THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[SIXTH SERIES.]

OCTOBER 1907.

XLI. *On the Properties and Natures of various Electric Radiations.* By W. H. Bragg, *M.A.*, *F.R.S.*, *Elder Professor of Mathematics and Physics in the University of Adelaide* *.

We are now aware of the existence of a number of different types of radiation, each of which is able to ionize a gas, to act on a photographic plate, and to excite phosphorescence in certain materials. Of these the α and canal rays consist of positively charged particles of atomic magnitude; the cathode and β rays are negative rays, and consist of electrons; the X and γ rays are supposed to be æther pulses; and ultra-violet light consists of short æther waves. The δ rays stand by themselves, for, though they consist of negative electrons like the cathode and β rays, they have so small a velocity that they possess no appreciable ionizing powers.

The present paper contains, in the first place, an attempt to find whether there is anything to be learnt from a comparison of the properties of the various rays; and, in the second place, a discussion of the possibility that the γ and X rays may be of a material nature.

* Communicated by the Author. Read before the Royal Society of South Australia in two parts; the first on May 7, 1907, the second on June 4, 1907.

It appears to me to be a first deduction from such a comparison that in all cases the bulk of the ionization which the rays effect is of the same character, and consists in the displacement of slow-moving electrons, or δ rays, from the atoms of the gas or other substance which they traverse. Let us consider the various rays in turn.

In the case of the cathode rays this principle has been clearly established by Lenard in the course of his long series of beautiful experiments. He has shown that cathode rays of the most varied speeds, impinging on bodies of various kinds, or traversing different gases, cause the liberation of slow-speed electrons from the atoms of the solid or gas. The speed of the electrons is in every case that due to the fall through less than ten volts. This is in no way a contradiction of the fact that cathode rays of high speed are also liberated from a solid surface struck by primary cathode rays; or from the atoms of a gas through which the primary rays pass. But, whether these high-speed secondary rays are scattered primary rays, or are true secondary rays, they must in their turn produce electrons of slow speed in the gas through which they pass; and so, directly or indirectly, by primary or secondary or tertiary or rays still more transformed, eventually the great majority of the electrons set free in the ionization-chamber of ordinary experiment are of the slow-speed type.

In the case of the α rays there is abundant evidence that their impact on, or emergence from, solid surfaces causes the ejection of slow-speed electrons (J. J. Thomson, Cambridge Phil. Soc. Trans., February 1905; Rutherford, 'Nature,' March 2, 1905; Logeman, Proc. Roy. Soc., September 1906). Now, it is generally characteristic of all these electric radiations that they are concerned with the individual atoms and molecules, and that they do not recognize any difference between the atom in the solid and the atom in the gaseous condition. Consequently, there is every reason to suppose that the heavy ionization caused by an α particle in traversing a gas consists in the production of the same slow-speed electrons as are set free from a solid, and indeed no trace of faster-moving electrons has ever been found. The slow-speed electrons originated by α rays have been called δ rays, and the term may be applied to all such slow-speed electrons as we are now considering.

Again, it has been shown by Fuchtbauer (*Phys. Zeit.*, Nov. 1, 1906) that δ rays are emitted from a metal surface struck by canal rays; and here also there is every reason to suppose that gas molecules struck by such rays emit the same δ particles. The same author has shown by a direct comparison that the velocity of these particles is the same as that of the δ rays displaced by cathode rays, *i. e.*, about $3{\cdot}3 \times 10^8$ cm./sec., or the velocity due to about 20 volts, a velocity only slightly larger than that found by Lenard.

As regards β and γ rays, it is true that it has not been definitely proved that most of the ionization which they cause is of the δ type. But this may be inferred from well-known experiments, such as those of Durack (Phil. Mag., May 1903), or McClelland (Trans. Roy. Dub. Soc., February 1906). When a pencil of β radiation is allowed to cross an ionization-chamber normally, and fall upon the opposite wall, it gives rise to a secondary ionization, less in quantity, but not much less in speed than the primary. A tertiary radiation is caused by the secondary rays if they impinge on the walls of the chamber, and there will doubtless be still further derivations. But it appears that the quantity of the derived radiations dies away much more quickly than the speed. Thus the chamber is crossed and re-crossed (a few times) by electrons of high speed, able to traverse an average path of about 100 cm. in air at atmospheric pressure. If the chamber is first exhausted and air gradually admitted, it is found that the number of ions produced by the β rays is proportional to the pressure. The paths of the β rays will not be appreciably affected by the introduction of the air; and so the experimental results are consistent with the simple hypothesis that the β particle (primary or secondary) makes slow-speed ions in proportion to the number of gas atoms traversed. Nor does any other hypothesis seem to be consistent with the facts. It cannot be supposed that the bulk of the ionization which is caused in the ionization-chamber consists of high-speed secondary rays, though, of course, these are originated when the primary rays strike the metal surface of the chamber, and to a small extent when they strike gas molecules. For if all the negative electrons set free by the β rays were of high velocity we should expect certain effects, as may be seen from the following considerations, and none of these effects have been observed.

