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W.H. Bragg M.A. F.R.S.

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XXXIX. *The Consequences of the Corpuscular Hypothesis of the γ and X Rays, and the Range of β Rays.* By W. H. BRAGG, M.A., F.R.S., Cavendish Professor of Physics in the University of Leeds*.

Introduction.

IN the following pages I have first restated briefly the case for the corpuscular hypothesis of the X and γ rays. I have then attempted to show the consequences to be

- (1) A simple view of the history of the X or γ ray.
- (2) The absence of true secondary radiation.
- (3) A true additive principle in radioactive phenomena.
- (4) The absence of specular reflexion.
- (5) The inability of X and γ rays to ionize directly; the effect is indirect, the real agents being the secondary cathode and β rays.
- (6) The general principle that if one radiant entity (α , β , γ , X, or cathode ray) enters an atom, one and only one entity emerges, carrying with it nearly all the energy of the entering entity.
- (7) A natural division into three groups of the phenomena attending the passage of each radiant entity through matter. These groups relate to (a) rectilinear movements during which energy is spent so long as ionization is being produced; (b) special encounters with atoms on account of which deflexions or scatterings take place without appreciable loss of energy; (c) transformations (γ into β , cathode into X, &c.).

* Communicated by the Author.

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- (8) The simple solution of at least two useful ionization problems. The second of these leads to a ready determination of the relative average ranges of β rays in various materials (the range being defined as the total length of the track when straightened out). These fit in very well with results obtained indirectly by H. W. Schmidt, and so furnish a general explanation of the form of the absorption curves of β rays.

THE idea that X and γ radiations are both to be regarded as consisting of streams of discrete entities has gained ground steadily in the last year or two. Sir J. J. Thomson looks upon the X ray as a kink in the one tube of force by which he represents all the properties of the electron. According to present knowledge the γ ray is of the same nature as the X ray, so that an hypothesis regarding the nature of the one must be taken to apply to the other also. J. Stark has recently developed* the theory, based on the work of Planck, that an X ray is a bundle of energy travelling without alteration of form. This differs from Thomson's theory in at least one important particular because the latter involves a change of form†. I have myself found it convenient to regard the X ray as a negative electron to which has been added a quantity of positive electricity which neutralizes its charge, but adds little to its mass.

Whatever view may be taken of the nature of the entity, the acceptance of the corpuscle idea modifies our views of the phenomena attending the passage of rays through matter, and alters the language which we use in describing experimental results. I think that it leads to a marked gain in simplicity, and my object in writing this paper is to show, if I can, that this is the case.

It will be convenient to begin with a brief statement of the main arguments for the entity hypothesis, though this plan involves some little repetition of similar statements previously given. For this purpose it will be best to use the results of recent investigations, since they are most fitted to serve as a foundation for the case, although I would not undervalue the older arguments which first suggested the discrete form of the X ray.

When a pencil of γ rays is directed normally upon a thin plate, for example a plate of aluminium one or two millimetres in thickness, β rays spring out from both sides of the

* *Phys. Zeit.* x. p. 902 (1909); xi. p. 24 and p. 179 (1910).

† *Phil. Mag.* Feb. 1910.

plate*, but very many more are found on the side of the plate from which the γ rays emerge than on the side through which they enter. In fact experiment shows that their distribution is just such as should be found if, when they are first formed, they simply prolong the line of motion of the γ rays, and if their subsequent movements are due to the usual scattering which β rays undergo. Cooksey† has shown that the same lack of symmetry is to be found in the cathode radiation which is caused by X rays.

It is also found that the speed of the β ray, which is caused by a γ ray, is independent of the nature of the atom in which it originates, but is directly connected with the quality of the γ ray. Again the parallel effect is to be observed with X rays, as is evident from the work of Dorn, Innes, and others, who have made it clear that the speed of the cathode rays which originate when X rays fall upon atoms depends rather on the nature or quality of the X rays than on the kind of atom. But the most accurate and complete proofs of these principles have been recently given by Beatty‡ and by Sadler§.

These facts are of fundamental importance when we come to discuss the source from which the β -ray energy is drawn. If it comes from the atom, as was first supposed, we have a trigger effect: the γ ray is to be considered as precipitating an explosion||. But if this were the case we should expect (1) that the direction of motion of the shot, viz. the β ray, would have no connexion with the direction of motion of the γ ray which merely pulled the trigger of the gun; (2) that the speed of the β ray would not depend on the quality of the ray, but on some property of the atom corresponding to the charge in the gun. The actual conditions are exactly the reverse. If we examine the alternative hypothesis, viz. that the energy of the β ray is brought to it by the γ ray, and the atom is merely the cause of a transference of energy, we find a perfectly satisfactory explanation. The momentum of the electron is a persistence of the momentum of the γ ray, and its energy is derived from the ray; the electron, therefore, continues the line of flight of the γ ray with a speed which has nothing to do with the atom to which the transformation is due, and depends entirely on the quality of the γ ray.

* Bragg and Madsen, *Trans. Roy. Soc. of South Australia*, Jan. and May 1908; also *Phil. Mag.* May and Dec. 1908.

† 'Nature,' April 2, 1908.

‡ *Proc. Camb. Phil. Soc.* vol. xv. pt. v. p. 416.

§ *Phil. Mag.* March 1910.

|| 'Conduction of Electricity through Gases,' 2nd ed. p. 320.

We therefore conclude that the energy of the β ray is derived from that of the γ ray, and similarly the energy of the cathode ray from that of the X ray. We are then in a position to take into account another experimental result. The velocity of the cathode particle ejected by the X ray is found to be the same, or nearly the same, as that of the cathode particle in the original X-ray tube. There is no doubt as to the approximate truth of this statement, though accurate experiment is wanting. Now there can be no question of the storage of X-ray energy in an atom until there is enough to provide for the ejection of a cathode ray, for then the nature of the atom would again be of influence, and we should revert to all our previous difficulties. One X ray must be enough to provide one cathode ray. Nor does it seem possible to suppose that the energy of several cathode particles can be stored up in an atom until there is enough to produce one X ray; for amongst other considerations there would then be no apparent reason why the speed of the cathode ray should influence the quality of the X ray so directly as it does. Hence the X ray cannot have more energy than was possessed by the cathode particle in the X ray bulb. Put the two statements together and we find that one cathode ray impinging on an atom may produce one X-ray and no more, and in its turn the X ray through impact on an atom (not necessarily the first it meets) produces one cathode ray and no more, handing on its energy and its direction of motion.

It is this conclusion which seems fatal to the spreading pulse theory. The latter taught us that when an electron was arrested the energy set free travelled out in all directions through space on an ever enlarging surface. We now find that we must have the energy of the X ray confined within very narrow bounds which are not to widen as the X ray travels, so that when at last the transference of energy takes place the energy is all in one spot ready for the sudden change. The speed of the cathode ray caused by the X ray is the same no matter where it comes into being. We cannot allow the energy of the X ray to spread even a little. The ray is to be considered as a minute entity of some sort, its energy as it travels being always bound up in an unaltering volume of atomic magnitude at the most.

This is a brief statement of the case for the entity hypothesis, containing only one main line of argument. Many subsidiary considerations are omitted. It is worth observing that it turns on questions regarding energy.

We must of course ask what we lose by the adoption of

the new hypothesis, with the consequent abandonment of the spreading pulse theory. Only one thing of value: viz. the easy explanation of the partial polarization of a primary beam of X rays, and of the more complete polarization of secondary beams. Those who would maintain that the entity contains a wave-motion within it might argue that there is no loss of this kind; but such a position would seem unsound until there is a clear expression of the meaning and properties of an entity or bundle of energy with a wave-motion inside it. It is to be observed that the polarization of light is a very complex phenomenon which is capable of the closest examination, and that the undulatory theory of light explains it with great exactness. It is possible to overrate the importance of the ability of the pulse theory to explain the polarization of X rays, because it may be imagined that in this case also a complex effect is successfully accounted for. As a matter of fact the polarization of X rays is quite a simple effect and bears but a meagre resemblance to the polarization of light; there are, for example, none of the elaborate and beautiful effects of crystals. The polarization of the X ray consists only in the fact that if it is deflected it is more liable to move in one particular plane passing through its line of flight than in another: a billiard ball with side on does as much, or more exactly still, a spinning tennis ball.

