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ART. XI.—*On the Velocities of Delta Rays*; by H. A.
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§ 1.

THE name "delta rays" was given by Sir J. J. Thomson in 1905 to the slow electrons which he found to be emitted by polonium, and which had previously masked the positive charge of the α -rays. Shortly afterward, and independently, Rutherford discovered a similar emission from radium and showed that it was not confined to the source of α -rays, but took place from any body which was struck by them. Some writers have made a distinction between these two phenomena, restricting the name delta rays to those which are emitted by the source of α -rays and calling the others secondary rays. There appears, however, to be little ground for this distinction; there is no appreciable difference between the two kinds of rays, and everything goes to show that Rutherford was right in his original suggestion that all δ -rays are secondary phenomena, due to the impact of α -rays upon matter. In the present paper, therefore, the name will be used in this sense.

The question of the velocity of the δ -rays has been attacked by a number of investigators.* They have all agreed that a large proportion of the rays have velocities which are small, as electronic velocities go, not very different, in fact, from those which are observed in the photo-electric effect. The estimates by different observers of the maximum velocity of the rays have been discordant; they have varied from zero to $3.9 \times 10^8 \frac{\text{cm}}{\text{sec}}$, the latter corresponding to a fall of potential of about 42 volts.

* For a historical sketch of the subject see Campbell, *Jahrb. d. Radioaktivität und Elektronik*, ix, p. 419, 1912.

Last year it was shown by Dr. McGougan and the present writer* that electrons were present in a beam of δ -rays which had much greater velocities than any of the above estimates; an opposing potential difference of 1700 volts was not sufficient to stop all of them, and very marked effects were produced by electrons having velocities corresponding to several hundred volts. The present paper contains the results of some further experiments upon these swifter rays. It will be seen that there is no gap between the swifter and the slower electrons, but that all intermediate speeds are found between the highest and the lowest. It seems reasonable, therefore, to include under the name "delta rays" all the electrons which are projected from the atoms of bodies by the direct action of the α -rays, the recently discovered swift ones as well as the slower ones previously known; this nomenclature will be adopted in the present paper. It is, however, to be observed that some, at least, of the slower electrons (under 10 volts) must be caused, not directly by the α -rays, but by the swifter δ -rays. When there is occasion to refer to these they will be called *tertiary rays*. It is impossible at present to make a sharp distinction between the slower δ -rays and the tertiary rays which come from the source of δ -rays, or to determine the proportion of each; so that in all numerical estimates the tertiary rays must be included among the δ -rays.

§ 2.

Tertiary electrons are emitted also by any body on which δ -rays fall and in numbers considerably in excess of the swifter δ -electrons which cause them. When an electric field is used to hold back the slower δ -electrons, this is the most conspicuous effect of the remaining swift rays; for the field which opposes the δ -rays assists the tertiary electrons to escape, and their larger number magnifies the experimental effect. The unsuspected presence of this phenomenon has undoubtedly had an influence upon the results obtained in previous experiments upon δ -rays, and helps to explain the discrepancies which have appeared in the work of different investigators.

Unfortunately this effect, which is easy to observe and measure, does not lend itself readily to a quantitative study of the swifter δ -rays. The number of secondary electrons, due to a single incident electron, varies markedly, and not in a very simple way, with the speed of the latter.† In a beam of δ -rays one has a complex of electrons of many different speeds, and when the opposing electric field is, for example, increased, the

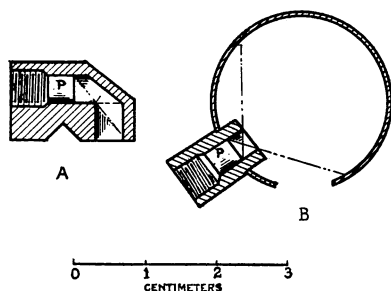
* Bumstead and McGougan, this Journal, xxxiv, 309, 1912; Phil. Mag., xxiv, 474, 1912.

† Gehrts, Ann. d. Phys., xxxvi, 1000 et seq., 1911.

slower of these are eliminated and all the remaining ones have their velocities reduced ; under these circumstances it appears quite impossible to draw any conclusions as to the variation in the number of incident δ -rays from observations upon the tertiary electrons.