Rutherford has shown ('Radioactivity,' 2nd edition, p. 434) that the α particle of Ra makes about 86,000 ions in air; that one β particle is emitted from Ra for every four α particles; and that the ionization due to β particles is of the order of 1 per cent. of that due to α particles in the case of Ra in equilibrium. Thus the β particle of Ra produces some thousands of ions. This is also evident from the experiments of Durack (Phil. Mag., May 1903), who has shown that the β particle produces about 130 ions per cm. in air at atmospheric pressure. Now, the β particle runs a course in the open air of an average length of 100 cm. This leads to an estimate of its ionization even greater than that obtained by Rutherford. If all the electrons, so liberated, had a high velocity, the energy set free would be out of all proportion to that of the original β particle. Yet if we are to ascribe a high velocity to the electrons set free, it must be a very high one, for it has been shown by Allen (Phys. Review, August 1906), that the secondary radiation of β rays consists of electrons moving with a speed approximating to that of the primary. We cannot suppose that all these electrons are of this high-speed type. Moreover, if this were the case, the free path of such electrons would become comparable with the dimensions of the ionization-chamber, when the air pressure was only moderately reduced, and the electrons would then be beyond the control of the electric field. Thus the ionization would not be proportional to the air pressure, as was found by Durack and McClelland. The difficulty as to the energy is not obviated by supposing each primary β particle to set free only a few secondary electrons of high speed, each of these to become in turn the originator of a few more, and so on. For if that were the case, a reduction of gas pressure would imply, not only that each primary electron set free fewer secondary electrons, but that each of the latter set free fewer tertiaries, and so on, so that the ionization would fall at a far greater rate than the pressure as soon as the free path of the electrons became comparable with the dimensions of the chamber. And, again, the β rays differ only in speed from cathode rays, which produce quantities of slow-speed electrons, even where their own velocity is great.

For these reasons I think it must be concluded that the β particle (and any high-speed secondary) produces slow-speed electrons along its path, in very much the same way as the α particle does, though not in such great numbers. The high-speed secondary rays, studied by McClelland, Allen, and others, are but few in number compared to the slow-speed electrons, though their greater energy puts them more in evidence. McClelland concludes from his experiment that the β rays do not produce any slow-speed electrons, when they strike a metal surface, which are comparable in number with the electrons displaced in the gas through which they have passed. This is quite consistent with what has been said above. There must be a few, but the number to be expected is quite small, for the β electrons dive so deep into the metal which they strike, and ionize so few of the molecules through which they pass, that very few of the slow-speed, highly-absorbable electrons can be discharged from the surface of the plate. Even in the case of the α particle these electrons are not readily observed; in the case of the β particle the difficulty must be much greater.

As regards X rays, we have no such accurate measurements of the velocities of the electrons which are ejected from the molecules of a gas traversed by the rays, as we have in the case of the cathode rays, so far as I am aware. But a very large amount of labour has been spent on the investigation of the secondary radiation caused by the X-rays, from which we may gather much indirect evidence on the point. Perrin (*Ann. Chim. Phys.* xi. p. 496, 1897), has shown that the rate of production of ions per cc. by rays of given intensity is proportional to the pressure of the gas. Again, we know from the investigations of Curie and Sagnac, Townsend, and Barkla, that metals struck by X rays return a secondary radiation, which, in the case of the low atomic weights, may be considered to consist principally of scattered primary radiation, and in the case of the high atomic weights to contain both X rays more absorbable than the primary and cathode rays. Dorn has shown that the latter have speeds averaging about 5×10^9 cm., so that they must produce considerable ionization, consisting of δ rays, in the few millimetres of air close to the metal. The free path of electrons having this speed is about one millimetre in air at atmospheric pressure. Since the X rays do not appear to produce cathode rays of any speed from the air molecules, which they traverse, or from the molecules of any gas consisting of atoms of small weight, and since they produce much ionization in some way or other, we may conclude fairly that they produce slow-speed ions themselves. Thus, whether they act directly or indirectly through cathode rays, the result is the same. The principal effect appears to be due rather to secondary than primary. As Sagnac remarks (*Ann. Chim. Phys.* xxiii. p. 196): "The transformation of X rays, by increasing the activity at any point, permits the detection there of very penetrating X rays, which would otherwise have passed unperceived."

In the case of the γ rays, such evidence as we have is also in favour of the existence of slow-speed ions, as the result of their action. It is known that β rays of high speed originate where they strike the molecules of a solid body (Eve, Phil. Mag., December 1904); such an action may, therefore, be expected in the case of gas molecules also. It is possible, however, that there may be a differential effect in respect to heavy and light atoms, as in the case of the X rays. The β rays will produce δ rays in their turn; and if, as is probably the case, the γ rays are themselves able to ionize, the product will consist of δ rays, a conclusion which may be safely adopted from the analogies of the cathode rays on the one hand and the X rays and ultra-violet light on the other. As in the case of the hard X rays, the existence of γ rays is often made clear by the secondary effects which they produce, as has been shown by Becquerel.

To sum up what has been said, the ionization which we measure in the ionization-chamber is almost wholly due to the emission of slow-speed electrons from the atoms of the gas contained in the chamber, or of the chamber-walls; and this is true for all forms of radiation.

