsilon^{-\mu_2 d})$. The value of $\Gamma_1$ is entered in the eighth column. The values of $\Gamma_1$ for different values of $d$ for the same metal were averaged and entered in the last column. Since separate constants had to be obtained for the different metals the values of the $\Gamma_1$, using different metals for the front, have a greater significance than the values obtained for different thicknesses of the same metal. The values for each metal were therefore weighted alike. The average of all these values is given at the bottom of the table. For the total radiation this value of $\Gamma_1$ must be corrected for glass and for the intervening air; for the hard radiation, it must be extrapolated to zero thickness of lead on account of the lead cylinder and corrected for the brass tube, glass and intervening air. Since the coefficient of absorption of the hard rays in lead is 0.47 cm$^{-1}$ Pb and the thickness of the lead cylinder was 1.55 cm, the exponential used in the extrapolation has the value 0.482. The coefficients of absorption in glass were found to be 0.117 cm$^{-1}$ for the hard $\gamma$-rays and 0.28 cm$^{-1}$ for the total $\gamma$-rays for small thicknesses of glass. The thickness of the glass wall was 1 mm, making the extrapolation exponentials 0.988 and 0.972 for the hard and total $\gamma$ radiations, respectively. The brass (protective) tube was used only in connection with the hard $\gamma$-rays and the correcting exponential was found experimentally to be 0.981. The correction for absorption in air was taken the same for hard and total radiation because complete data are lacking on the coefficient of absorption in air and the value used is that of Chadwick,[13] namely, $6.0 \times 10^{-5}$ cm$^{-1}$ air at ordinary room temperature and pressure. The exponential used for the correction for 310 cm air has the value 0.981.

Using these corrections the final value obtained for the total $\gamma$-radiation emitted from radium B and C is $6.94 \times 10^{10} \times 1/0.9537 = 7.28 \times 10^{10}$

[13] Chadwick, Phys. Soc. London, **24**, 145 (1912)

per gram radium per second, and for the hard radiation $2.55\times10^{10}\times 1/0.4583=5.56\times10^{10}$ per gram radium per second. The $\gamma$-radiation from radium D and E is absorbed by the glass and air. Consequently the number $7.28\times10^{10}$ represents the number of $\gamma$ rays emitted per second by radium B and radium C in equilibrium with one gram of radium. Since at the equilibrium condition the rate of disintegration of atoms is the same for all substances in radioactive equilibrium, we may take one-half of the above number, namely, $3.64\times10^{10}$ to represent the number of $\gamma$ rays emitted by radium B and the other half by radium C in equilibrium with one gram of radium. Furthermore, since the number of radium C atoms disintegrating per second per gram of radium as found by $\alpha$ particle counts,[14] is $3.57\times10^{10}$, it follows that the number of $\gamma$-ray entities emitted by one atom of radium B or radium C is one, within 2 per cent, a difference which may be due to experimental error arising most probably for the most part in the determination of $D$.

## Discussion of the Results

It was mentioned at the beginning that the $\gamma$-ray energy may possibly be absorbed partially at different places producing $\beta$-particles perhaps far apart from each other. In such a case the counts of all the $\beta$-rays would give a value greater than the number of $\gamma$-ray entities. The average number of counts at any one place would be greater than the number of $\gamma$-rays. The fact that the number of $\gamma$-rays per atom disintegrating deduced from the data of these experiments comes out one $\gamma$-ray per atom, within the possible experimental error, seems to negative this assumption because one would expect an integral number of $\gamma$-rays per atom. The writer concludes that a $\gamma$-ray gives up its energy to produce one $\beta$-particle or two or more $\beta$-particles from the same atom or molecule.

The number of hard $\gamma$-rays from radium B and C was found to be $5.56\times10^{10}$ per gram radium per second. This is 76.4 per cent of the total radiation, thus leaving for the soft radiation 23.6 per cent of the total. The experiments of Tuomikoski[15] on the absorption coefficients of $\gamma$-rays by the ionisation method gave for the hard radiation 72.2 per cent and for the soft radiation 27.8 per cent. These experiments were repeated by the writer using more thicknesses of lead (below 1 cm thickness) than were used by Tuomikoski and using a strong magnetic field on the source. A large cylindrical block of lead, 25 cm in diameter and 7 cm thick, with a hole in the center in line with electroscope and the source, was used to protect the electroscope from scattered radiation.

[14] Rutherford, Phil. Mag. **28,** 320 (1914)
[15] Tuomikoski, Phys. Zeits. **10,** 372 (1909)

The electroscope 6 cm×6 cm itself had 2 cm of lead on all sides except the one facing the source. The absorbing lead was placed between the electroscope and the large cylinder, the space between being 6 cm, and for zero reading 20 cm of lead were placed between the lead cylinder and the source so that about 26 cm of lead were in the direct path of the γ-rays. The hard radiation came out to be 73.7 per cent and the soft radiation 26.3 per cent of the total, which agrees fairly well with Tuomikoski. The coefficient of the hard radiation (lead 1 cm to 4.2 cm) came out 0.51 $cm^{-1}$ Pb against Tuomikoski's 0.50 $cm^{-1}$ Pb, and for the heterogeneous radiation (0 to 1 cm Pb) came out 0.88 $cm^{-1}$ Pb against 0.95 $cm^{-1}$ Pb. Now, the coefficient of absorption by the counting method, as indicated in this work, is for the hard γ-rays 0.47 $cm^{-1}$ Pb, and for the heterogeneous rays (0 to 1 cm Pb) 0.78 $cm^{-1}$ Pb. It is evident that the ionisation experiments give a higher value for a coefficient of absorption than the counting experiments, a fact already alluded to, and indicate a softer radiation. This indication from ionisation experiments may be misleading because the ionisation is produced by the β-particles emitted from the metal by the γ-rays and the softer the β-rays are the greater is the ionisation produced by them. This fact readily explains the greater rise of the absorption curve at the beginning and, therefore, the steeper log $I$ vs. $d$ straight line, and hence the greater value obtained for $\mu$. It also explains the somewhat greater percentage of the soft radiation obtained by the ionisation method. It must be remembered that in the counting method the effect counted is one event for the γ-ray whether it be of long or short wave-length, whereas the ionisation produced in a given space by the fast moving β-particle emitted by a high frequency γ-ray is less than that produced by a slower moving β-particle emitted by a γ-ray of lower frequency. The difference between the percentages of the hard γ-rays and soft γ-rays as obtained by the counting method, and the corresponding values obtained by the ionisation method is in the right direction and seems to be of the right value. Since the counting method gives the numbers of γ-rays, the percentages represent the ratios of the actual γ-rays of the two types of radiation respectively to the total radiation without the qualifications which must be applied to similar values obtained by measurements of ionisations. The figures in these ratios include the penetrating radiations and the soft radiations from both radium B and radium C.

## Conclusion

It is concluded from this statistical study of the γ-rays from radium B and radium C that the γ-ray energy is absorbed at one place to produce

one or more $\beta$-particles at that place and that the number of $\gamma$-ray entities from radium B and radium C in equilibrium with one gram of radium is $7.28 \times 10^{10}$ per second, or that one $\gamma$-ray entity is emitted when one atom of radium B or of radium C disintegrates.

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