If we accept the entity hypothesis the processes of the X-ray tube assume a new aspect. We gain in precision of statement and in clearness of outlook. The stream of cathode rays is directed against the anticathode; we no longer say, somewhat vaguely, that part of the energy goes in heat, part in secondary cathode radiation, part in X rays. We must not imagine a cathode ray to ricochet hither and thither among the atoms of the anticathode radiating X-ray energy at every turn. No doubt it does so radiate some energy, but the amount is trifling, and has nothing to do with X rays. We must rather say, that when each cathode particle strikes the anticathode it may fritter away its energy into a form which finally takes that of heat, or it may be splashed back against the glass wall of the tube, and cause phosphorescence and other effects, or, again, it may disappear (not necessarily at its first meeting with an atom, nor before it has spent any of its energy), and the complete disappearance of the cathode ray as such will then be simultaneous with the production of the X-ray entity. In the last case the entity starts off on its straight line course endowed with a penetration which the cathode ray did not possess. When it meets an atom,

there is an overwhelming probability that it will go through without effect; but it may be deflected, and again it may in its turn be replaced by a cathode ray like the original one. We may think of the whole affair as the history of a small quantity of energy carried first in the X-ray bulb by a cathode ray, transformed into the energy of an X ray, with perhaps further reconversions; frittered away while it takes the cathode ray form, carried intact while it has the X-ray form, until finally it has all been spent.

It is never reinforced at any stage of its journey, for there is no unlocking of the internal stores of atomic energy, according to the most recent experimental evidence. Both Bumstead and Angerer, working independently, found there was no trace of a difference in the amount of heat generated by a stream of X rays in two different metals, such as would be expected if any part of the heat were due to atomic energy set free by the X rays. Moreover, no arrangement of screens or reflectors about a stream of X or γ rays causes any increase in the total ionization produced by the stream, so far as we have been able to discover. It is only possible to increase it in one place at the expense of a decrease in another. In this sense at least there is no such thing as "secondary radiation."

The term "secondary radiation" is largely used, and is often quite satisfactory; but it may have many meanings not all of which are true to fact. It is convenient for the time to continue the argument of this paper in the form of a discussion of the circumstances under which the use of the term is justified. For it is obvious that as long as we retain the idea that secondary radiations may add themselves to primaries, tertiaries to secondaries, and so on, we are oppressed with the sense of a complexity which must add greatly to our difficulties. If, on the other hand, we can permit ourselves to think that there is no indiscriminate addition of this kind, but that the appearance of each individual secondary entity is marked by the simultaneous disappearance of a primary entity; further, that the secondary inherits the energy of the primary, and, in some cases, its direction of motion; and further still, that the secondary can for all practical purposes be looked upon as a continuation of the primary, sometimes modified in form, then we obtain a simplification worth having. Let us, therefore, consider the matter a little more in detail.

When the electron, as a β or a cathode ray, dives into an atom and is thereby deflected, as is occasionally the case, the electron moves off in a new direction, but it can hardly be

called a new ray. We may call it a secondary ray if we please, but we may just as well say that every molecule of a gas is a primary molecule before a collision, a secondary afterwards, a tertiary after two collisions, and so on ; and it would be worse than useless to do so. Again, when Geiger shows that an α particle may be deflected or scattered he does not speak of a secondary α ray. When an X ray entity is transformed by an atom's action into a cathode ray, or a γ ray into a β ray, we may speak of the new rays as secondary rays, and now the term is really convenient ; but it must not be taken to mean too much. There is a change of form of the entity, and that is all. When an X ray entity is deflected in passing through an atom, or is "scattered" in the usual phrase, the term secondary radiation is really inappropriate, because it is but the X ray entity swinging off in a new direction. Barkla has shown that when primary X radiation falls upon any metal (from Cr to Ag at least), so long as the penetrating powers of the primary exceed a certain limit peculiar to that metal, a homogeneous X radiation is emitted which is characteristic of the metal, and is less penetrating than the primary. Here the term secondary would seem to have a real meaning, for we wish to describe the fact that a primary X ray entity possessing energy of any amount above a certain minimum is replaced by a secondary X ray entity possessing an energy characteristic of the particular metal, and always less than that of the primary. The effect is simple enough to be described in this way, for energy considerations show that it can only be a case of one entity replacing another, not of two or three replacing one, nor of one being added to the original. It is not clear, however, that a transformation of this kind actually occurs, a transformation, that is to say, which makes the primary differ so much from the secondary that a real difference is to be recognized by the use of different terms. I hope to be able to show later that there are good grounds for presuming a double transformation, the first stage being a conversion of the primary X ray into a cathode ray stage, during which a loss of energy occurs, and the second a reversion into the X-ray form. In any case it is enough for the present that the secondary must draw its energy from the primary, and the appearance of the former implies the disappearance of the latter.

There is another case which must be considered specially. McClelland* has explained certain of his experiments on the

* Proc. Roy. Soc. lxxx. p. 501 (1908).

scattering of β rays by supposing a real secondary radiation to be added to a reflected primary. The experiments are simple. When a stream of β rays falls at an angle of, say, 45° upon an aluminium plate, it is found that the β rays which leave the plate on the incidence side are not distributed symmetrically about a normal to the plate, but show a maximum in a direction which is separated by the normal from that of the incident stream. When the plate is of lead or any other substance having a high atomic weight, the effect is much less marked. In fact it looks as if there was a confused specular reflexion at the surface of the plate coupled with a radiation scattered in all directions. McClelland therefore divides the scattered rays into two groups, the first of which consists of β rays from the primary stream reflected by the surface of the plate like light by a mirror, the second of a set of true secondary rays.

Let us first consider the question of specular reflexion. All the evidence we have regarding the actions and reactions between atoms and radiant entities shows that each atom when in collision with an entity has to bear the shock alone: it receives no support from its neighbours, even when they form parts of the same molecule, *a fortiori* when they are only neighbouring atoms in the surface of a plate such as McClelland used. It is this which makes radioactive measurements independent of physical and chemical conditions. The point seems to be firmly established now, for though at times evidence has been brought forward which has at first appeared to contradict the principle, more careful examination has always shown the evidence to have been mistaken. The principle may be expressed by the statement that the action of a molecule on one of the radiant entities is the sum of the effects of the actions of its component atoms, no allowance for constitutive influences being necessary. One or two examples will be sufficient.

The stopping power of a molecule for α rays is the sum of the stopping powers of the individual atoms of the molecule. During 1908 I measured as carefully as possible the stopping powers of a number of gases which were prepared in a very pure state by Dr. Rennie and Dr. Cooke of the Adelaide University. The range of the α particle can be measured to much less than one per cent. The additive principle was found to be true within the errors of experiment; both for stopping powers measured with respect to Ra C, and those measured with respect to the α particles of Ra A. The two sets are not quite the same*.

* Bragg, Phil. Mag. April and Sept. 1907.

Again, the absorption and scattering coefficients of liquids and compounds for β rays have lately been the subject of careful measurement by Schmidt* in Giessen, and by Borodowsky† in Manchester, and the additive principle was fully confirmed in this case also.

A radiant entity, therefore, acts on one atom at a time; and if its direction of motion is altered by a collision, the alteration is determined by the mutual relations of the entity and the atom alone. Neighbouring atoms have nothing to do with it, and it is quite immaterial whether or no there is a surface close by which separates one lot of atoms from another. On the other hand, specular reflexion, such as the reflexion of light in a mirror, depends on the conjoint action of the atoms of the reflecting surface. It cannot be supposed, therefore, that one part of the scattered β radiation examined by McClelland consists of rays reflected like light; and this being so, it is probable that the description of the remainder as a true secondary is wrong also. In fact there is a much more direct explanation of the whole effect.