Moreover, there is some evidence to show that the speed of the δ rays is almost independent of the cause and manner of their production. As has already been said, Fuchtbauer found the velocity of the δ rays, caused by canal rays, to be about $3{\cdot}3 \times 10^8$, and the same in the case of cathode rays. Logeman found the velocity of the δ rays, emitted from a plate struck by α rays, to be such that they were deflected by a weak magnetic field. Ewers found (*Phys. Zeit.* March 1906) the δ rays of polonium to possess a speed of $3{\cdot}25 \times 10^8$. With these may be compared Lenard's estimate, viz. 10^8, of the speed with which the ions leave a plate struck by ultra-violet light. It seems probable that we have here a critical speed for the electron. Below this, it is not able to leave the parent atom. If its velocity exceeds the critical amount it possesses powers of penetration and of causing ionization, the extent of these powers depending on the excess.

The existence of a common speed for all δ rays may, of course, imply that the ejection is not directly effected by the ionizing agent, but that the latter simply precipitates the discharge. A man running through a battery might pull the triggers of some or all of the guns which it contained, and the velocity of the shot would not depend on the strength of the man, nor the rate at which he ran, nor how much energy he spent in the transit. And so it may be understood why δ rays are projected at a speed which is independent of the nature of the agent, as has been said above. So also it appears to be independent of the intensity of the agent's action. Fuchtbauer found the velocity of the δ rays produced by canal rays to be independent of the intensity of the primary rays: Lenard found the same for ultra-violet light.

In my own experiments on the α rays (Phil. Mag., March 1907), I have brought forward evidence to show that the amount of ionization produced in an atom is proportional to the volume of the atom approximately. Taking this in conjunction with the rule that the ionization produced in a gas is nearly proportional to the inverse of the speed, we have the very simple, if approximate, law, that the ionization produced by an α particle in any atom under any circumstances is inversely proportional to the time spent inside the atom. This appears to point to the ionization as purely a trigger effect. Not that the α particle spends no energy in the atom; it is clear it must do so, since its speed is gradually reduced, but there is not a direct connexion between the energy spent and the number of ions produced. But whatever energy the ionizing agent may spend, or in whatever way it spends it, it seems likely that the issue of the δ particle is the result of some disruption in the atom, or sub-atom, which is the same for all atoms and under all circumstances.

If we turn our attention now to all secondary radiation other than the δ rays, it seems to be, in general, a rough reflexion or scattering of the primary. Allen has shown that there is only a little less velocity in the secondary rays than in the primary β rays, or in the tertiary than in the secondary. McClelland has measured the total ionization produced by the secondary as compared with the primary β radiation; and since he used a small ionization-chamber with which he explored the whole space traversed by the secondary rays, which chamber the secondary rays would, as a rule, completely cross if they entered it, it may be taken that he really compared the number of β particles in the secondary beam with the number of those in the primary. The numbers which he obtained varied from 15 per cent. to 50 per cent., according to the substance, which is the order of things we should expect if the secondary were simply scattered primary radiation. Again, the loss of velocity of the cathode particles, which is found to occur on scattering at a plate, presuming the secondary radiation to be scattered primary, is just what we should expect. In the case of the α rays no secondary radiation other than δ rays has been found; but a small reflexion of canal rays has been observed, *e.g.*, by Fuchtbauer (*Phys. Zeit.* March 1, 1906). Barkla has shown that the secondary radiation produced by X rays consists in part of scattered primary radiation, especially when the surface struck is of material whose atomic weight is low. The only cases in which a secondary radiation appears that is neither δ radiation nor reflected primary rays, are those in which β rays are produced at the impact of X or γ rays, and in which X rays are produced by cathode rays. It is remarkable that in the former of these cases there is very great difficulty in accounting for the high speed which is possessed by the secondary radiation, caused by X rays and γ rays (Wien, *Ann. d. Phys.*, December 28, 1905). It may well be that further research will bring these cases into better agreement with the rest.

The next question which it is interesting to consider in relation to the various types of radiation, is that of the law of absorption in passing through matter.

Absorption in the case of the material radiations appears to be due to two main causes: loss of energy, which causes a gradual loss of speed; and scattering, which means a diminution in the number of particles in the primary beam. There is a possibility of a third, viz., absorption of the flying particle by an atom which it is traversing.

In the case of the α particle, I have shown that the first of these causes operates alone, so that the particle pursues a rectilinear course throughout its career (Australasian Association for the Advancement of Science, January 1904; Phil. Mag., December 1904). It is the absence of any effective amount of scattering that makes the study of the motion of an individual α particle comparatively simple. The loss of energy in traversing an atom, or more exactly the probable loss in crossing a given space occupied by an atom, is nearly proportional to the square root of the atomic weight, and the effects appear to be exactly additive.

On the other hand, if we consider a stream of β particles projected into matter, and attempt to find the history of their motion, we are faced with a problem of great complexity. If we look for an answer expressed statistically, we must find the number of particles in each unit volume of the absorbing matter as a function of the time, the velocity, and the direction of motion. If, on the other hand, we try to follow the motion of any one particle, we must find the chance that the particle considered has any particular position, velocity, and direction of motion at any given time; which is really equivalent to finding the function just mentioned. Moreover, the data are very uncertain. We know so little of the interior of the atom that we are unable to say with what forces the electrons will be influenced when it penetrates within; whether, for example, we may neglect the action of the positive electricity of the atom, and consider only the electrons as repelling the β particle with a force varying as the inverse square of the distance, or whether we are to consider positives and negatives arranged in doublets, whose moment will be the important power, and whose law of attraction will not be that of the inverse square. It is a certain simplification to suppose that scattering is mainly responsible for the fading away of a stream of β particles. The experiments of Allen, McClelland, and others show that the secondary radiation has a velocity not much less than that of the primary; and, therefore, that this simplification is justifiable; though, clearly, it cannot be pushed too far. This allows us to concentrate our attention on the deflexions of the particles only; but even then the difficulties are still immense. It is not like any problem in the kinetic theory of gases, for there we deal with established conditions; here with a gradual development from initial conditions *.