In attempting to determine the distribution in velocity of the swifter δ -rays, the essential thing, therefore, is to eliminate the effects due to the tertiary electrons. The first method by which I attempted to do this was to receive a beam of δ -rays in a Faraday cylinder, the whole arrangement being in a very high vacuum. Two different forms were tried for the source of the δ -rays ; (A and B, fig. 1). In both of these the α -rays from

FIG. 1.



the polonium, P, struck the inner walls of a small brass chamber ; a hole in this chamber was placed so as to allow some of the δ -rays to escape but none of the α -rays. The beam of δ -rays issuing from this hole was caught in a Faraday cylinder after passing through an opposing electric field ; there were suitable diaphragms and earthed screens about the Faraday cylinder. But although I had in the neighborhood of a millicurie of polonium, the arrangement was not sensitive enough to do more than indicate the presence of the swifter rays, certainly not to measure them. Only a small fraction of the δ -rays generated in the chamber escaped through the hole, and, even so, the beam was so divergent that the Faraday cylinder had to be rather large (5.5×4^{cm}) ; thus its electrostatic capacity was considerable and one could not gain any advantage by substituting a sensitive electroscope for the quadrant electrometer.

The next attempt was by insulating the source (either A or B) from the case and connecting it to the measuring instrument ; as its capacity was small, an electroscope could now be used to advantage. A negative potential applied to the case would send back to the source all the electrons whose kinetic

energy was not sufficient to overcome the opposing potential difference. Here the difficulty was to prevent the tertiary electrons, set up by the impact of the δ -rays upon the case, from being carried to the source by the electric field. I first tried to obviate this by means of a magnetic field. A long cylindrical case was used (the one shown in fig. 2), with the source of δ -rays near the top and the rays striking the bottom and the lower part of the sides of the case. A magnetic field of about 50 gauss was applied to this part of the case. To prevent this field as much as possible from having an effect upon the emission of the δ -rays themselves, the source was inclosed in a sort of upper chamber made of a plate and a ring of soft Norway iron, 1.5^{cm} thick; (this is not shown in fig. 2). A tapered hole in the plate allowed the beam of δ -rays to pass into the lower chamber; both chambers were coated with soot. Preliminary measurements of the magnetic field in the upper chamber by means of a swinging needle showed that, with a field of 50 gauss near the bottom of the case, the field near the source was not more than 0.5 gauss.

This method was not wholly unsuccessful. In a charcoal vacuum which had been maintained for several days, the source lost negative electricity in the face of an opposing potential of 300 volts, but beyond that it acquired a negative charge. The form of the relation between current and potential for the lower voltages was quite similar to those obtained later with the final form of apparatus; with potentials over 250 volts, however, the effects of the tertiary electrons began to be conspicuous. Moreover, on account of the limited beam of δ -rays the values of the currents were small and necessitated the use of a very sensitive, and consequently troublesome, electro-scope.

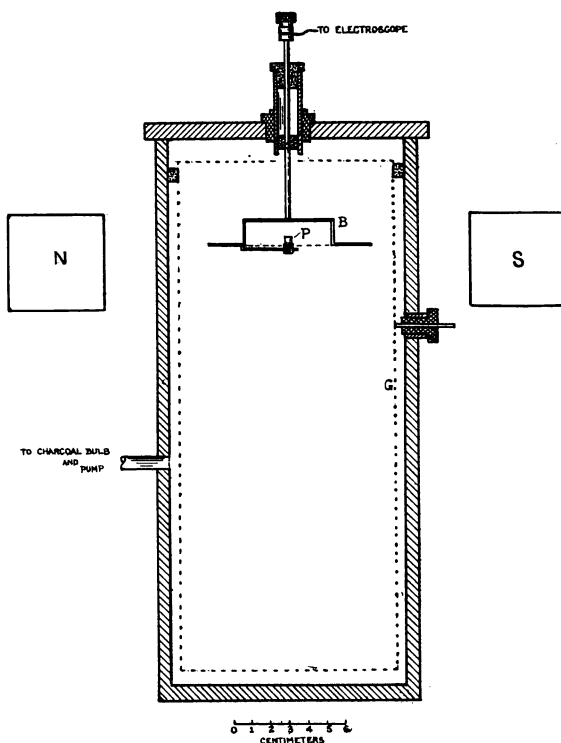
§ 3.

