XXXIX. Secondary γ radiation

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To cite this article: J.P.V. Madsen D.Sc. B.E. (1909) XXXIX. Secondary γ radiation , Philosophical Magazine Series 6, 17:99, 423-448, DOI: [10.1080/14786440308636618](https://doi.org/10.1080/14786440308636618)

To link to this article: <http://dx.doi.org/10.1080/14786440308636618>

Published online: 21 Apr 2009.

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XXXIX. *Secondary γ Radiation.* By J. P. V. MADSEN, *D.Sc. (Adel.), B.E. (Syd.), Lecturer in Electrical Engineering, University of Adelaide* *.

[Plate VIII.]

INTRODUCTION.

AS a result of the passage of γ rays through matter, secondary rays of two types make their appearance. As it will be necessary to distinguish between the secondary rays which proceed from the sides at which the original γ rays enter and emerge from the plate which they penetrate, we shall refer to these as the "incidence" and "emergence" rays respectively.

The secondary radiation consists of β and of γ rays.

The former appear on both sides of the plate; the "incidence" β rays have been recently investigated in some detail by Kleeman (Phil. Mag., Nov. 1907) and by Eve (Phil. Mag., June 1908).

In papers by Professor Bragg and myself (Phil. Mag., May 1908; Trans. Roy. Soc. S. Aus. vol. xxxii. 1908) it is shown that most of the experimental results so far obtained with these rays can be very simply explained on the "material" theory, if we suppose that the β radiation is produced directly from the γ particle and at the outset moves in the direction of the original γ radiation, subsequently undergoing scattering in the ordinary manner of β rays.

The second type of secondary radiation resulting from the primary γ rays, viz., the secondary γ rays, has been investigated on the incidence side of plates of different material by Kleeman (Phil. Mag., May 1908), and later by Eve (Phil. Mag., Aug. 1908).

It was a deduction made by Professor Bragg (Trans. Roy. Soc. S. Aus. Jan. 1908) from the theory of the material nature of X and of γ rays previously propounded by him, that "the existence of modified or softened γ rays might be suspected, since there is an analogous effect in the case of X-rays; and probably they would be found more at the back of the penetrated plate than in front of it." The back and front sides spoken of here refer of course to the sides of emergence and incidence respectively.

* Communicated by the Author. From 'Transactions of the Royal Society of South Australia,' vol. xxxii. 1908. Preliminary account read July 17, 1908.

It will be shown in the present paper that this prediction is fulfilled very exactly ; that the want of symmetry in the amount of radiation from the two sides of the plate is very marked, that a softening of the original rays is effected, and that in addition there is in some cases a lack of symmetry in the quality of the emergence and incidence γ radiation.

Kleeman, from a study of the incidence radiation, has advanced a theory of selective absorption, not only for the secondary but also for the primary γ rays. In the light of the more comprehensive information which can be obtained from a study of both the emergence and the incidence radiation, an attempt will be made in the present paper to show that most of the secondary ray effects can be explained, if we suppose that from the radium there are originally emitted two sets of homogeneous γ rays, which each subsequently suffer modification by the process of scattering, becoming softened and in some cases broken up, giving rise to β rays.

The present paper is intended to give a preliminary outline of the experimental work and general theory.

The measurements are in many cases small and difficult to make with any very great accuracy, but the effects to be described seem well marked. It will be necessary to extend with greater care many of the details of the work before it can be considered as at all complete.

§ I.

The arrangement of apparatus employed in the first experiments is shown in fig. 1 (Pl. VIII.). The radium is placed near the apex of a conical hole made in a block of lead. By means of a powerful magnet, the poles of which are shown, most of the β rays could be prevented from passing out of the conical hole. The magnet and lead block containing the Ra were surrounded by an iron case, to prevent the magnetic field from producing any effect in the ionization-chamber. Resting upon the iron case and suitably insulated from it is placed a lead plate one inch thick, with a circular portion removed from the centre. The ionization-chamber standing upon this lead plate is made of lead 1.25 mm. thick, and contains an insulated electrode in the form of a circular wire ring, suitably protected by sulphur, and connecting to the electrometer or to earth by suitable keys.

In the path of the γ radiation which proceeds from the conical hole, plates of material which are used as radiators

can be placed horizontally as at *e*. When increasing the thickness of radiator the top plate is always kept in the position *e*, and additional thicknesses are placed immediately below and in contact with it. When large thicknesses are required, plugs of the material may be inserted in the conical hole.

The ionization-chamber was filled with ethyl chloride; this increased the effect considerably and worked very satisfactorily.

It was necessary to balance the leak due to natural ionization in the chamber, and to γ radiation which was not completely absorbed by the lead block and plates. For this purpose a balance chamber of about the same size as the ionization-chamber was placed against one of the sides of the iron case insulated from it.

This was connected up in the usual manner, and was found to give quite sufficient balance with the ionization produced by the γ radiation which came through the sides of the lead block containing the Ra. The electrometer was a sensitive instrument of the Dolezalek pattern, giving a scale reading of about 4000 divisions per volt; each division could easily be subdivided to tenths. The charge was allowed to pass into the electrometer for 30 sec., and the mean of the first and second swings was taken as the deflexion.

In fig. 2, curve A shows the effect of increasing the thickness of a Pb radiator. In an experiment, the zero leak was first obtained as a mean of several determinations, and this was subtracted from the measurement obtained with the radiator in position. It will be seen from the curve that the effect increases until a thickness of between 5 and 6 mm. of Pb is reached, after which it decreases gradually.

If, now, a hemispherical dome of Pb 4 mm. thick, with its central portion removed so as not to intercept the original stream of γ rays, be placed in the position shown by *h, h*, fig. 1, and a set of observations be taken as before, subtracting the reading with the radiator in from that with it not in position, the curve B is obtained. Again, a maximum is reached for about the same thickness of radiation as before, but the effect is for the different thickness of radiator about 60 per cent. of its previous value. We may conclude that it is γ radiation which is being intercepted by the dome, as in neither case can any but a very small amount of β radiation pass obliquely through the thickness of 1.25 mm. of lead forming the sides of the ionization-chamber; and that from the radiator are proceeding secondary emergence γ rays

which produce ionization in the testing chamber, as shown in previous papers by means of—

- (a) “tertiary emergence” β rays as at l ;
- (b) tertiary incidence β rays as at k ;
- (c) β radiation produced in the gas of the chamber from the γ rays as they pass through it ;
- (d) possibly some ions produced directly in the gas by the γ rays ; and
- (e) subsequent β and γ ray effects of a higher order.