But if we turn from the theoretical to the experimental investigation we find a much more encouraging prospect. The experiments of Lenard are practically a complete graphical solution of the question. (See Taf. iv., Wied. *Ann.* Bd. 51.) We know that an assemblage of atoms behaves just the same in respect to these radiations, when it is condensed in a solid or spread out as a gas. Thus the sketches which Lenard gives us showing the way in which the cathode rays diverge from a small window and scatter in going through various gases at different densities, must be quite applicable to solids also.

* In his 'Conduction of Electricity through Gases,' 2nd edition, p. 376, Professor Thomson investigates the motion of a stream of β particles through an absorbing layer. It appears to me—I say it with very great diffidence—that the solution does not take a true account of the facts. The solution may be stated briefly thus:—Taking u, v, w as the components of the velocity V of the moving corpuscle, an expression is found for the probable change in u at the next encounter. Calling this change δu, we have $\delta u = -uK$, say, where K is a function of the mass of the corpuscle, the effective mass of the electron of the absorbing body, the velocity V of the corpuscle, which is taken as constant, the atomic charge, and the shortest distance between two corpuscles and the atom. K is then multiplied by the probable number of encounters in moving a distance δx along the axis of x, from which follows an exponential law for u in terms of x. It seems to me, in the first place, that, assuming such a multiplication to have any meaning, the proper factor should have been greater than that adopted in the proportion of V to u, for in advancing a distance δx along the axis of x the corpuscle moves a distance $V\delta x/u$, not δx. If this change is made, the exponential form disappears from the answer. But, apart from this, it does not seem that the step is justifiable at all. It is tantamount to putting the corpuscle back in its old track after each encounter, and is equivalent to neglecting the existence of the function mentioned above, and the absolute necessity of finding it.

Lenard found that his results could be accounted for on the supposition that there was an absorption according to an exponential law, over and above the weakening due to spreading from a centre.

If a β particle or cathode particle were liable to complete absorption by an atom which it entered, such an exponential law would result at once. As a matter of fact, it looks as if several violent deflexions might take place before the final disappearance of the particle's activity. It looks, also, I think, as if deflexions were usually not at all great during the progress of the particle through the atom, but were apt to be severe when they did happen, as if, in fact, the field of force which deflected the particle was strong but circumscribed. This would happen if the positives and negatives were arranged in doublets. When a particle is deflected from a beam crossing a thin plate, it starts off on a new path which leads much less directly to the open air, and its velocity is somewhat diminished. It may be, therefore, that the infrequency but severity of the particle's encounters makes it possible to look upon each encounter as an absolute, or at least a definite, loss to the stream, so that an exponential law results.

Certainly the application of this law to the interpretation of experiments has had very great success, both in respect to cathode and to β and γ rays. As examples of the latter we may take Rutherford's determination of the absorption of the β rays of uranium, and Godlewski's similar determination for actinium (*Jahrbuch der Rad. und Elek.* Bd. iii. Heft 2, p. 159). In experiments of this kind the radiating material is spread evenly on a level surface, and sheets of absorbing material are placed upon it. The ionization produced in the space above the sheets is compared with the thickness of the sheets; and the two variables are found to be connected together more or less exactly by an exponential law. There is some difficulty whether such measurements give more nearly the number or the energy of the stream of particles which emerges from the plate, as Rutherford ('Radioactivity,' 2nd ed. p. 134) and Thomson ('Conduction through Gases,' 2nd ed. p. 375) have pointed out. The point was also discussed in my address to Section A of the Austr. Assoc. for the Adv. of Science, Dunedin, 1904, p. 69. There is also an uncertainty due to the application of a formula to radiation from an assemblage of points which is really only applicable to a plane wave, or a stream moving normally to the plate. If a point source of radiation is placed below an absorbing plate of thickness d, and there is a true coefficient of absorption λ, the fraction that emerges from the further side of the plate is not $e^{-\lambda d}$; much of the radiation passes obliquely through the plate and is absorbed to a greater degree than that which passes normally. This has often been pointed out, *e.g.*, by N. R. Campbell (Phil. Mag. April 1905, p. 541), who also gives some figures from which the proper curve of absorption may be drawn. I am not aware, however, that it has been noticed that the form of the absorption curve, which is far from an exponential curve for a thin radiating layer, approximates much more closely to it for a thick radiating layer. And it is interesting to find that the experimental curves which are most nearly exponential are those for which the layers of radioactive material were thick compared to the penetration of the rays under investigation. As examples, we may take those of uranium and actinium already mentioned. On the other hand, the curve which H. W. Schmidt (*Ann. d. Phys.* Bd. xxi. 1906, p. 651) has obtained for the β rays of RaC, the radioactive material being deposited in a very thin layer on metal foil, shows just about the amount of departure from the exponential form which is to be expected if the absorption is truly exponential, and there is only one absorption coefficient, not two, as Schmidt has suggested.