When an entity passes into an atom there is a chance of deflexion through any given angle. Radii may be drawn from the atom, each representing by its length the chance of deflexion into the direction in which it is drawn. The extremities of these radii will lie on a surface the form of which will represent graphically the probable results of the encounter; and its form will vary with the atom, with the nature of the entity, its speed, and so forth. As a rule the lighter the atom the more eccentric is the oval surface. The surface is one of revolution, the axis being the original line of motion of the entity. A section through the axis will therefore express all there is to express; and such a section may be called a "deflexion oval." It must be one of the objects of experiment to determine the forms of the deflexion ovals in all possible cases, for clearly, until we know the probable results of an encounter between a given entity and a given atom, we cannot calculate the result of the attempt of an entity to pass through a plate which is an aggregate of many atoms; in other words, we are not in a position to calculate with safety the absorption coefficients or reflexion coefficients of β rays. Although we do not yet know the exact form of the oval when a β ray impinges on an atom, we do know that it is far more eccentric for an aluminium atom than for a lead one. The heavy atom is much more likely to swing round the electron than the light one; when

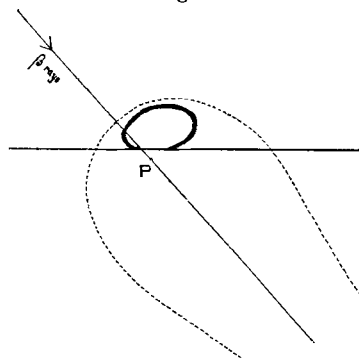
* *Phys. Zeit.*, xi, p. 262 (1910).

† *Phil. Mag.*, April 1910.

a stream of β rays falls upon a lead plate far more are turned back than when the plate is made of aluminium.

Suppose that β rays fall on an aluminium plate, as in the figure. Suppose one of the rays to be scattered by some atom in the plate at P. The chances of deflexion in various

Fig. 1.



directions are represented by the radii of the deflexion oval, which is roughly drawn as a dotted line. The chances of emergence have now to be taken into account; the deflected ray has less chance of getting out the more parallel is its line of movement to the surface. Each radius of the oval must be multiplied by a factor approaching the form $e^{-d \sec \theta}$, where d is the depth of the atom below the surface and θ is the inclination of the radius to the surface normal. The ends of the radii thus obtained lie on a new surface which is similar to McClelland's; its section is indicated by the firm curved line in the figure. It is in the right sense asymmetrical with respect to the normal; and the asymmetry is greater for light atoms than for heavy, because the lighter the atom the more eccentric is the oval. Thus McClelland's results are explained without the necessity of introducing the two hypotheses of specular reflexion and true secondary radiation with all the complexities they bring in their train.

Yet there is one way in which a sort of secondary β radiation might occur. Can an electron in flight so collide with another as to give it a large share of its energy, so that one β ray is replaced by two of much less penetrating power? There is no obligation to think so at present; but the case is worth considering, for it simplifies matters very much if we can conclude that no such obligation is likely to arise. There is however, not much to guide us. We may to some extent argue from the behaviour of other entities. An α particle

has a considerable speed, say 2×10^9 cm./sec., and as an atom of helium it must contain several electrons, yet we never find in the gas traversed any electrons moving with a speed of more than a few volts: that is to say, we find only δ rays. Again, one α ray never gives rise to two α rays: nor one X ray to two X rays, so far as we can see. The enquiry really resolves itself into the difficult question of the way in which ionization comes about. There are indications that it is not a straightforward process in which the moving entity drives out the electron from the atom by direct collision, because, in the case of the α particle at least, the energy spent is not always proportional to the ionization produced—there must be an intervening link; and because, as already said, the ejected electrons all seem to have speeds of the same low order. There is indeed little certain information on these points, and it can only be said that to all appearances ionization is the result of the passage of entities through molecules, and that the observed facts can be expressed on the simple hypothesis that there is a gradual drain on the energy of the entity but no large change at any one encounter with an atom. Of course it may well be asked, what then does happen when one electron moves so directly upon another that we may expect a collision such as occurs when one billiard ball strikes another? But then we have here preconceived ideas of volumes, surface contacts, and elasticities, which we must not carry over to the case of electrons encountering each other. There is really nothing to compel us to handle such electrons as anything more than mere centres of force: if we give them dimensions, it is only to make them have the right amount of electromagnetic mass. Even when we take this view we have no sure ground on which to base a calculation as to the probable result of an encounter, because the electrons in the atom cannot be considered separately; each one is backed up by unknown linkages with positive electricity and with the general framework of the atom, as we know from the fact that the scattering of β rays depends very greatly on the atomic weight of the scattering material. To sum up, there is nothing to be said against, and something to be said in favour of, the simple hypothesis that the β particle gradually spends energy along its track, but does not lose any material portion of its energy on account of the violent deflexions to which it is frequently subjected. Its career is like that of an α particle with many more deflexions in it, though there is nothing at present to prove that if the track were straightened out the length of it would be constant, as in the case of the larger entity, the

range of which can be found with precision. We may think of the β particle as possessing an average range in a given material, best expressed perhaps as a weight of material crossed. For purposes of definition we may suppose the track to be the axis of a cylinder of a small cross-section s ; then if ds is the weight of the cylinder, d is the range. I hope to be able to show presently that it is possible to find the relative values of d for given β rays in various substances.

We have already sufficient information to give us some idea of the lengths of the short portions which make up the total range. The work of Madsen* shows that such β particles as have been turned aside from a main stream passing normally through an aluminium sheet .004 cm. thick are not likely to experience a second deflexion in the same plate. Thus β particles of a speed approximating to that of light must often go through a tenth of a millimetre of aluminium without deflexion, or through the equivalent 20 cm. of air. Similar conclusions may be drawn from an earlier paper by Crowther†. Crowther does indeed state that the scattering of a pencil of β rays is complete when it has passed through 015 cm. of aluminium; but he uses the term in a special sense relating to the details of his experiment. It does not mean that after going through such a plate the stream of β rays has lost all sense of direction, and the various rays are heading every way; for his figures show that 30 per cent. of the rays which emerge from the plate and were originally directed normally upon it retain so much of their original direction as to be grouped about the emergent normal in a cone of a semi-vertical angle between 4° and 5° . The solid angle of such a cone is about $\frac{1}{250}$ of that of a hemisphere.

I have now considered one by one several possible causes of complexity; and I would conclude that on the whole they can be put aside as having at present no obvious existence. In this way we arrive at a comparatively simple idea of the history of the radiant entity whatever its kind, α , β , γ , X, or cathode ray. In each case there is an initial store of energy communicated to the entity: the subsequent motion is rectilinear, varied by encounters which change the direction of the motion but not its energy: ionization, if it takes place at all, takes place along the track; and it is in this way that the energy is drawn upon. The form of the entity may change, γ into β , X into cathode ray, and so on; but there is so little change in anything but form that practically we may assume a continuity of existence.

* Phil. Mag. Dec. 1909.

† Proc. Roy. Soc. March 1908, lxxx. p. 186.

There are therefore three main subjects of measurement in respect to each entity: (a) the expenditure of energy along the path, (b) the form of the deflexion oval, (c) the chance of conversion of form. Let us consider to what extent these measurements have been made, and also some methods of making them.

Let us take the α particle first. The case is an especially simple one because there is no conversion of form, and very little chance of deflexion until the speed has greatly diminished and the range is nearly completed. Hence the particle's properties are almost entirely expressed when its range is determined; and this has been done with some thoroughness. The feeble but very interesting deflexions which do take place have been measured by Geiger. Our knowledge of the α particle is fairly complete in the sense that we know what to expect when any given screen is placed in the path of any given stream of radiation. We may go on to consider some of the other radiations of which we know less.