The results of a similar set of experiments without a Pb dome and with Zn as radiator are shown in fig. 3, curve A. The maximum value of the effect measured is considerably greater than in the case of Pb and occurs at a thickness of about 2 cm. of the radiator ; for increased thicknesses the curve falls as in the case of Pb. It will be noticed that with sufficient thickness of radiator in this case the curve falls below zero. This was found to be due to the fact that a considerable amount of secondary γ radiation, proceeding from the sides of the conical hole in the Pb block containing the Ra, could enter the ionization-chamber as shown by the line c, f (fig. 1). As any radiator is increased in thickness, it not only sends out its own secondary but absorbs that coming from the sides of the conical hole. It will be shown later how proper correction can be made for this effect.

A third set of experiments was carried out with Al as radiator ; the effects were of a similar nature to those from Zn, the maximum value being about the same in amount as for Zn, and was obtained with a thickness of about 4.5 cm. ; but it was found that an appreciable difference was made when a plug of Al was placed at b in place of d as shown in fig. 1, even though the total thickness of Al was kept the same in both cases. It will thus be seen that some secondary radiation can, after emerging obliquely from a depth of several cm. of Al, produce an effect in the ionization-chamber. The present form of apparatus was therefore not suitable for obtaining from Al all the results so far obtained for Pb and Zn ; in these latter it was found that similar errors were very small. It may, however, safely be said for Al as for Zn that the effect produced is considerably greater than for Pb.

We have so far neglected all consideration of the secondary radiation which comes from the sides of the conical hole ; this it will now be shown is by no means small, but the correction which it introduced was found not to be

sufficient to interfere with the deduction just made. Consequently we may say that Zn and Al both give out more secondary emergence γ radiation than does Pb, provided of course that the quality of the radiation in the two cases is not so different as to balance the effect.

In order to find the amount and nature of the radiation which proceeds from the sides of the conical hole, Pb domes were placed as at *h, h*, or Pb cylinders as at *i, i*, fig. 1. When the latter were used, their equivalent thickness was found in terms of corresponding domes. A cylinder was found to be approximately equivalent to a dome 1.5 times its thickness.

The results of experiments upon the radiation from the sides of the cone are shown in fig. 4, curve A, in which thicknesses of dome are shown horizontally and the corresponding leaks per 30 secs. vertically.

The curve A can be represented approximately by the expression $500 + 570e^{-1.25d}$.

That the radiation comes from the sides of the cone can be shown by placing at *e* (fig. 1) Pb plates in which circular holes are cut so as not to intercept the main stream of γ radiation coming from the Ra.

The results now obtained for different dome thicknesses are shown by curve B, fig. 4, which it will be seen can again be represented approximately by the expression $500 + 430e^{-1.25d}$.

It seems reasonable to suppose that besides the constant normal leak in the ionization-chamber, secondary γ radiation from the sides of the conical hole can enter the chamber, and that this radiation may for the purposes of correction to which it is to be applied later on, be taken as equivalent to a homogeneous radiation for which $\lambda = 1.25$.

If now a Pb plug, 4 cm. deep, be placed in the conical hole in the position shown by *a*, fig. 1, so as to intercept the main stream of γ radiation, but still leave the sides of the cone exposed to the ionization-chamber, and a set of experiments similar to the above be performed, the results shown in curve C, fig. 4, are obtained. These again are approximately represented by $500 + 270e^{-1.25d}$.

It is not surprising that the constant normal leak has not been reduced to any appreciable extent, for it will be seen from fig. 1, that the plug would hardly intercept any γ radiation passing directly from the Ra to the ionization-chamber. On the other hand, we obtain a rather important result, for assuming, of course, that the interpretation put upon these experiments is correct, even when the Ra is

completely surrounded by a thickness of 4 cm. of Pb, a secondary radiation escapes, which has a value of λ approx. 1.25. Now it has been shown by Wigger (*Jahrbuch der Rad.* Bd. ii. 1905) that practically all soft γ rays coming from the Ra are stopped by a thickness of Pb considerably less than 4 cm., and that the hard γ rays which can penetrate such a thickness have a value of $\lambda = .24$.

Again, the amount of the secondary radiation has only been reduced from 570 to 270 by the insertion of the 4 cm. plug of Pb, so that we must suppose most of the secondary radiation we are dealing with to be produced from the hard γ rays and very little of it from the soft γ rays. This result, it will be shown later, is supported by other experiments.

It is now possible to apply the necessary correction to the curve A, fig. 2. The result is shown by the full line curve C, the proper correction being obtained by adding a quantity $400(1 - e^{-(1.5 \times 1.25d)})$ to the original values. Part of the secondary radiation from the sides of the cone was in these experiments cut off by suitable Pb screens; the factor 1.5 is introduced to allow for the obliquity with which the rays coming from the sides of the cone cross the radiators.

In order to investigate now the quality of the secondary radiation which comes from the Pb radiators, a Pb plate 5 mm. thick was used as radiator, and the emergence radiation was absorbed by Pb domes. In each experiment the dome having been placed in position, two sets of measurements were taken, one with, the other without, the radiator, and the results of these subtracted. The mean of a number of experiments is shown in Table I., and in fig. 5, curve A, the value of the thickness of the dome multiplied by its density is shown horizontally, and the log. of the corresponding current vertically, the reading with no dome being reduced to 100. It will be seen that the emergence radiation from Pb, within the range of thickness of dome, over which it has been measured with sufficient accuracy, is approximately equivalent to a homogeneous radiation for which $\lambda = 1.33$.

Now these results require correction on account of the absorption by the 5 mm. Pb radiator of the secondary radiation from the sides of the cone. As, however, this latter has been shown to have approximately the same value of λ , viz., 1.25, it is hardly necessary at the present stage to attempt to apply the correction.

The quality of the radiation from Pb was now tested by Zn and by Al domes. The results are shown in the curves B and C, fig. 5. It will be seen that λ/Δ is of much the

same value when the radiation is tested by Zn or Al; but is considerably greater when tested by Pb. This is similar to the results which are obtained when the original γ radiation coming from Ra, which apparently consists of a mixture of hard and soft rays, is tested by small thicknesses of absorbing screen.