The following figures give the proportional amount of the original radiation which passes through a plate of thickness n/λ, where λ is the absorption coefficient: (1) for a thin layer; (2) for a thick layer. The figures are also given, for the sake of comparison, for the case of a plane wave, or a pencil of rays passing through the plate normally:—

n.	Radiation from thin layer.	Radiation from thick layer.	Plane wave (purely exponential).
0	1·000	1·000	1·000
·1	·723	·831	·905
·2	·573	·702	·819
·3	·467	·600	·742
·4	·387	·510	·671
·5	·323	·437	·607
·6	·274	·378	·548
·7	·235	·328	·498
·8	·200	·283	·450
·9	·171	·248	·405
1·0	·145	·214	·368

The absorption of a material used in a thin sheet naturally appears greater than the absorption when the thickness of material is increased, because the rays which are moving obliquely are absorbed first.

The absorption of γ and X rays appears to follow a purely exponential law so far as experiment has been made. The δ rays are absorbed by molecules immediately on their production.

Having thus discussed certain properties of the various rays which do exist, it seems interesting to make an attempt at the estimation of the properties of some rays which might exist, though the fact has not been proved as yet. Radioactive substances emit both positive and negative particles. It does not seem at all out of place to consider the possibility of the emission of neutral particles, such as, for example, a pair consisting of one α or positive particle and one β or negative particle. The recent additions to our knowledge of the laws of absorption of α and β particles give us some grounds on which we may attempt to found an estimate of the properties of such pairs.

We know that the α particle moves in a rectilinear course throughout its whole range, and passes through the atoms which it encounters without deflexion. It does not pursue a course which is straight on the whole, but zigzag in detail; the direction and amount of a particle in motion are the whole characteristics of that motion at any instant, and no memory of any previous motion exists. If, therefore, a particle pursues a straight line in its motion as a whole, it must keep to that line entirely and make no excursions from side to side. We must, therefore, suppose that an atom, or at least an α particle, endowed with sufficient speed, can pass directly through another atom without appreciable deflexion. The α particle loses speed as it penetrates atoms in this way; and there can be little doubt that its charge, that is to say, the field which is about it, is a main cause of this loss of energy. But if a β particle is associated with the α particle so that the tubes of induction pass from one particle to the other, and the field is greatly contracted, it would seem that the chief cause of the stopping of the α particle has been removed *. The penetrating power of a pair might be very great indeed, and its ionizing power correspondingly reduced; for, although there does not seem to be a direct connexion between energy spent and ionization produced, there can be no doubt that the two are simultaneous. The limitation of the field of the pair would depend on its moment; if the latter were small, that is to say, if the positive and negative were close together, the field would be more circumscribed. It is, therefore, possible to provide for

* See also Rutherford's 'Radioactive Transformations,' p. 272.

pairs to have varying penetrating and ionizing powers; a pair of small moment being a good penetrater but a bad ionizer. Such a pair would be incapable of deflexion by magnetic or electric fields, and would show no refraction. It is conceivable that it might show a one-sided or polarization effect, for if it were ejected from a rotating atom it would itself possess an axis of rotation.

When X-rays were first investigated, and again when γ rays were discovered, it was often suggested, in each case, that the radiation might consist of material particles. Röntgen himself proposed in the third of his memoirs a theory of this nature. But it was always felt that the difficulty of accounting for the great penetration of these radiations was insuperable. It seems now that this difficulty was quite exaggerated, and even imaginary. It does not appear out of place, therefore, to reconsider the position in the light of the more recent knowledge.

Assuming, then, that the neutral pair has great penetrating, but weak ionizing powers, is uninfluenced by magnetic or electric fields, and shows no refraction, it does so far conform to the properties of the γ ray. And, further, if it has any moment at all, and therefore any external field, it may at last suffer some violent encounter which will resolve it into a positive and a negative, an α and a β particle. Of these the β particle would be the one possessed of much the greater velocity, and would appear as a secondary ray. Thus, in the neighbourhood of the point of impact, an ionization would appear of much greater intensity than anything produced along the track of the pair itself. So Becquerel has found the action of the γ rays on a photographic plate to be almost entirely due to the secondary rays which they produce. On this view the appearance of the β secondary ray would be really a scattering of the incident ray; and this would make the γ ray fall into line with other radiations whose secondary radiations are either scattered primary or δ rays.

If the gradual disappearance of a stream of γ radiation were caused by collision in this way, the number disappearing in any unit of length of the course would be proportional to the total number in the stream, so that an exponential law would result.

It appears, therefore, that all the known properties of the γ rays are satisfied on the hypothesis that they consist of neutral pairs.

If the γ ray is material and contains an α particle, this fact must be considered in reckoning the number and magnitude of the steps from the atomic weight of radium to that of lead.

It has been suggested to me by my colleague Dr. Rennie that the rayless changes of Ra may really be accompanied by the emission of neutral pairs of very small moment. This adds another unknown factor to the calculation. The energy involved in such emissions might be quite small, and, moreover, if pairs can be taken up into atoms, so as to form new atoms, the whole of the energy may not appear as heat.