The X and γ rays have also their special points of simplicity, but they form an almost exact antithesis to the α rays. Here it appears that the expenditure of energy along the track is either negligible or non-existent. The rays do not ionize directly. Nor is the deflexion oval a very important thing. The most important feature is the chance of transmutation of form, the X ray being sometimes replaced by a cathode ray, the γ by a β ray.

The argument that the X or γ entity spends no energy along its track arises simply from the fact that it produces a cathode or a β ray of the same speed, no matter how much material it has already traversed. It cannot keep its energy intact while traversing matter and at the same time cause ionization which involves the expenditure of energy. Gases which are crossed by X and γ rays are ionized, but that is because they produce cathode and β rays respectively: and these latter do the work. Of course it may be said that the conversion of one X ray into one cathode ray is ionization: and so it is; but it is natural to keep this solitary and peculiar event distinct from the general ionization of the gas along the track of an entity.

This deduction seems to afford an opportunity for putting our hypothesis to the proof. What experiments have been made from which we may determine whether or no X and γ rays ionize gases directly?

McLennan describes an experiment (Phil. Mag. Dec. 1907) in which he shot γ rays through two ionization-chambers, one made of lead, the other of lead lined with aluminium,

and compared the ionization current in the two cases. He supposed that the ionization could be assigned to two sources, one the direct action of the γ rays on the gas, the other the secondary rays caused by the γ rays to issue from the metal sides of the chamber. The former would be the same for the two chambers, let it be called I_P : the second would not, let it be I_{SL} for the chamber which is all lead, and I_{SA} for the one which is lined with aluminium. He then assumed that $I_{SA} = .286 \times I_{SL}$, since Eve had shown that when γ rays fell on lead and aluminium plates the returned β rays were in the proportion of 100 to 28.6.

Thus :

$$I_P + I_{SL} = 90.05 \text{ (total ionization in the lead chamber).}$$

$$I_P + I_{SA} = 49.5 \text{ (the aluminium lining having been inserted).}$$

$$I_{SA} = .286 \times I_{SL}.$$

Hence he found that $I_P = 33.05$, $I_{SL} = 57.00$, $I_{SA} = 16.3$; and concluded that I_P , that is to say the result of the direct action of the γ rays upon the gas, was very considerable.

The source of error in this calculation is the assumption that $I_{SA} = .286 \times I_{SL}$. It was not known at that time that this relation only holds in respect to the β radiations from the front face on which γ rays fall: the β radiations which issue from the face of a plate from which γ rays are emerging may even be greater for aluminium than for lead: and McLennan's results depended on both incidence and emergence rays. It was not right to use Eve's figures, which referred to a special case of incidence rays; and there is no contradiction of the deduction we have drawn from the entity hypothesis, viz. that I_P is zero.

Again, W. Wilson records * measurements of the ionization in an electroscope made partly of aluminium and partly of brass when the pressure of the air was varied from one to forty atmospheres: the γ rays came from RaC. He supposes that "the total ionization due to the secondary β rays at different pressures will be given by $B(1 - e^{-\lambda p})$ where B is a constant, p the pressure and λ the coefficient of absorption," and further that "the ionization due to the γ rays will be given by a term of the form $A p$, where A is a constant." He then finds that B must be 6.6 times A , and that the ionization due to the secondary rays is therefore several times the ionization due to the direct action of the γ rays on the gas. This is of course nearer than McLennan's result to what we now expect, but it still ascribes some effect to the direct

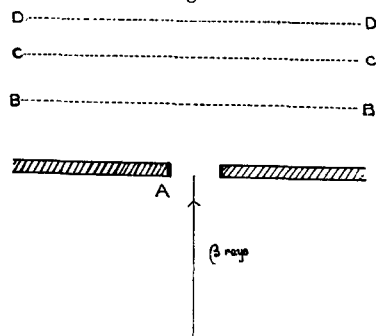
* Phil. Mag. Jan. 1909.

action of the γ rays. The fact is, however, that the division of the ionization into these two terms is not quite right, even supposing the ionization due to the γ rays to include the ionization due to the β rays generated by the γ rays in the gas.

Let us consider so far as we can what should be the amount of ionization in a gas through which γ rays are passing, assuming the entity hypothesis and its consequences. There are two cases at least in which the solution is fairly easy and satisfactory. The easier one is the case of an ionization vessel lined completely with any material, provided only that it is so thick that β rays cannot cross it. The other is the case of a large but shallow ionization vessel, the top and bottom of which consist of two parallel plates, one of which is made of a substance having about the same atomic weight as the air which the vessel contains. Let us take the latter case first.

It simplifies considerations of this kind to remember that the spacing of atoms plays a subordinate part in them. Suppose, for example, that a stream of β rays passes up normally to a plate through an opening in it at A, and that

Fig. 2.



B, C, and D are imaginary surfaces in the air parallel to the plate. The β rays cause a certain ionization in the air between the planes B and C. It would make no difference in this amount if the air between C and D were compressed into a thin layer lying along C or indeed anywhere above it, so long as the air between B and C remained in a uniform layer between and parallel to B and C. It would be the same even if air were brought down from above C and laid in a layer along C in such quantities that no β rays could get through it; or if a plate composed of atoms of nearly the

same weight as the air atoms were placed along C. If the distances of the planes from A were b , c , and d , and if we might assume the β rays to be spent exponentially with a space coefficient λ , the ionization between the planes B and C would be $I(e^{-b\lambda} - e^{-c\lambda})$ in all the cases just described, I being the initial energy of the radiation as it comes through the hole at A. There is no need to trouble about secondary radiation from a plate at C containing light atoms only, even though we know that atoms of carbon and oxygen can return some β rays: all such effects are already fully accounted for in the formula.

Consider now a stream of γ rays passing normally upwards through the lower plate bounding such an ionization-chamber. The upper plate can be made of cardboard, or some material having approximately the same average atomic weight as air.

Let k be the absorption coefficient of the material of the plate for γ rays in the sense that rays of energy I lose an amount of energy $kIdx$ in passing normally through a sheet weighing dx grams per sq. cm.: k is then the weight absorption coefficient. The meaning of this is to be that the energy $kIdx$ becomes energy of β rays which at the start continue the line of motion of the γ rays.

Let λ be the similar coefficient of the plate for β rays such as these γ rays produce. This means that when a layer of the same material as the plate, weighing x grams per sq. cm. is placed normally to a stream of β rays of energy I, the energy which gets through the plate and is spent in ionizing the air on the other side is $Ie^{-\lambda x}$. It is worth observing that if some other gas, say a heavy one like methyl iodide, were substituted for the air, the gas would return more of the radiation into the plate, so that more would be spent in the plate and less in the gas: it might be said that the absorption of a plate depended on the gas or other material above it.

Let k' and λ' be the corresponding coefficients for the γ and β rays in air.

The β rays originated in a layer of weight dx , which is at such a distance down in the plate that a layer of weight x lies above it, will have an energy $kIe^{k'x}dx$, where I is the energy which the γ rays possess as they enter the ionization-chamber. These β rays at first move directly upwards towards the chamber, and a certain fraction, viz. $e^{-\lambda x}$, of their energy is transmitted across the layer x into the ionization-chamber. The whole energy emerging is therefore $\int_0^t kIe^{(k-\lambda)x}dx$; and if the plate is thick enough to stop all β rays we may put the thickness t equal to infinity. The

emerging energy of β rays is therefore $kI/(\lambda - k)$, which may practically be simplified to kI/λ , since k is usually so small compared with λ .