TABLE I.

PB DOMES.

Radiation from Pb.

Thickness of Dome, mm.	0	1	4	6	10
	100	80	60	43	26.5

Radiation from Zn.

Thickness of Dome, mm.	0	2	4	6	10
	100	64	46	33	21

Radiation from Al.

Thickness of Dome, mm.	0	2	4	6	10
	100	63	45	32	20

ZN DOMES.

Radiation from Pb.

Thickness of Dome, mm.	0	5.4	11.7	25.3
	100	85	67.5	44

Radiation from Zn.

Thickness of Dome, mm.	0	5.4	11.7	25.3
	100	84	63	34

Radiation from Al.

Thickness of Dome, mm.	0	5.4	11.7	25.3
	100	81	59	33

AL DOMES.

Radiation from Pb.

Thickness of Dome, mm.	0	8	21
	100	88	75

Radiation from Zn.

Thickness of Dome, mm.	0	21
	100	74

Radiation from Al.

Thickness of Dome, mm.	0	21
	100	72

It has already been shown that the radiation from the sides of the cone is approximately of the same quality as that
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from a Pb radiator ; we may therefore assume without much possibility of error that the value of λ by Zn for this radiation is $\cdot 34$.

It is now possible to apply the necessary correction to the curve A, fig. 3. A quantity $570(1 - e^{-(1.5 \times .34)d})$ has been added to the previous readings ; the result is shown in the full-line curve B. The last two readings require a slightly less correction on account of the Zn plug cutting off some of the original γ radiation which produces the effect from the sides of the cone ; the necessary correction in this case was determined by a separate experiment.

The quantity of the emergence radiation from Zn and from Al was now tested by Zn and by Al domes. The results are given in Table I., proper correction being applied in each case for the absorption of the radiation from the sides of the cone.

The Zn radiator was 12 mm. thick, the Al 17 mm. Measurements were also made with radiators of other thicknesses, but the results were not sufficiently accurate to enable one to say whether the quality of the emergence radiation varied with the thickness of radiator.

The results are plotted in fig. 5, from which it will be seen that the radiation from Zn and Al is far from homogeneous when tested by Pb domes.

The emergence radiation from Zn and Al appears to consist of two sets of γ rays—one of much the same quality as those which are produced from Pb, the other a very much softer bundle. A rough analysis of either the Zn or Al curve, if such is legitimate, would suggest that it may be derived from a hard and soft bundle of γ rays, for which the values of λ by Pb are 1.3 and 5 respectively, the effect of the hard bundle being initially almost twice that of the soft.

It will be seen from the figure that mass for mass Al and Zn domes are not able to bring out so clearly as Pb domes the distinction between the quality of the secondary radiations from Zn and Al as compared with that from Pb.

This, again, is much the same as is found when one attempts to sort out the original hard and soft γ rays of Ra by such screens.

However, the radiation from Pb always appears somewhat harder than that from Zn and Al, no matter what screen is used.

This result has been checked on different occasions with care, and is of importance, as the results obtained by Kleeman from the secondary incidence γ rays, and the theory of selective absorption founded thereon, and extended to the original γ radiation, should apparently apply also to the secondary emergence rays.

§ II.

To investigate the secondary incidence γ rays the ionization-chamber (fig. 1), was inverted, and the large plates which served as radiators were laid directly upon the ionization-chamber as at p, p . This enabled the secondary incidence rays from the radiator to enter the ionization-chamber, not only by the sides i, i but also through the top of the chamber, and should more than compensate for any decrease in effect due to the primary γ rays falling upon a larger area than they did in the case where the emergence radiation was measured.

The secondary incidence radiation increased in amount as the thickness of the radiator was increased. In fig. 6 is shown the relation between the mass of the radiator and the amount of the secondary incidence γ radiation for C, Al, Zn, and Pb.

C and Al gave maximum values of nearly the same amount, viz., 300; Zn not quite so much, viz., 270; while Pb gave only 100. Comparing these with the corrected values for the emergence radiation from Pb and Zn respectively, which were 680 and 1400 approximately, it is seen that the lack of symmetry between the effects on the two sides of a plate is very marked—the effect on the emergence side being from about 4.5 to 6.5 times that on the incidence side. The quantities on the incidence side are consequently so small that they become difficult to measure with any great accuracy, especially when an attempt is made to determine the quality of the radiation.

To measure the quality of the incidence radiation the top of the ionization-chamber was covered with a lead sheet about 1 cm. thick, from the centre of which was cut a circular hole 17.5 cm. diameter. One of the larger domes was then inverted and placed so as to intercept the radiation from the radiator, which was placed in the large circular hole just mentioned. A thickness of radiator sufficient to give the maximum effect was used in all cases. There appeared to be very little difference in the quality of the radiation returned from C, Al, and Zn. A Pb dome 4 mm. thick reduced the effect to approximately 20 per cent., indicating a radiation for which the value of λ is 4, if we can suppose it homogeneous.

In the case of Zn and Al it will be seen from Table I. that a 4 mm. Pb dome reduces the effect of the emergence radiation to about 45 per cent. There is thus a considerable difference in the quality of the emergence and the incidence γ radiations from these substances.

That the incidence radiation from these substances is softer than the emergence, is also supported by the experiments of Kleeman and Eve already referred to, both these observers having found the value of λ for the incidence rays from these or similar substances to be of the order 4, measured by Pb. In the case of the incidence radiation from Pb the measurements were not sufficiently accurate to decide whether the incidence radiation was softer than the emergence; it appeared to be of much the same quality, *i. e.*, $\lambda=1.3$ approximately.

§ III.

As the apparatus described in fig. 1 was unsuitable for measuring the amount of secondary emergence radiation from substances such as Al and C, and as we do not know that the distribution of the emergence radiation is the same in all directions for all substances, an experiment was set up as shown in fig. 7.