It is interesting to carry the speculation a little further and to observe that a pair possessing a very circumscribed field might cause little or no ionization, and be capable of very great penetration. Its end might be incorporation with an atom traversed: Professor Rutherford has suggested to me that such a fate may befall the α particle at the end of its range. On this view it would be possible for a portion of a disintegrating atom to break away, to pass over an appreciable distance, and finally to become part of another atom, the atomic weight of which would be thereby increased. Internal atomic energy might be transferred at the same time. For if we suppose that it is possible for some of the internal energy of an atom to be set free, and recent discoveries seem to compel the supposition, then we must also consider it possible for atoms to withdraw energy from circulation and add it to their internal store. If, therefore, the handing of neutral pairs from one atom to another is a process which actually occurs, then matter and energy may be continually transferred from atom to atom without our being aware of it: the whole operation may take place in a world apart. We cannot follow it by radioactive tests, for the ionization may be so feeble; nor chemically, because the quantity of atomic change may be so slow; nor thermally, because the energies appear at no stage in tangible form.

Since the properties of γ rays are amongst the properties of X rays, an hypothesis which will suit one form of radiation will also so far suit the other. But we know much more about the latter form of radiation than we do about the former. It is of interest, therefore, to consider the extent to which our additional knowledge can be fitted to a neutral pair hypothesis. It is true, of course, that the æther pulse theory has been most ably developed, and is now widely accepted. Nevertheless the evidence for it is all indirect: and indeed some of it is, I think, a little over-rated. It is quite possible that æther pulses may not, after all, constitute the bulk of Röntgen radiation. If, therefore, there is anything to be said in favour of any other hypothesis, it seems right that it should be said and considered.

Let us therefore for the moment suppose the X rays to consist mainly of a stream of neutral pairs.

We have at once an explanation of the absence of deflexion in electric and magnetic fields, and of regular reflexion and refraction. There should be great penetration, whose amount might vary with the moments of the pairs, or the velocity, if the latter were a variable. We can understand that a pair which struck a light and yielding atom might be returned unchanged: yet if it struck a heavier and more resisting atom it might be disarranged so as to acquire a greater moment, and thus to become a better ionizer, but more readily absorbed. Or it might be shattered altogether, giving rise to a secondary ray of the cathode type. The softer the ray, *i. e.* the greater the moment of the pair, the more readily might this be done, and the lighter the atom that would do it. (See J. J. Thomson on Barkla's researches, 'Electrician,' April 5, 1907.)

In order to explain these known effects on the æther-pulse theory it is necessary to suppose that in light atoms the corpuscles are not appreciably acted on by forces due to other corpuscles, but that in heavy atoms there is a strong influence of this kind. In the former case, the thickness of the secondary pulse is the same as that of the primary: in the latter it is not. It is also necessary to suppose that when the atom is heavy enough to cause a modification of the primary radiation, it differs from a light atom in such a way that the pulse can cause cathode particles to be ejected at a speed due to thousands of volts: whereas this is impossible with light atoms.

If the cathode particles in the X-ray tube so affect the motion of an atom which they strike as to make it throw off a pair, then the plane of rotation of the pair will be the same as that of the atom from which it has come, and will contain the direction of the translatory motion of the pair. The pair will therefore be able to show polarization effects. And if such a pair falls upon a reflecting surface, it is not unreasonable to suppose that it is liable to be taken up only by an atom revolving in the same plane, and sometimes to be ejected again. Thus its subsequent rotation and translation will continue to take place in the one plane. The tertiary ray will therefore be strongest when it is in the same plane as the primary and secondary; and this is Barkla's polarization effect.

If the X ray is an æther pulse, it is difficult to understand why the spreading pulse affects so few of the atoms passed over ('Conduction of Electricity through Gases,' pp. 294–297), why the high-speed secondary cathode rays are ejected with a velocity which is independent of the intensity of the pulse, and why it should be able to exercise ionizing powers when its energy is distributed over so wide a surface as that of a sphere of say 10 or 20 feet radius. All these phenomena are more simply explained if we suppose the ray to be a neutral pair which has only a local action, *i.e.* can only affect the molecules on its path, which can penetrate to great distances in air, losing little speed as it goes, and which gives rise to a cathode ray when it is broken by impact.

It seems to me that the material-nature hypothesis shows to advantage when we consider the secondary radiation of the X rays. The rays cause the emission of cathode rays whose speed averages about 5×10^9 (Dorn). We have no experience of any æther wave causing the emission of any but δ rays, *i. e.*, electrons with a speed of about 10^8. It can hardly be said that differences in intensity of the æther pulse can account for this remarkable contrast. For the speed of the δ rays caused by ultra-violet light has been shown by Lenard to be independent of the intensity of the light; and the velocity of the X-ray secondary radiation does not depend on the intensity of the X rays. It may be argued that the breadth of the pulse is the prime factor, on the grounds that Lenard found the velocity of the δ rays due to ultra-violet light to depend somewhat on the nature of the light; but it is hard to believe that a diminution of the width of the pulse, no matter how extreme, can increase the energy of the ejected electron about a thousand times.

But if we regard the secondary radiation as the result of the break-up of a neutral pair, the high velocity of the ejected electron (5×10^9) may be more readily explained. The action must be entirely different from that of ultra-violet light.