The ionization produced in the ionization-chamber may be taken as $kI(1 - e^{-\lambda'D})/\lambda$, where D is the depth of the chamber multiplied by the density of the air. This is not strictly correct, because some of the β rays will strike against the side walls, which we cannot do without, and will not spend so much energy in the layer of air (of weight D) as they ought to do according to the definition of λ' . If we had a material which threw back all β rays completely, we could avoid this error; but there is no such material. It can be lessened by having a wide and shallow chamber. There is an error of a different nature in that λ' was defined with reference to rays striking a layer of air normally, whereas the β rays emerging from the plate will be moving in all directions. But it is not worth while to attempt to avoid such errors just now: it is probably a still greater error to have assumed an exponential law, and our object is to obtain a theoretical result accurate enough to tell us what we should look for.

We have now to take into account the ionization due to the β rays produced by the γ rays in the air of the chamber. This may be done by direct calculation, or in the following way which seems interesting.

If the plate which forms the base of the chamber were replaced by a plate of nearly the same atomic weight as the air in the chamber, the γ rays would then pass through the same sort of atoms throughout their course. Considering a short path of the course in which there is no great absorption of the γ rays, strata of equal weight convert equal quantities of γ -ray energy into β -ray energy, and will show equal ionization even though the ionization in any stratum is not wholly due to the β rays made in that stratum. The energy spent on ionization in any stratum is practically equal to the γ -ray energy converted in that stratum: thus the ionization in this particular ionization-chamber is measured by $k'DI$: the λ' does not come in. If we now replace the bottom plate of constants k' and λ' by the plate of constants k and λ , we add a source of ionization amounting to $kI(1 - e^{-\lambda'D})/\lambda$, but we take away a source of ionization amounting, by the same rule, to $k'I(1 - e^{-\lambda'D})/\lambda'$. We also provide a plate which turns back more effectively some of the β rays made in the air of the chamber and in the plate at the top, but these are not many and we may neglect them. Thus the ionization in the

$$I \left\{ Dk' + \left(\frac{k}{\lambda} - \frac{k'}{\lambda'} \right) (1 - e^{-\lambda'D}) \right\}.$$

If $k/\lambda = k'/\lambda'$ the expression becomes IDk' simply : and the relation between ionization and pressure, measured by D , becomes a linear equation. If k'/λ' is greater than k/λ the curve is convex to the pressure axis, and if less it is concave. So far as I know, no experiments have ever been carried out with an ionization-chamber of this form in which γ rays have been employed to ionize air at different pressures. In the experiments of Kaye and Laby * the ionization-chamber was wholly made of one metal aluminium : in those of W. Wilson† it was partly of brass and partly of aluminium. If the γ rays have been hardened by a lead screen, k and k' are nearly equal, in fact the absorption coefficients of a number of substances are nearly the same. Now the β ray absorption coefficients are somewhat smaller for light atoms than for heavy, so that k/λ is less than k'/λ' and the curve, in the case I have considered, should be slightly convex to the pressure axis. When the top and bottom plates are both of aluminium, it should be slightly concave, as will be shown presently: Kaye and Laby found this to be the case.

In the case of γ rays, $\lambda'D$ is generally small, unless the pressure of the air in the chamber is very great : the expression then becomes

$$I \left\{ \frac{Dk\lambda'}{\lambda} + \left(\frac{k'}{\lambda'} - \frac{k}{\lambda} \right) \frac{\lambda'^2 D^2}{2} \right\}.$$

There is a term in this expression which is proportional to D and therefore to the pressure, but it does not represent exactly the action of the γ rays on the air, as some have supposed. Nor does it represent the action of the secondary rays from the walls entirely. And again it has sometimes been stated that a term proportional to the square of the pressure will be required to represent the ionization due to the β rays made by the γ rays in the gas. Clearly this is not quite true.

In the case of X rays k is usually so much greater than k' that the latter may be neglected, and $\lambda'D$ is so large that $e^{-\lambda'D}$ is negligible also. The exponential term is only to be retained when the pressure of the gas is so low that the cathode rays originating in the walls of the chamber can get across it in

* Phil Mag. Dec. 1908.

† Phil. Mag. Jan. 1909.

appreciable quantities. At ordinary pressures the formula becomes $I(Dk' + k/\lambda)$.

In this form it may be tested experimentally. It may be well to repeat that this formula is deduced on the supposition that X rays do not ionize a gas directly, but indirectly through the intermediate action of the cathode rays produced by the X rays in the metal through which they enter and in the gas which they cross. The term Ik/λ represents the effect due to the cathode rays from the metal; IDk' represents the effect due to the cathode rays formed in the gas. The first of these can be determined by experiment in a given case; the second can be calculated from the first when measurements have been made of k/k' , λ , and D . If then the ionization produced by the X rays in the gas (directly or indirectly) is also found experimentally, it can be seen whether the calculated indirect effect is sufficient to account for it all, or whether there is something left over which must be ascribed to the direct action of the X rays.

I have made a number of experiments of this kind and have found that the results were always to be explained on the supposition that there was no direct action of the X rays. An example will show the usual extent of the agreement.

An ionization-chamber was made of brass, lined with aluminium to avoid disturbances due to the secondary X rays of brass, and again with paper to cut out the secondary cathode rays from the aluminium. The chamber was cylindrical, 3.6 cm. deep and 10 cm. in diameter. A pencil of primary X rays was passed in along the axis through an opening 1 cm. in diameter. When a card was placed over the opening, and nine thicknesses of silver-foil placed on the card on the side next the ionization-chamber, the current was 150.0 on an arbitrary scale: when the foils were placed the other side of the card the current was 70.3. The difference 79.7 was due to the cathode rays from the silver: *i. e.* we may take Ik/λ to be 79.7. The absorption coefficient k was then found by placing various thicknesses of silver under the card, and measuring the current in each case. The curve obtained when the results were plotted was not far from exponential, and gave k equal to 43.2 for the primary rays after passing through 9 foils. The absorption coefficient required is that which measures the conversion into cathode ray energy, excluding secondary X rays. It is therefore better to put the absorbing sheet close to the ionization-chamber so that secondary X rays may be taken in, though there is still some error due to the difference in quality of the primary and secondary rays. The absorption coefficient for

the β rays in silver was found by placing one, two, four, eight, and twelve silver foils on the side of the card next the chamber and observing the gradual rise in the cathode ray effect: this gave λ equal to 3550. The quantity k was not found directly. The absorption coefficient of card was determined by experiment to be 2.28: card may be taken as cellulose, $C_6H_{10}O_5$; and the figures given by Thomson, 'Conduction of Electricity through Gases,' p. 307, may be used to show that the coefficient of air must be greater than that of cellulose in the proportion of 8 to 7. In this last calculation the absorbing power of H is neglected, which possibly makes the ratio too large; but there are no data from which to determine the error; it must be small, This gives $k' = 2.61$. Lastly $D = 3.6 \times .0012 = .00432$.

$$\begin{aligned} \text{Hence } IDk' &= \frac{Ik}{\lambda} \cdot \lambda \cdot D \cdot \frac{k'}{k} \\ &= 79.7 \times 3550 \times .00432 \times \frac{2.61}{43.2} \\ &= 73.8; \end{aligned}$$

whereas the ionization actually found, when the card was next the chamber and the nine silver foils on the outside of the card, was 70.3 as already stated. In this case therefore the ionization was somewhat overaccounted for.

Generally the other experiments gave results of much the same kind; it would not be justifiable to expect more accurate confirmation under present conditions.

The ordinary primary ray which was used in these experiments might well be replaced by one of the streams of homogeneous X rays which Barkla has shown us how to obtain from various metals. Recent papers by Beatty* and by Sadler† actually give results from which the desired information may be obtained in part, but neither author has had occasion to measure the value of λ . Moreover there is no published determination of k' , the absorption coefficient of homogeneous X rays by air. Mr. Sadler has been good enough to tell me that he finds $k' = 9.3$ for copper rays. Using this value, and taking λ in silver to be the same as λ in air, though it is probably greater, I find that on Beatty's results about two-thirds of the ionization can be ascribed to cathode rays: the figures of the latter author give a rather smaller proportion. The agreement would be better if a larger value were assumed for λ . Moreover these rays are

* Camb. Phil. Soc. Proc. vol. xv. pt. v.