The lower portion of the diagram shows the arrangement of the Ra, magnet, and iron case which is the same as previously described. Some distance above the Ra was supported—upon an insulated stand—a flat cylindrical ionization-chamber. The floor of this chamber was of sheet lead 1.25 mm. thick, the sides were of Zn, and for a lid was used a thin Al plate. The conical chamber, shown by dotted lines, was used in experiments to be described later. The radiators were in the form of flat plates, the first of which in any experiment was placed in the position p, p . Additional thicknesses were added immediately below p, p and in contact with the top plate, while for very great thicknesses plugs of the material could be inserted in the conical hole in the Pb block, through which the γ radiation streamed.

In the first set of experiments the Pb plates L, L were used in the position shown, the large central hole in them allowing the γ rays to pass without obstruction to the ionization-chamber; while a considerable amount of secondary γ radiation from the radiating plates p, p was prevented from reaching the chamber. A strong magnetic field was applied during the experiments. The floor of the ionization-chamber, consisting of Pb 1.25 mm. thick, was sufficient, as has been shown in previous papers, to give the full amount of emergence β radiation. Several readings were taken with each thickness of radiator in position, and the readings were sufficiently large with the chamber filled with air. From any reading it is necessary to subtract an amount corresponding

to the leak produced by the natural ionization in the chamber, to the radiation which comes directly from the Ra and has not all been cut off by the interposed screens, such as L, L, and to secondary γ radiation from surrounding bodies, which

Fig. 7.

The radiators shown by horizontal dotted lines below p, p intercept the radiation from the Ra. By means of Pb plates L, L an amount of the secondary radiation may be prevented from entering the ionization-chamber. The dotted conical chamber was used in a separate set of experiments.

may be able to enter the chamber. This latter quantity was found to be by no means negligible, and so far as I know has not been allowed for in many experiments by previous

observers. To obtain with great accuracy the zero reading necessary for subtraction, is a course exceedingly difficult.

In the present experiment a close approximation to its value was found by inserting a large Pb plug in the conical hole and placing plates of Pb above this, so as to make in all a thickness of about 20 cm. This, as shown by previous observers, should be sufficient to reduce even the hard γ radiation, which streamed through the conical hole, to almost a negligible amount, while it should not affect to any great extent the secondary radiation coming from surrounding bodies.

The results of experiments with different materials used as radiators are given in Table II., and in fig. 8 are shown by full-line curves the thickness of radiator multiplied by its density, plotted horizontally against the logarithm of the corresponding currents vertically. The value of the current with no radiation in position at p , p has in each case been reduced to the common value 100, and the zero for the ordinates has in some of the curves been altered so as to prevent overlapping. It will be seen that Pb, Bi, and Hg give results almost identical; while Sn, Zn, Al, and C all give results very similar to each other, but differing from those of the first group in that a more sudden drop of the curve is shown for the initial thicknesses of radiator. From a value of $d\Delta=7$ onwards the curves for all the substances become practically parallel.

The Pb screens L, L, fig. 7, were now removed, and radiators were used in the form of large, flat plates, the first of which was placed horizontally just below the floor of the ionization-chamber, merely separated from it by a small thickness of ebonite for insulation.

Successive thicknesses of radiator were added immediately below the first. By this means it was thought possible to allow a large proportion of all the emergent secondary γ radiation to add on its effect in the chamber. The results of these experiments, given in Table III. and shown by the dotted curves in fig. 8 (Pl. VIII.) show that this anticipation was realized.

The dotted curves $\textcircled{\text{Al}'}$ and $\textcircled{\text{Zn}'}$ need not be considered at present; they were obtained with a carbon floor introduced into the ionization-chamber, and show the effects which previous work would lead us to expect.

Al, C, Zn, Fe, S, and Sn give results which are all very nearly identical, and the curves show a considerable difference in slope to what they did in the previous experiment.

TABLE II.

Lead Floor.											
C.		Al.		Zn.		Sn.		Bi.		Pb.	
<i>d.</i> mm.	I.	<i>d.</i> mm.	I.	<i>d.</i> mm.	I.	<i>d.</i> mm.	I.	<i>d.</i> mm.	I.	<i>d.</i> mm.	I.
0.0	100.0	0.0	100.0	0.0	100.00	0.0	100.00	0.0	100.00	0.0	100.00
10.0	90.4	4.8	92.5	6.7	73.60	7.8	67.60	5.12	54.50	1.1	83.50
20.0	81.2	10.0	86.5	12.0	57.40	15.0	51.70	10.50	38.20	2.5	69.30
30.0	71.0	18.5	73.5	18.0	44.80	22.8	38.80	15.70	27.50	5.0	54.50
40.0	64.7	33.5	57.3	24.0	33.80	37.3	21.00	25.20	16.95	7.5	44.20
54.0	54.4	43.5	49.2	30.0	25.60	47.8	14.70	35.70	10.65	11.6	31.40
76.0	42.6	63.5	35.8	40.0	18.40	67.8	9.00	55.20	5.28	16.6	23.00
99.0	33.7	93.5	22.3	60.0	8.90	87.8	5.37			21.6	17.40
128.0	23.4	133.5	12.7	80.0	5.99	107.8	4.17			26.6	12.80
				100.0	3.78					36.6	8.10
										46.6	4.90
										56.6	3.64
										66.6	2.76

TABLE III.

Lead Floor.										Carbon Floor.			
Al.		Zn.		C.		Pb.		Fe.		Al.		Zn.	
d. mm.	I.	d. mm.	I.	d. mm.	I.	d. mm.	I.	d. mm.	I.	d. mm.	I.	d. mm.	I.
0.0	100.00	0.0	100.00	0.0	100.0	0.00	100.00	0.0	100.0	0.0	100.0	0.0	100.00
10.0	94.00	3.0	92.50	10.0	89.0	1.10	84.00	0.0	50.7	10.0	93.7	3.0	89.70
17.0	85.50	4.5	87.60	30.0	83.0	2.55	71.20	22.0	S.	27.0	77.2	6.0	82.70
34.0	72.00	6.0	84.20	57.0	72.5	5.10	55.70	0.0	100.0	44.0	64.5	9.0	74.00
61.0	54.80	9.0	75.80	77.0	59.6	10.20	39.60	13.0	91.4	78.0	45.5	12.0	69.00
78.0	46.00	15.3	62.20	87.0	53.8	16.30	26.00	27.0	Hg.	112.0	30.4	15.3	61.40
95.0	37.60	21.6	50.00	107.0	49.5	21.60	18.20	0.0	100.0	139.0	20.6	21.6	51.50
112.0	29.40	28.0	41.60	132.0	39.0	26.70	14.20	6.0	48.0	169.0	15.5	28.0	42.30
129.0	25.60	37.0	30.80	152.0	37.0	31.80	10.80	15.3	21.0	199.0	11.6	34.0	35.30
149.0	20.80	52.0	20.60			44.00	8.00		Sn.	239.0	7.6	40.0	29.50
169.0	14.70	58.0	15.60			54.00	5.15	0.0	100.0			46.0	24.10
199.0	10.30	64.0	13.30			64.00	3.40	25.0	46.0			55.0	18.10
239.0	6.15	72.0	10.15									61.0	13.70
		81.0	7.52									67.0	11.50
		102.0	4.82									79.0	9.05
												91.0	6.45
												109.0	4.90

Pb and Hg, however, are distinctly different from the other substances, of which we may hereafter take Zn as typical.