It is difficult to found any arguments for or against either theory on considerations of the relative energies of the original cathode stream, the X rays, and the secondary rays. For if the energies of any transformation do not balance, it is easy to square the account by postulating either some release of the internal energy of the atom, or the reverse, viz. the absorption of energy by the atom involving a disappearance of the visible energy. On the neutral-pair hypothesis the cathode rays would probably have a trigger action, and the pairs would draw their energy from that internal to the atom: it might not be necessary to invoke the aid of internal atomic energy in order to account for the energy of the secondary radiation. In the case of the æther-pulse theory it is necessary to suppose that the secondary radiation derives its energy from the atom's store ('Conduction of

Electricity through Gases,' p. 321). It is not clear whether such a call must also be made at the transformation of cathode into X rays. The whole question, taken into conjunction with the diffraction experiments of Haga and Wind, has lately been under discussion by Wien (*Ann. d. Phys.* xviii. p. 991, 1905; and xxii. p. 793, 1907) and van der Waals, Jr. (*Ann. d. Phys.* xxii. p. 603, 1907): but no definite conclusion is reached.

It is not easy to see how the irregular stoppage of the cathode particles can give rise to pulses of sufficient definition and uniformity to show diffraction. It would be easier to explain such an effect as the result of uniform disturbances arising when pairs of uniform nature are torn from the atoms of the anode.

On the æther-pulse theory hard X rays are supposed to be thin pulses, soft rays to be thick pulses. Swift cathode particles are supposed to take less time in deflecting and stopping than slower particles, and therefore to give rise to thinner pulses. On the other theory we must suppose that the rays are hard when the moments of the pairs are small: or possibly that hardness is due to high velocity. If the former is the case, it may be that fast cathode particles spend less time within the anode atoms than the slow ones do, and therefore disarrange the pairs less before they are ejected.

There is another entirely different argument, which seems to support the neutral-pair hypothesis.

The α, β, and γ rays all ionize the gases which they traverse. It has just been shown by Kleeman * that the ionization per atom due to β and γ rays is nearly proportional to the ionization per atom due to α rays (and, therefore, approximately proportional to the volume as I have shown, Proc. Roy. Soc. of S. A., Oct. 1906; Phil. Mag. March 1907). The figures for the heavier atoms are rather larger for the β than the α rays, and still larger for the γ rays. It is known that the ionizations due to X rays differ considerably from those due to γ rays when the X rays are soft; but approximate to them when the X rays are hard.

All this fits in excellently with the theory that all four types of rays are material. Take the α particle first, since its circumstances are the most simple. It moves directly through the atoms, without scattering or transformation.

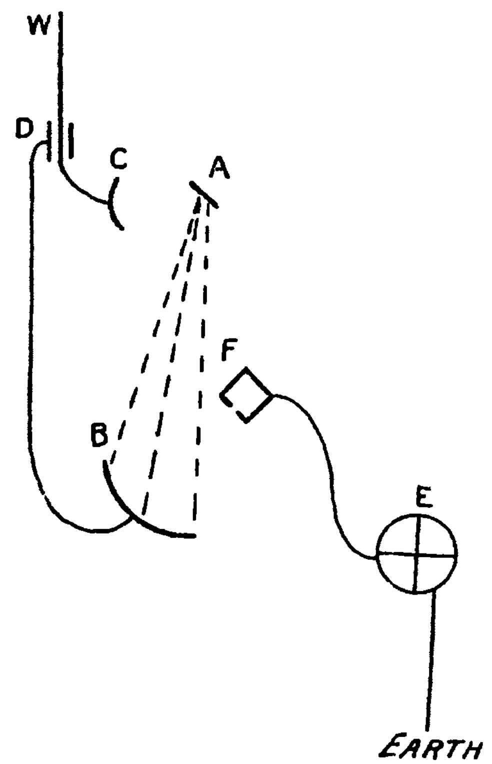
* Mr. Kleeman has been good enough to inform me of his results by letter; but I believe I am at liberty to quote them, since he has, I understand, recently read a paper on the subject before the Royal Society.

It liberates ions in the form of δ rays as it goes, approximately according to the volume law. The β ray is also a charged particle, and it is readily to be supposed that it would, if its whole motion were rectilinear, liberate ions according to the same law (comparing atom with atom) as the α particle, though the numbers would be less. But the β particle is liable to scattering, and each act of scattering generally implies an increase in the length of the particle in the gas, and increased ionizing power since its speed is a little diminished. Now, scattering is proportional to the atomic weight, whilst the ionization is more nearly proportional to the square root of the atomic weight. Thus a heavy atom is the cause of more than its proper amount of ionization; and so we find in Kleeman's table that the ionizations of the atoms Cl, Br, and I are rather higher than in the case of the α particle. Again, the γ particle is liable to resolution into its elements, with a relatively large amount of ionization. Since this transformation is chiefly effected by impact with heavy atoms, these latter will be the cause of a disproportionately large ionization, as compared with the α rays; and this is also shown by Kleeman's figures. Passing on to X rays, we find a further illustration of this effect, until we come to very soft rays, when we find that the heavy atoms are the occasion of exceedingly large ionization ('Conduction of Electricity through Gases,' 2nd ed. p. 300). There is a good continuity in all these phenomena, with gradual divergences just where we should expect them. The α, β, γ, and X rays all produce the same primary ionization, comparing atom with atom, and differ only in the effects due to scattering and transformation; that is to say, differ only as regards their production of secondary ionization. Now, the α and β rays are certainly material particles, possessing electric fields. There is, therefore, a reasonable argument that the γ and X rays are also material, and possess electric fields. This is the case if they are pairs, and the smaller the moments are the more circumscribed are the fields and the less the ionization and the loss of energy.

If the X rays contain æther pulses only, it is difficult to see why their effects should run so exactly in parallel with those of the α and β rays.