† Phil. Mag. March 1910.

peculiarly liable to spend only a part of their energy in producing cathode radiation in the metal through which they enter ; some of the energy is spent on secondary X radiation ; or, which comes to the same thing effectively, some of the cathode radiation is liable to be reconverted into X radiation. In this way the measurement of Ik/λ becomes too small.

There is another method by which it is sometimes sought to separate the ionization effect due to secondary β rays from the supposed effect due to the direct action of the γ rays upon the gas, viz. the method of the magnetic field. Kleeman *, for example, has tried in this way to deflect from the ionization-chamber all secondary β rays, and has been able to reduce the ionization current to less than half its original value. Finding, however, that a considerable effect remained which he was unable to remove with the strongest magnetic fields at his disposal, he has concluded that this must be due to the direct action of the γ rays upon the gas.

The effect of a magnetic field is, however, a very difficult question to solve. It is to be remembered that the field may actually increase a β -ray effect in some ways while it lessens it in others. A β -ray path in the chamber may be lengthened by its being forced into a circular form, and the ionization due to the particle be made greater. Moreover, β particles are scattered by impact on the atoms of the surfaces upon which the magnetic field deflects them, and by successive impacts may travel considerable distances in spite of the field : for the field does no more than convert the rectilinear portions of the path into circular portions ; it has no influence on the direction which the particle will take after an impact. It cannot be asserted that the results obtained by the magnetic deflexion method are yet capable of clear interpretation : further work in this direction is much wanted.

Crowther has described an experiment from which he has drawn the conclusion that X rays passing through a gas ionize it directly, and that consequently the cathode rays made by the X rays in the gas have no appreciable ionizing effect. He passed a fine pencil of X rays between two parallel plates so as to touch neither of them, and measured the ionization for various pressures of the gas. He found it to be very nearly proportional to the pressure : if cathode rays from the atoms of the gas were responsible for some of the ionization, the ionization due to them ought to show a marked decline as soon as the pressure of the gas is low enough to permit them to strike either of the plates, and so to leave their paths in the gas unfinished. He could not find

* Proc. Roy. Soc. lxxxii. 1909, p. 358.

a deficiency from the proportionality to pressure, as already said, and hence his conclusion.

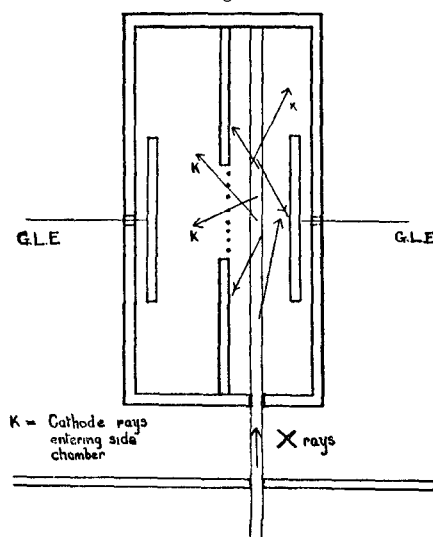
But it is clear that this experiment proves too much. One of the gases he used was methyl iodide. If X rays strike iodine atoms there is a very large conversion into cathode rays, as may be shown easily by scattering a little iodoform on a card through which X rays are entering an ionization-chamber when the current may be doubled under quite usual conditions. When the thinnest sheet of tissue-paper, equivalent to 1.5 cm. of air, is laid over the iodoform, this extra radiation is absorbed and the current returns to its former value. It is a clearly established principle that the effect of an atom upon an X ray is the same, no matter whether the atom is part of a solid or of a gas. Consequently there is a large production of cathode rays in the vapour of methyl iodide through which X rays are passing*, and a considerable fraction of the ionization of the gas is caused by these cathode rays. The amount can be calculated on the principles laid down above; but even if the complete accuracy of such a calculation be denied, it is still clear that the cathode ray ionization is large. Yet Crowther found there was none at all. Again, Mr. Edmonds has shown in this laboratory that if a hole is made in one of the parallel plates of Crowther's experiment and a piece of wire gauze placed over it, cathode rays pass through the hole from the X-ray stream in quantities which show a large increase as soon as the pressure of the air is sufficiently lowered. The distance from the X-ray stream to the window is about a centimetre, and the ionization current which is measured on the side of the gauze away from the stream increases rapidly relatively to the ionization in the air through which the X rays are passing: at first there is even an absolute increase in spite of the lowering of the pressure. The relation of the increase to the pressure alterations is just such as would be expected if the ionization outside the gauze window was due to cathode rays made in the X-ray stream and passing through the meshes in the gauze.

If the ionization of the gas in an ionization-chamber across which γ rays are passing is caused wholly by the β rays coming out of the walls of the vessel or out of the atoms of the gas, then, since the former of these sources of β rays is usually far more important than the latter, the ionization is

* It is worth observing that in a mixture of methyl iodide and any gas of small atomic weight the iodine atoms would be responsible for a large ionization, but only a fraction of the ions would be formed from the methyl iodide molecules.

due to an agent which does not change when the gas is changed, viz. the β rays from the vessel walls. The relative ionizations in different gases due to the γ rays must be the same as the relative ionizations due to β rays; and this is

Fig. 3.



found to be the case very exactly, unless there is such a mass of gas in the chamber that the second source of β rays becomes important. This occurs when the gas contains heavy atoms like those of iodine. The "atomic ionizations" by β and by γ rays are set out below and show the close parallelism. They are taken from a paper by Kleeman*.

	H.	C.	N.	O.	S.	Cl.	Br.	I.
β	0.18	0.46	0.475	0.58	1.60	1.44	2.67	4.10
γ	0.18	0.46	0.45	0.58	1.60	1.44	2.81	4.50

If any part of the ionization in the gas were due to a direct action of the γ rays, and we were to reject the simple explanation just given, we should certainly find it extraordinarily difficult to explain the almost exact similarity of these two rows of figures. This would be the case on the entity hypothesis: if the γ rays were supposed to be spreading pulses,

* Proc. Roy. Soc. lxxix. p. 220, Feb. 1907.

differing therefore in every imaginable way from β rays, an explanation would surely be hopeless.

Considering all this evidence for and against the existence of a direct ionization of a gas by X and γ rays, I would conclude that the entity hypothesis leads us to expect that there is no such effect, that many experiments fall in readily with this view, and that others are quite likely to show a like agreement when obvious defects have been removed.

Let us therefore accept this simplification, provisionally at least; and let us go on to consider a second problem of the ionization-chamber which may then be taken in hand with some success: the problem of the chamber of any form made wholly of any one substance.

Suppose a block of any material to be crossed by a stream of γ rays, and let us try to estimate so far as we can the whole length of track covered by β rays in any element of volume in a second, irrespective of direction. The number will in the first place depend on the strength of the γ radiation in the neighbourhood of that element of volume: after allowing for that, it will depend on two things only, (a) the number of β rays originated in each unit weight of the substance, *i. e.* the absorption coefficient of the γ rays by the substance, (b) the weight of material traversed by each β ray before it disappears. If different β particles traverse different amounts of material, the average is to be taken: we may call such average the average range, or briefly the range. The important thing to observe is that the range need not be all in one straight line: the β particle may make any number of twistings and turnings during its total path, and the range is the length of the path if it were straightened out, or rather the weight of material which the particle traverses. The deflexion oval and the scattering which the oval represents do not come into consideration at all. Let us say that k is the absorption coefficient of the γ rays and d the range, then the sum of the tracks of β rays in a unit volume is directly proportional to lkd , l being the intensity of the γ rays. It may be of some service to give an analogy. If k points were taken at random in each square centimetre of a sheet of paper, and a line of length d were drawn from each point, then the quantity of ink used and the quantity of ink on each square centimetre would be just the same, on the average, whether the lines were straight or curved or made up of any number of short pieces so as to be zigzag in form. The ordinary coefficient of absorption of β rays is a compound of d , and of the dimensions of the deflexion oval. We are here dealing with a much simpler

thing. If we take different substances and take I to be always the same, the " β ray density" in each substance is represented relatively by kd .