The curve for Pb has not been altered to such a large extent by the change of arrangement of the experiment as has that for Zn and such substances.

The results for Zn are shown separately in fig. 9 (Pl. VIII.) by curves A and B, in which the values of thickness of absorbing screen multiplied by its density are shown horizontally and the corresponding currents vertically. The difference between the ordinates for any value of $d\Delta$ represents the amount of secondary radiation which it was possible to cut out by the Pb screens L, L in the first experiment. This difference is shown by the dotted curve C. It will be seen that the amount of secondary γ radiation increases with the thickness of absorbing screen or radiator, until a value corresponding to $d\Delta = 18$ has been reached, after which it gradually falls. For certain values of $d\Delta$ the effect produced by the secondary γ rays may be almost as great as that which is being produced by the primary γ rays.

It is thus seen that the effect produced in an ionization-chamber in an ordinary absorption experiment depends largely upon the position of the absorbing plate relatively to the ionization-chamber, and the shape of an absorption curve may consequently be made to vary between considerable limits. The shape of the chamber, however, appears to make very little difference to the shape of the absorption curve, within of course certain limits.

A conical ionization-chamber, as shown by the dotted diagram in fig. 7 (p. 433), gave results for the first few thicknesses of radiator almost the same as those shown by the dotted curves, fig. 8 (Pl. VIII.) ; while, again, with the plates placed at p , p results similar to those shown by full-line curves in the same figure were obtained, without of course the necessity of using Pb screen such as L, L.

This is readily explained if we remember that probably most of the effect produced in the ionization-chamber is due to emergence and incidence β rays coming from the floor and lid of the chamber ; these rays being the product of the original γ rays and of the secondary γ rays. The β rays as a result of the scattering they undergo emerge in all directions from the floor and lid of the chamber, and any alteration in the shape of the chamber will affect the ionization produced by the β rays which come from the secondary γ rays to much the same extent as it will those which come from the original γ rays.

Returning to fig. 8 it will be found that the ordinary absorption curve, corresponding to the dotted curve Pb 1, *i. e.*, in which as much secondary radiation as possible is included, can be represented very accurately by the expression: $30e^{-.32d} + 70e^{-1.35d}$.

Again, the full-line curve Pb 2, from which as much as possible of the secondary radiation has been excluded, is represented by the expression: $24e^{-.32d} + 76e^{-1.35d}$. The difference between these two expressions, *viz.*, $6(e^{-.32d} - e^{-1.35d})$ is a measure, therefore, of the total emergence secondary γ radiation from Pb. Now it has been shown in previous experiments in this paper that the secondary γ radiation from Pb can be approximately represented by a homogeneous radiation, for which the value of λ is 1.25; we are therefore able to account for the results which have just been obtained if we suppose that the original hard bundle of γ rays, which proceed from the Ra, makes all, or at least very nearly all, the secondary radiation which comes from Pb; this is in agreement with the result obtained previously (p. 425).

In the case of substances of the nature of Zn the difference between the two absorption curves, as shown in fig. 9, cannot be explained so simply. The secondary radiation after reaching its maximum value falls off more rapidly than we should expect, had all the secondary been derived from the hard set of original γ rays. We must suppose that in such substances the soft γ rays from the Ra also produce a certain amount of secondary emergence radiation, or that even though such may be produced in all substances it is better able to escape from such substances as Zn than from substances of the nature of Pb. This of course is merely another way of saying that Pb absorbs the softened secondary radiation to a much greater extent than Zn.

Again, it has been shown earlier in this paper that the emergence radiation from such substances as Zn appears, when tested by Pb, to be divisible into two quantities corresponding to a hard and soft bundle of γ rays, the hard having about the same penetrating power as the secondary rays from Pb. As it will be shown presently that there is good reason to believe that two distinct bundles of γ rays—a hard and a soft—are given out from the Ra, we may for the present look upon the two bundles of secondary rays which are produced from Zn and such substances as the products of the corresponding hard and soft bundles of the original radiation.

It will be seen from fig. 8 that when as much secondary

radiation as possible is excluded the curves for all substances very nearly correspond. Let us suppose that had it been possible to exclude all the effects of secondary γ radiation, the curves for all substances would have become identical. This supposition must apparently be very near the truth, for it can be seen from the geometry of the arrangement in fig. 7 that by no means can all the secondary radiation have been excluded in the first set of experiments. We arrive, then, at this result: that, excluding all secondary γ radiation and its effects, we may consider the Ra to give out two distinct sets of γ rays, one more penetrating than the other, each practically homogeneous, with values of $\lambda/\Delta = \cdot 028$ and $\cdot 12$ respectively, these values being practically independent of the nature of the absorbing substance.

When the secondary γ radiation is allowed to produce its effect in addition to that produced directly by the original γ rays, this law may be modified to a very considerable extent. In the usual arrangement of apparatus used for determining the quality of a radiation the absorbing plates are as a rule placed close to the ionization-chamber, and the values of λ deduced from the tangent to the absorption curve—that is to say, it is generally with the dotted-line curves of fig. 8 that we are dealing, and the effects of secondary radiation may, as has already been shown, be in some cases very nearly as important as the effects produced directly from the original γ radiation.