It has been announced by Marx, as the result of a most ingenious experiment (*Phys. Zeit.* 1905, p. 268), that Röntgen rays move with the velocity of light. It is extremely improbable that material particles can possess such a velocity: and the experiment of Marx might seem at first sight to be strongly against any material nature of the X rays. But it is not clear that Marx really measured the velocity of a radiation causing the emission of high-speed electrons, which is the characteristic feature of X rays: all that he showed was that the bundle of X rays contained radiation capable of exciting δ rays. To see this it is necessary to consider briefly the details of the experiment.

An electric pulse is made to travel along a wire, W, as shown in the accompanying sketch. When it reaches the



cathode, C, cathode rays are driven against the anode, A, and X rays are given out, some of which travel towards the saucer-shaped electrode, B. At the focus of B is a small Faraday cylinder, F, connected to an electrometer, E. A small impulse is derived from the wire, W, by electrostatic induction at D, and travels down to B. If the various distances and wire-lengths are properly adjusted, so that the X rays arrive at B at the same moment as the derived impulse, electrons are liberated at B by the rays, and guided by the impulse into the cylinder, F, and thence to the electrometer. If now the distance of the X-ray bulb from B is altered, say, by an increase of 10 cm., the wire from D to B has to be lengthened by 10 cm. Thus, according to Marx, the X rays travel with the same velocity as the impulse in the wire, and therefore with the velocity of light.

But it is to be remembered that the electrons which are liberated by X rays have an initial velocity averaging about

5×10^9 per sec., *i. e.*, a speed due to thousands of volts, and are scattered in all directions from the surface on which the rays fall. Neither the weak impulse applied to B by the wave coming along the wire, DB, nor the peculiar form of the surface, B, could have any sensible effect in the way of guiding these fast-moving electrons into the cylinder, F. Only slow-moving electrons or δ rays could be guided by such means. It is no doubt true that X rays do liberate a certain number of δ rays, but it is clear that the experiment of Marx is quite consistent with the hypothesis that the X rays are complex, and consist in part of æther pulses travelling with the velocity of light, and producing δ rays, and in part of material particles, or pairs, travelling at a speed as yet undetermined, and exciting high-speed cathode rays. It would be reasonable to expect that a stream of pairs should be accompanied by æther pulses which had their origin at the time and place where the pairs broke away.

It is possible that the example of the α particle shows that a pair cannot possess a velocity greater than 10^9, since at a higher speed it would be stripped of an electron, and become an α particle. J. J. Thomson has suggested that at this critical speed the α particle becomes electrically neutralized by the attachment of an electron. Presumably such a pair would then go on as a γ ray. No such consequence has been observed; and on the present hypothesis it would be better to suppose that the α particle ends its career by being taken up by an atom, as Rutherford has suggested. There is no reason to suppose the γ ray or X ray to possess any great speed, so as to give it enough penetrating power. The latter might depend rather on the limitation of the field of the pair; and a sufficient range for the velocity can be found between the minimum speed of the α particle and the maximum speed necessary for penetration, which appears to be about 10^8 for a charged particle, but may be less for one without charge. A moderate speed would account for the reflexion or scattering of the X ray, and would indeed be necessary for this purpose.

To sum up, it is clear that a stream of X rays contains some æther pulses, but it is not easy to explain all the properties of X rays on the æther-pulse theory. The explanations are easier if the rays are supposed to consist mainly of neutral pairs; and the existence of such pairs is not improbable *a priori*.

Added July 18.—Since this was written several important papers have appeared, with which the outlined theory seems to me to be in harmony,

I have supposed it possible for positive electrons to be detached from atoms of matter in the X-ray tube, and to be sent out in company with negative electrons, one of each going to the formation of a neutral pair. Now J. J. Thomson has just shown (Phil. Mag. May 1907) that the canal-rays consist of positive electrons, which may be H or H_2 or He, according to circumstances; and that these appear no matter what the material is in the tube. It will be remembered that Villard (*Ions*, *Electrons*, *Corpuscules*, p. 1022) was so impressed with the continual presence of hydrogen in vacuum-tubes, that he supposed the cathode particles to consist of hydrogen, until accurate measurements of the mass and velocity of the particles were made. He was largely influenced by the reducing action of the rays. After all, it may be that H is produced where they strike, and that Villard's observations can be explained in this way. Sir William Ramsay (Journ. Chem. Soc. May 1907) has shown that there is an excess of hydrogen in water decomposed by radium emanation; but the circumstances are too complicated to make the connexion more than a possibility at present.

H. W. Schmidt has arrived at the conclusion (*Phys. Zeit.* June 1907) that the "secondary" radiation caused by β rays striking aluminium consists of scattered primary rays: this is in agreement with the argument stated above. He has also shown that undeflected β particles lose no speed in passing through a metal plate. This implies either that the energy required to produce ions does not come from the β particle or that the β particle does not produce ions until it is deflected. There seem several difficulties in the way of the latter supposition: though it is of course a possibility. It seems to me probable that the β particle rarely produces more than one ion from a traversed molecule, but that an α particle may produce many: and that initial recombination is to be explained in this way. Kleeman has pointed out, in his Royal Society paper, that an α particle which has lost several ions has not yet been observed; but it is to be remembered that such a molecule would probably dissociate at once, and it is well known that the α particle does produce dissociation.