Suppose a cavity to be made in the substance. This makes no difference whatever in the value of kd anywhere in the metal, even on the borders of the cavity. This follows from the fact that every β particle has to cross a weight d of the substance: crossing the cavity does not count in its total path. The only inaccuracy in this statement arises from the fact that the value of I may not be the same in all parts of the substance that border on the cavity. It will be found to have little importance so far as our present purpose is concerned, and we will not take it into account. Then we can say that just as many β rays cross each unit volume of the cavity as would cross it if it were filled with substance of the kind considered, or of any other substance having the same kd . The shape of the cavity is immaterial. We may in fact take it to be the inside space of an ionization vessel, provided only that the walls are thick enough to prevent the passage of β rays either way.

It is curious but not uninteresting to consider that if we had a substance with no k , but with the power of reflecting every β ray that fell upon it, and made a closed vessel of the substance, and shot γ rays across it, we should then get the following results. If a vacuum existed in the vessel, kd would be zero: if a single atom of any ordinary substance were placed in the vessel, kd would in time mount to its full value for that substance, and would not increase if the one atom were added to by putting in any number of like kind. If atoms of other kinds were inserted, there would be a compromise, the density of β rays becoming $\Sigma k/\Sigma(1/d)$.

To go back to the cavity in the substance traversed by γ rays, the introduction of air into it makes little difference in the value of kd in different parts of it unless the kd of the substance differs considerably from the kd of air, and there is so much air that an appreciable fraction of β -ray energy is used up when a stream of such rays tries to cross the cavity. Hence the cavity must not be so big, nor the pressure of air inside it so great, that this source of inaccuracy becomes serious. If there were any doubt about it in a given case, it could be tested by varying the pressure of the air; if the relation between pressure and ionization required a curved line to represent it, it would be necessary to use the initial portion of the curve for which the pressure is small. This precaution is usually unnecessary, and we may take the ionization in the air of the cavity as proportional to kd . If,

therefore, we make a number of ionization vessels of different materials but the same form, and cause γ rays to pass into them, the amount of ionization produced inside becomes a measure of the kd of that substance. The experiment may conveniently be carried out by making a thick lead ionization-chamber and inserting different linings. The γ rays must of course be kept at the same strength inside each lining, or if not any differences must be allowed for.

Mr. H. L. Porter has recently carried out some experiments for me in this way, the results of which are shown in the table below. The first column gives the material of the lining, and the second its thickness, which was enough to give the true value of kd in all cases except perhaps those of aluminium and cardboard. The third column gives the results obtained when the γ rays had to pass through little more than the lead wall of the ionization-chamber, which was 0.47 cm. thick, and the fourth the results when the rays had to pass through a screen of lead 1.1 cm. thick in addition. The figures are corrected for differences in volume and for differences in the strength of the γ rays due to absorption in the linings.

I. Metal.	II. Thickness of screen.	III. Ra unscreened.	IV. Ra screened.
Lead .....	...	100	100
Tin.....	.16	58	68
Zinc .....	.21	47	55
Iron .....	.155	45	54
Aluminium .....	.21	40	49
Card. ....	.24	39	46

The height of the chamber, which was cylindrical in form, was 15 cm., and the diameter 9 cm. The radium was placed on the axis of the cylinder, 10 cm. away from one end.

The differences between the figures in the last two columns are really due to a change in the relative value of lead only. The rays have been so hardened by passing through the extra cm. of lead that the absorption coefficient of the lead lining has fallen to the same value as that of the other metals. In the first case there is a special production of softer β rays by the lead which does not take place in the second.

In these experiments the strength of the γ rays is not the same all over the cavity as it ought to be ; but the inequality

cannot have much influence on the relative values of kd for the different linings. Mr. Porter finds that the figures are indeed somewhat altered when the radium is moved about into different positions, but the alterations are such as would be expected from the variations in the quality of the γ rays. In some positions the γ rays pass more obliquely through the walls, and therefore through a greater thickness of lead, so that they are so much the more hardened.

When all allowances for error are made we still have a set of figures which show with considerable accuracy the relative values of kd in certain substances, and, since k is practically the same for all of them, the relative values of d , the range of the β particle. It may be well to point out once more that this range does not give directly the power of penetrating screens of different metals; and indeed it varies in the opposite direction. The power of penetration depends also on the form of the deflexion oval which represents the scattering effect. In the definition of the range, and in the experiment which measures it, scatterings or reflexions, or so-called secondary radiations, have no part at all. In fact these experiments allow us to investigate separately one of the three main subjects of measurement already referred to, viz. the expenditure of energy along the track of the β particle, since this must determine the length of the track.

In order to complete a proper set of investigations of the β particle phenomena, it is further necessary to find the form of the deflexion oval in all cases. This may be done by observing the scattering of the β rays in various directions as they pass through very thin plates, since in such cases the scatterings are due to one encounter with an atom in each case, as Madsen has shown (*loc. cit.*). The third subject of measurement is the conversion of form: so far as we know this is unimportant in the case of the β ray, but it is just possible that an effect of this kind has been overlooked.

Until satisfactory investigations have been made under these heads, it is impossible to find true foundations for calculation of the effects to be observed when sheets of material are placed over a substance emitting β rays, that is to say, of the so-called absorption coefficients. For these coefficients must necessarily vary in a complicated manner from material to material and thickness to thickness, since they are involved functions of the range and of the scattering. It is too much to attempt a theory of the absorption of β rays until these intermediate steps have been hewn into shape. H. W. Schmidt has tried to fill up the gap by arguing back from a

large number of measurements of absorption and of scattering coefficients †. He has defined two constants which he has called the “reflexion” and the “true absorption” coefficient. The former really represents roughly the facts of the deflexion oval, the oval being reduced to its axis, and the atom placed at various positions upon it; the latter represents the expenditure of energy along the path. His two constants actually stand approximately for the two independent subjects of measurement which we have seen to be important in the case of the β ray. It is therefore very interesting to compare his calculated values of the true absorption coefficient with the quantity d , which should be approximately in the inverse ratio. To what extent this is due is shown in the following table. The second column gives the values which Schmidt‡ calculated for the true absorption coefficients of the β rays of uranium, *i. e.* the values of his α/D . I do not think the values for radium are available. But it must be quite allowable to use the former instead of the latter, since the β rays of radium do not differ much in penetrating power from the β rays of uranium; while the values of α/D for uranium and for actinium are very much the same relatively to one another, and yet the β rays of actinium are much less penetrating than those of uranium. The third column gives the relative values of kd , or practically of d , and the last the product of the figures in the two preceding columns.

Substance.	α/D .	kd .	$\alpha/D \times kd$.
Lead	1.69	100	169
Tin.....	2.14 (2.40)	68	145 (163)
Zinc	3.00	55	165
Iron	3.08	54	166
Aluminium	3.26	49	160
Card	3.32*	46	153

* Calculated as for carbon from later figures given by Schmidt.

The uniformity of the figures in the last column is only broken seriously by tin. Strange to say, the value 2.14 which Schmidt gives for tin is quite out of line with the values he gives for all the other metals; if these values are plotted and a value for tin obtained from the curve we get

† See also McClelland and Hackett, Dublin Trans. 1907. ix. p. 37.