This, for example, affords a ready explanation of the effect observed by Eve (Phil. Mag., Aug. 1908), who states:—“It is noteworthy that the Ra in 2.2 cm. of nickel-steel gives an effect about 1.5 times as great as when the Ra is in 1 cm. of Pb. From the relative densities we should expect 2.2 cm. of steel to be equivalent to 1.5 cm. of Pb, and therefore the Ra in the steel cylinder should give, by the density law, two-thirds of the effect of the Ra in Pb. It actually gives one and a half times as much; thus the primary γ rays traverse steel much more readily than Pb, but the rays passing through iron are subsequently absorbed more readily by Pb than if the Ra were in Pb.”

From the results of the present paper we can say that in going through 2.2 cm. of steel or 1.5 cm. of Pb, the soft primary γ rays will have suffered in each case the same number of collisions, but that the effect of a collision with an atom of Pb, or rather with the constituent of such an atom, is much more definite than in the case of substances of lower atomic weight; that in the case of Pb the collision

has broken the original γ ray up, immediately sending out a β ray, or has so shattered the original γ ray as to make it easy for Pb to subsequently complete the process.

In the case of Zn, &c., the effect of the collision has not been so definite; much scattered γ radiation is produced, somewhat softened by the effects of collision, but still able to suffer further modification as a γ ray before being eventually broken up and sending out the β ray.

It must be noticed that in experiments upon the secondary incidence γ rays, such as have been carried out by Kleeman and by Eve, the nature of the secondary effect may be modified to a very considerable extent if the Ra be covered directly by a considerable mass of a substance such as Zn. Where a similar screen of lead would appear to have hardened the primary beam which is being experimented with, the screen of Zn may very well appear in some cases to have softened the primary beam, more especially if the secondary effects produced by hard and by soft rays do not conform to the same law of distribution.

It may be observed that the value of λ/Δ obtained in the present investigation for the hard γ rays from Ra is .028, whereas the mean value obtained by Wigger was .021. The difference probably arises from the fact that Wigger appears to have taken the natural ionization in the chamber as the amount to be subtracted from all the readings. It seems quite possible that a considerable amount of secondary radiation from surrounding bodies may have been able to enter the chamber, in which case the correction should have been greater, and this applied to all the readings would increase the value of λ/Δ which he obtained.

Again, since the hard γ rays produce a considerable amount of secondary radiation in Pb, it is not surprising that with a long, narrow chamber, such as Wigger used, the shape of the absorption curve for Pb differs from that obtained in the present experiments.

We have now sufficient information to enable us to construct at least a working theory. The main points to be observed are, firstly, the lack of symmetry in the amounts, and secondly, a lack of symmetry in some cases in the quality of the secondary γ radiation.

The asymmetry shown by the secondary emergence and incidence β rays, which are produced from the primary γ rays of Ra, has already been put forward as an argument in favour of the "material" theory propounded by Professor Bragg.

The modification of the æther-pulse theory, recently advanced by Professor Sir J. J. Thomson, may possibly

furnish a partial explanation of the facts ; but there are many difficulties in the way of a pulse theory, even modified to this extent ; some of these have been pointed out in a recent paper by Professor Bragg and myself (Trans. Roy. Soc. S. Aus. vol. xxxii. 1908).

When one attempts to further explain by the pulse theory the lack of symmetry which exists in the case of the secondary γ rays, the difficulties become much greater.

If we are to suppose that the incidence and emergence γ rays are true secondary effects produced by vibrations of electrons in the absorbing material, the effect resembles very closely that of fluorescence. The corresponding optical problem, however, gives rise to no such lack of symmetry ; we find in its case no corresponding asymmetry of distribution or of quality of the secondary effect.

If, however, we attempt an explanation upon the "material" theory, these difficulties at once disappear.

Let us consider in the first place the effects produced by a homogeneous bundle of hard γ rays. These in passing through matter suffer collision ; the effect of such collision is to change the direction of motion of the incident primary ray—in other words, to scatter it ; at the same time the scattered ray loses a certain amount of energy—it has become softened ; this softening may be due either to a change in its speed or to a change in moment of the γ pair, or it may be both. The distribution of the scattered radiation will probably depend upon the nature of collision, and may be influenced largely by the atomic structure of the matter with which the γ particle has collided. We have seen for instance that in the case of Pb, where the secondary radiation is produced mainly from the hard bundle of γ rays proceeding from the Ra, that much more of the scattered γ radiation moves on in the direction of the original rays than returns in the opposite direction.

Consider the case of a fine stream of homogeneous rays moving in the direction x , a plate of absorbing material of thickness L being placed in their path, at right angles to the direction of motion of the particles. Let I_0 be the number of γ particles which are sent out by the Ra per unit time. The number I which are able to proceed a distance x through the absorbing plate without suffering appreciable effect is such that $I = I_0 e^{-\lambda x}$. In a distance dx , the number which have suffered serious collision is $I_0 \lambda e^{-\lambda x} dx$. Of these let a fraction, q , be merely scattered, at the same time softened or reduced to what we may call an intermediate stage, in which their coefficient of absorption (so called) is λ' .

The remainder represented by the fraction $(1-q)$ are turned into β rays at once. Let $i_0 = qI_0\lambda e^{-\lambda x}$.

As a result of scattering in a direction inclined to the original at an angle θ , let $i_0 F\theta$ represent the number of particles per sec. which cross the unit area of a spherical surface of unit radius described with centre at the point where scattering occurs; then the number of scattered rays which emerge per sec. from the flat plate of thickness L

$$= \int_0^L \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} 2\pi \sin \theta \cdot F\theta \cdot qI_0\lambda e^{-\lambda x} e^{-\lambda'(L-x) \sec \theta} d\theta dx.$$

In addition to these rays we have emerging per sec. a number $I_0 e^{-\lambda L}$ which have suffered no scattering.

We are not at present able to evaluate the expression given above, from want of knowledge regarding $F\theta$. However, we may proceed to make an approximate calculation of the effect which might be expected in such a case as we have investigated in fig. 1.

Considering as before a fine pencil of homogeneous γ rays falling normally upon a plate of thickness L , we may express the emergence radiation as—

$$kI_0\lambda \int_0^L e^{-\lambda x} e^{-\alpha\lambda'(L-x)} dx = \frac{KI_0\lambda}{\lambda' - \lambda} (e^{-\lambda L} - e^{-\alpha\lambda' L})$$

where k is a constant, λ the coefficient of absorption of the primary set of rays, λ' a similar coefficient for the secondary rays, and α a constant obliquity factor, which in the present case is taken as 2, a value obtained by considering the geometrical arrangement of the radiators in fig. 1 with regard to the ionization-chamber.

Let us now apply this result to the case of a Pb radiator; the values of λ and λ' are .32 and 1.3 respectively. The curve corresponding to $e^{-.32L} - e^{-2.6L}$ is shown by the dotted line in fig. 2, the maximum having been adjusted to the same value as for the experimental curve.

The agreement between the theoretical and the actual curve is very good.

The maximum value is reached for about the same thickness of radiator, and for thicknesses of radiator greater than that required to give the maximum effect the curves slope away to about the same extent. This, taken in conjunction with previous experiments, seems to show that

practically all the secondary γ radiation obtained in these experiments from Pb may be considered as derived from the original hard γ rays of the Ra.

It must, however, be remembered that the secondary emergence rays have to penetrate the Pb sides of the ionization-chamber, and allowing for obliquity this corresponds to a thickness of about 2 mm., so that it is still quite possible that a fair amount of very soft secondary γ radiation may have escaped detection.

If we now proceed in a similar manner to construct the corresponding curve for Zn, viz., $e^{-21L} - e^{-64L}$, it is found that it by no means corresponds to the experimental curve. If, however, we assume that for a thickness of about 10 cm. of the Zn radiator the primary soft bundle is producing very little of the secondary emergence γ radiation, the curve as calculated above may be placed in the position shown by C, fig. 3. The curve D is now drawn to represent the difference between the curves B and C. We may now see how closely this remainder corresponds to what might be expected if the soft bundle of original γ rays produced a corresponding softer secondary. The maximum in the case of this remainder curve is further to the left than in the case of curve C, and after reaching its maximum value the curve falls away much more rapidly than does C. It corresponds, in fact, very well with what we might reasonably expect to be produced by the soft bundle of γ rays coming from the Ra. Again, although for any given thickness of radiator the ratio of the ordinates to the curves C and D is by no means constant, it is of the order indicated in fig. 5 by the curve A''.

If, now, the curves C and D represent the effects due respectively to the hard and soft γ rays from the Ra, it should be possible to show experimentally that the quality of the radiation from a Zn radiator depends to some extent upon the thickness of the radiator. No serious attempt has so far been made to carry out this investigation. However, we may check the result in another way. The quality of the radiation from Zn should show some change if we absorb some of the soft γ rays coming from the Ra by means of a Pb screen or plug before allowing the radiation to fall upon the Zn radiator. As we have already seen, it is possible in this way to reduce the softer radiation without cutting down the hard to such an extent as would be necessary if a plug of material such as Zn were used.

Using 17 mm. of Al as radiator, with no plug, the reading with no dome was to the reading with a 6 mm. dome as

100:31. With a 9 mm. plug, however, inserted in the conical hole just over the Ra the reading with no dome was to the reading with a 6 mm. dome as 100:39. A similar effect was also obtained with a Zn radiator.

We see, then, that hardening the primary radiation has the effect of hardening the secondary, and this is in agreement with the suggestion put forward, viz., that in the case of Zn, Al, and such substances the secondary emergence γ radiation consists of two bundles corresponding to, in fact derived immediately from, the two corresponding bundles constituting the original γ radiation.

In fig. 9 the dotted curve C has been plotted to a larger scale, and the curve D obtained previously in fig. 3, and shown in that fig. curve B, has been plotted with the same maximum value as C' for comparison with it. It will be noticed that the curve D reaches its maximum for a smaller thickness of radiator than does C'. This we might expect as the secondary rays will be able to emerge from a greater depth of the radiator, when some of them come out more normally, as happens in the case represented by curve C'.

In the experiment from which the curve D is derived the rays emerge very obliquely, and their self-absorption by the radiator is much greater for a given thickness of radiator.

Otherwise the curves are in very good agreement. It is to be noticed that in curve C' certain effects may show themselves which are probably not present to such a large extent in the case represented by D. Soft radiation, for instance, has a much better opportunity of producing its effect in the former case.

Returning now to a brief consideration of the secondary incidence γ radiation. Although no attempt has as yet been made to determine whether the radiation from different substances is strictly homogeneous, it was thought advisable to find out how its amount varied for any substance as the Ra was covered with different screen thicknesses of Pb.

In these experiments C, Zn, and Al showed much the same effect. With no plug, a 5 mm. plug, and a 10 mm. plug over the Ra, the corresponding readings were as 100:60:35. Now, since the value of λ for the soft γ radiation from Ra is 1.35 for Pb, it should have required about 8 mm. of Pb to reduce it to 35 per cent. of its original value, and had the incidence secondary radiation been due entirely to the original soft γ rays it should apparently have been reduced to much the same amount. It is shown above that

10 mm. of Pb, placed in the path of the primary, reduces the secondary effect to 35 per cent., so that it appears that very nearly all the secondary incidence γ radiation from Zn and such substances is derived from the soft bundle of primary γ rays.

In the case of the radiation from Pb the measurements could not be performed with any great accuracy. However, it was found possible to place a 2 cms. Pb plug over the Ra without cutting off all the incidence radiation; the reading was reduced to about 30 per cent.

The experiment is accurate enough to enable us to say that the secondary incidence radiation from Pb is derived to a large extent from the original hard bundle of γ rays; its quality, as tested by Pb domes, shows also that it is of much the same nature as the emergence radiation, which appears to be the product of the hard γ rays.

In all these experiments, and especially in those which deal with the incidence radiation, it must be borne in mind that the radiation has to penetrate a thickness of Pb, corresponding to 2 mm. before its effect is measured, and consequently the effect of very soft γ radiation may have been missed.

The lack of symmetry in quality of the emergence and incidence radiation from some materials may be explained if we suppose that the distribution of the scattered radiation which is produced from the hard γ rays is not the same as for that produced from the softer rays. The secondary radiation produced from the hard γ rays appears to move on more in the direction of the original stream than do the secondaries produced from the softer rays.

The distribution of the secondaries may also to some extent depend upon the nature of the medium in which scattering has taken place, and it does not seem at all unlikely that the atomic structure of the radiator should determine to some extent the nature and result of a collision between the γ particle and the constituent part of the atom.