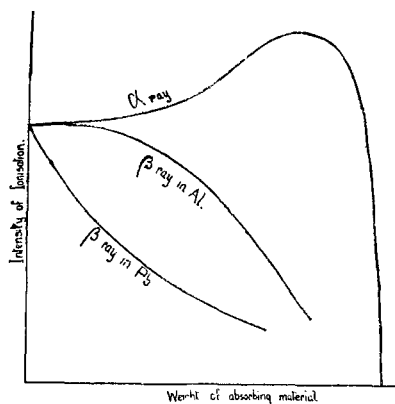
‡ *Ann. d. Phys.* xxiii. p. 671 (1907); *Jahrb. d. Rad.* 1908, p. 451.

2.40, which leads to a value 163 in the last column. Schmidt's values of α/D for the β rays of actinium do not show this irregularity in the case of tin.

The values of d are clearly less for the smaller atomic weights. The whole track of a β particle in lead is actually greater, weight for weight, than in aluminium. Yet as is well known a β particle can penetrate a heavier screen of aluminium than of lead. The reason is that the lead atoms turn back the β particles so much more than the lighter atoms do. In lead the particle finishes its course much more closely to its starting-point; it is really a longer course, but there are many more turns in it.

It is easy to see that there will consequently be considerable differences in the "absorption curves" of different materials; *i. e.* the curves which show the relation between the thickness of a screen placed normally to the path of a stream of β rays, and the ionization in a chamber on the other side, a chamber which the rays can usually cross. A β ray going through aluminium behaves rather more like an α particle than when it goes through lead, since it is less liable to deflexion in the former case, and the α particle has very few departures from a straight line course. The absorption curve of the β ray in aluminium should, therefore, be more like that of an α particle than the curve of β ray in lead. Now the α particle actually causes more ionization when screens are placed in its path, unless the screen is too thick, than when it is unimpeded;

Fig. 4.



that is to say, the curve which is plotted with thickness of screen as abscissa and ionization on the other side of the screen as ordinate rises at first; subsequently it falls rapidly

to the axis of α . Experiment shows that the absorption curves for β rays in aluminium screens do really possess a trace of this peculiarity, for they fall slowly at first and much more quickly afterwards. On the other hand, the absorption curve for lead is more like an exponential curve, which is to be expected since scattering is the most prominent cause of absorption.

Sir J. J. Thomson has recently published (Proc. Camb. Phil. Soc. xv. part v. p. 465) a theory of the "scattering of rapidly moving electrified particles." It seems to me to be inapplicable to the actual case because it considers scattering to be due to a multitude of small deflexions experienced by the particle in passing by the various centres of positive and negative force in the atoms, all the centres acting independently of each other. Apart from the question as to whether it is likely that the positives and negatives do not interfere with each other's actions, the argument is limited to cases where the total deflexion is so small that the particle has hardly moved from its original direction when it emerges on the other side of the screen. This is necessary because the deflexion is taken to be the average of a number of deflexions, and the reasoning tacitly assumes that all these deflexions are grouped symmetrically about the original direction of the particle throughout the whole of the transit of the particle across the absorbing layer. The scattering of a pencil of β rays is looked upon as a gradual opening out of the whole pencil, and the calculations refer to a state in which the absorbing layer is so thin that only slightly scattered rays are worth considering. Actually there is no such state; however thin the plate the highly scattered rays are in a certain proportion to the slightly scattered rays, which does not alter as the thickness of the layer is increased, unless the thickening is carried too far. From the very first large deflexions must be considered. The many slight deflexions which the β particle experiences along the comparatively straight portions of its track are of no real consequence; little more than in the case of the α particle. Moreover, while the plate is still fairly thin, another important effect comes in, viz. the loss of speed; and it is by the mutual interplay of these two that the differences in the absorption curves are caused. Crowther (Camb. Phil. Soc. Proc. xv. 5, p. 442) shows absorption curves of aluminium and of platinum. The curves show the special characteristics just discussed; but I think it is only by accident that the aluminium curve fits the formula derived by Sir J. J. Thomson. The curve for platinum will not fit the theory in the same way, and

Crowther supposes that secondary radiation must be present and be responsible for the want of agreement; but there does not seem to be any good reason for selecting secondary radiation as the cause of the error. On the other hand, the entity hypothesis leads naturally to a simple explanation of the general form of the curves both of aluminium and of platinum.

In the case of β and cathode rays there is very little accurate knowledge of the third of the phenomena which I have tried to distinguish above, viz. the conversion of form. The conversion of β rays into γ rays is often doubted altogether; but it can hardly be safe to deny it, for if the number of γ rays produced by a given number of β rays were relatively as few as the X rays produced by a stream of cathode rays, the effect produced by the γ rays would be almost imperceptible. The conversion of cathode rays into X rays is, however, a very obvious and common process, and it is rather striking that so little work has been done to discover the laws of it. It would be a great help to know whether there is a critical speed or more than one critical speed at which an electron should strike an atom in order to get an X ray effect. Let us suppose that there is a speed which it is necessary for a cathode ray falling on a given atom to possess in order that the conversion may take place, which does not seem at all unlikely considering the general behaviour of X ray tubes. Let us suppose, further, that the critical speed increases with the atomic weight, for which also there is something already to be said. Then we seem to have a reasonable chance of explaining the very remarkable phenomena of the homogeneous secondary X radiations which Barkla has discovered. The explanation given by Barkla himself is not at all in accord with the arguments which I have tried to state above. He supposes the primary pulse to shake an atom in passing and make it give out its own characteristic quivers. But this suggests that a single primary X ray is the cause of many secondary X rays.

We have to explain why one single primary entity—an X ray—is replaced by one secondary X ray entity after collision with a certain atom, the energy of the secondary being characteristic of the atom not of the primary, and its direction of motion being also independent of the primary, *i. e.* of the direction of motion of the primary. We have to explain further why the X ray emitted by zinc can excite the copper atom to emit its own characteristic X ray, and why the reverse does not take place, the copper X ray is not able to excite the zinc X ray. Let X rays from zinc, that is

to say secondary X rays coming off a plate of zinc on which sufficiently hard X rays are falling, be made to strike a plate of copper. Their energy is gradually converted into that of cathode rays, which possess a certain definite power of penetration, *i. e.* a certain definite speed (or perhaps average speed) as Sadler has shown. These cathode rays possess more than the critical speed for copper; we may imagine them to scatter in the zinc, losing all sense of original direction very quickly and falling in speed. When they reach the critical speed for copper and the maximum conversion of form takes place, the characteristic X rays of copper will flash out in all directions. If they pass this speed without conversion their energy is spent merely on the copper atoms, transforming itself in the usual ways into heat. But if X rays produced by some means in a copper plate are allowed to fall on a zinc plate, and there form cathode rays, the speed of these latter rays is below the critical speed for zinc, and no X rays characteristic of zinc are produced. Thus all Barkla's effects are qualitatively explained. Until the conversion of cathode ray energy into X ray energy has been more fully investigated, such an hypothesis can be no more than a provisional one, but it seems simple and reasonable, and suggests promising lines of research.

In the foregoing pages I have tried to follow out the consequences of adopting the "entity hypothesis" of X and γ rays, and to show how we are led to modify our views of well known theories and our interpretations of well known experiments. Since there is so much to consider, the discussion has, I fear, been rather lengthy; but I think the result is simple. We are to think of each entity as possessing initially a certain store of energy which it spends gradually as it goes along, the result being ionization of the material through which it passes; there are no sudden accessions or withdrawals of energy; the path is not necessarily straight, but made up of a number of small pieces more or less straight, the deflexions or turnings being the results of intra-atomic collisions; the β rays are very liable to such deflexions, and the cathode rays even more so. Certain conversions of form may take place, γ into β , X into cathode ray, and so on; but in such cases the energy is handed on, and in some cases at least the momentum. The essence of it all is the recognition of the individuality of each entity which is to be followed by itself from its origin through all its changes of direction and sometimes its changes of form, until its gradually diminishing energy becomes too small to render it distinguishable.