It has already been stated that these experiments give little or no support to the theory of selective absorption advanced by Kleeman; the effects seem much simpler than we might be led to suppose from that theory. It seems possible, also, to suggest probable causes for the effects which Kleeman has observed. In some cases the absorbing screens used by Kleeman seem not to be of sufficient thickness to preclude the possibility of a certain amount of β rays, given off by the radiator, penetrating the screen. Secondly, it has

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been assumed that the incidence γ radiation from all the substances experimented with is homogeneous. If, for example, the incidence radiation from Pb contained a very soft bundle in addition to the hard, many of the results obtained by Kleeman could be immediately explained. With the present form of apparatus I have not of course been able to test this point; it does not, however, seem at all improbable that Pb should give out an exceedingly soft bundle of γ rays, the product of the soft γ rays in the original radiation; indeed, if it is safe to make comparisons from the behaviour of such substances as Zn, it would be surprising if such a soft bundle did not exist, although of course its effect may be small. Thirdly, in dealing with the very soft γ rays, which constitute the secondary incidence radiation, it seems necessary to take into account the effect of tertiary radiation.

In conclusion it may not be out of place to discuss one or two points of some interest which have arisen during the progress of these experiments.

In fig. 8 it will be observed that for a mass of absorbing screen 70 the result of cutting out a considerable amount of the secondary radiation has been to change the value of the effect produced with Zn screens from 56 to 43. In the case of Pb the corresponding change is from 38 to 30. In other words, the ratio of the effect produced by a Zn screen to that produced by a Pb screen of the same mass is apparently much the same whether secondary radiation is included or not. It appears almost as if the effect produced in the ionization chamber were due more to the secondaries produced from the hard γ rays than to direct effects of these hard γ rays. The hard γ rays are not apparently broken up as the result of the first collision; a few may be, but most of the rays seem capable of passing into what we may for convenience speak of as an intermediate stage. A second collision when the ray is in this stage may be more effective in breaking up the γ ray and causing the β particle to be sent out. In some cases the γ ray may still retain the characteristics of the γ ray even after many collisions.

It would seem possible for a γ ray to produce some ionization in a gas as a result of its passage through that gas, slow-speed delta rays being produced from the atoms of the gas. Where high-speed electrons appear they are to be considered as having been produced from the γ ray itself, being originally a part of it, as already suggested by Professor Bragg.

It has been found by Eve (Phil. Mag. 1906) that the γ

rays from thorium have an absorption curve, measured by Pb, very nearly the same as that for Ra. We should expect, then, that thorium gave out two homogeneous sets of γ rays as does Ra, the values of λ by Pb for these groups being $\cdot 32$ and $1\cdot 35$. It has also been found by Eve that the value of λ for the γ rays given out by Ur is $1\cdot 4$, and that these rays appear nearly homogeneous. The γ rays of Ur appear, then, to correspond very closely with soft bundle of rays emitted by both Th and Ra.

Again, it seems rather striking that the secondary rays produced by the hard γ rays of Ra produce in Pb, and apparently in all substances, a secondary, for which the value of λ is of the same order as for the Ur rays and the soft rays of Ra and Th.

In the case of the secondary rays produced from the hard γ rays of Ra it has been possible to treat them as practically homogeneous over the range of thickness of screens which have been used. It will, however, require much more careful research to determine the exact quality of this radiation.

Again, the value of λ/Δ for the soft primary bundle of rays has been shown to be nearly four times that of the hard. It seems possible that this may have some connexion with the result obtained previously by Professor Bragg and myself for the β rays which are produced from the γ rays of Ra. It was found that the value of λ for the hard and soft β rays was approximately as one to four.

SUMMARY.

1. The γ rays of Ra and possibly of Th appear to consist of two distinct homogeneous bundles, the value of λ/Δ for the soft set being approximately four times that for the hard.

2. For each set of rays the value of λ/Δ is constant and practically independent of the nature of the absorbing material with which λ is measured, provided that in the case of the soft rays secondary effects be excluded.

3. Secondary γ radiation appears on both sides of a plate which is penetrated by a stream of γ rays. There exists a marked lack of symmetry between the amount of secondary radiation which proceeds from the two sides.

4. A lack of symmetry exists in the case of some substances between the quality of the radiation on the two sides.

5. The last results seem very difficult to reconcile with a pulse theory. On the "material" theory propounded by Professor Bragg no such difficulty arises.

6. The secondary γ radiation appears to be derived from the primary by a process of scattering. This process generally involving a reduction in the subsequent penetrating power of the ray affected.

7. There appears to be reason to believe that the distribution of the scattered radiation depends to some extent upon the hardness of the radiation which is scattered; also upon the nature of the material in which the scattering is produced. The softer radiation appears to be turned back to a somewhat greater extent than the hard. Materials of high atomic weight seem to be able to produce more complete scattering than those of lower atomic weight.

8. The absorption of γ radiation which has already passed through a thickness of one substance by screens of a different substance may not in all cases give a true measure of the absorption of the original radiation which has been effected by the first screens.

In conclusion, it is a pleasant duty for me to acknowledge my indebtedness and sincere thanks to Professor Bragg for his keen interest and advice during the progress of these experiments.

University, Adelaide,
Sept. 1908.

XL. *Notices respecting New Books.*

Annuaire pour l'an 1909 publié par le Bureau des Longitudes.
Paris: Gauthier-Villars. 1 fr. 50.

IN accordance with the new plan adopted by the Bureau, of selecting material from different branches of science in alternate years, the present issue contains data respecting Metrology, Money, Geography, Statistics, and Meteorology. The chemical and physical data which appeared in 1908 will be again inserted in 1910. This year we may call attention to the very detailed notices of M. Bigourdan on Variable Stars, and of M. Lallemand on Movements and Deformations of the Earth's Crust.

FIG. 1.

The γ radiation proceeds from the Ra through the conical hole. Radiators may be placed in its path as at e . The quality of the secondary radiation may be tested by the domes h, h or the cylinders i, i .
When measuring the effects of the secondary incidence radiation the ionization-chamber is inverted and radiators placed as at p, p .

FIG. 2.

FIG. 3.

FIG. 4.

FIG. 5.

FIG. 8.

FIG. 6.

FIG. 9.