The final form of the apparatus is shown in fig. 2. The source of δ -rays is the shallow, open, cylindrical box, B, made of brass; in some of the later experiments, in which a magnetic field was used, the box was surrounded by a flat ring of brass, as shown in the figure, giving to the source the shape of a sailor's hat. Below, and opposite the middle of this box, a thin brass arm supported a cylindrical copper plug, P, with a deposit of polonium on its upper surface, which was 4^{mm} in diameter.* The end of this plug projected into the box so that none of the α -rays escaped, but fell upon the top and

*I am again indebted to Professor Boltwood for the polonium used in these experiments. For three successive years he has most kindly supplied me with the annual crop of polonium grown from a preparation of radio-lead in his possession.

sides of the box; the open character of the latter and the smallness of the obstacle presented by the polonium and its support enabled a large proportion of the δ -rays and tertiary rays to get away. This source was enclosed in a large, cylindrical brass case which could be highly exhausted by the help of charcoal and liquid air; the charcoal bulb was placed between the evacuated chamber and the pump and gauge, and

FIG. 2.



was so constructed as to free the chamber of mercury vapor by its distillation into the cold bulb. Within the case and $\frac{1}{2}$ cm from its walls was a cylindrical cage of bronze wire-gauze which was insulated from the case and could be separately charged by means of an external electrode. It was found to be important that the insulators supporting the cage should not be struck by the δ -rays; if they were, they acquired charges which gave rise to erratic results. Accordingly the cage was supported by three small pieces of ebonite near the

top, and out of the path of the δ -rays. The gauze had 5.5 meshes to the centimeter; of its entire area 83 per cent was open, the remaining 17 per cent was occupied by the wires.

The rod which supported the source, B, was insulated from the case and provided with an earthed guard-tube in the usual manner. It was connected to the gold-leaf of a sensitive electroscope of the Hankel type which has been previously described.* The magnitude of the effects obtained, even when all the slower δ -rays were stopped, was such that the electroscope could be used at the very moderate sensitiveness of 200 divisions per volt. Under these circumstances the deflections were strictly proportional both to potential and current over the whole range of the eye-piece scale in the microscope (100 divisions); the sensitiveness remained quite constant, so that there was no need of continual checking up by means of a potentiometer. When changes in the zero position occurred they were slow and steady and could easily be taken into account, and they caused no alteration in the sensitiveness; often the zero would not vary more than one or two divisions in an entire half-day's work.†

On account of the emission of δ - and tertiary rays, the source as soon as it is insulated acquires a positive charge which increases with the time. When there is no opposing field this charge is far too great to be measured with the arrangements described above. When the case and cage are both charged to the same negative potential, all the electrons, whose kinetic energy is less than the work which this potential can do upon an electron, are returned to the source and only the swifter ones escape; thus the rate at which the source acquires a positive charge is diminished. When, however, the negative potential applied to the gauze and case is more than about 25 volts, the source begins to acquire a *negative* charge, which (as the negative potential is increased) soon reaches a maximum and then steadily decreases; this continues up to, and beyond, 2000 volts. This effect has been shown to be due to the emission of tertiary electrons by the case when struck by the swifter δ -rays; the tertiary electrons are returned to the source of δ -rays by the field, and, as they exceed in number the δ -rays which produce them, the source acquires a resultant negative charge, which falls off, however, as more and more δ -electrons are restrained from reaching the case.‡

* Bumstead, this Journal, xxxii, 403, 1911; Phil. Mag., xxii, 910, 1911.

† In order to secure fair steadiness of the zero reading, it is necessary to protect any sensitive electroscope against sudden changes of temperature. With the electroscope mentioned, satisfactory protection is given by covering it with felt about $\frac{1}{4}$ inch thick, and by setting it up in a wooden box (with an open front), to keep off drafts in some degree. A glass window in the back of the box admits light to the gold-leaf.

‡ Bumstead and McGougan, I. c., § 3.

It was for the purpose of eliminating, if possible, this complication that the wire-gauze cage was introduced as a substitute for the magnetic field mentioned in § 2. Retarding fields may be set up by putting negative potentials on the gauze while the case is kept grounded. As the tertiary electrons have small velocities, those which are set up at the surface of the case, by the δ -electrons which have surmounted the field and passed through the meshes of the gauze, will not get back to the source on account of the field between the gauze and the case.* The electric force is much greater between gauze and case than between gauze and source, (though the potential difference is the same) because of the smaller distance; thus a considerable fraction of the tertiary electrons which originate on the wires of the gauze itself will be captured by this field and will not get to the source of δ -rays. As the case and source are always kept at zero while the potential of the gauze is changed, the *shape* of the lines of force, in the neighborhood of the wires of the gauze and within its meshes will not change, and it seems reasonable to assume that a nearly constant fraction of the tertiary rays originating upon the gauze will be captured in this way, and that the number which get back to the source in any case will be a small part of the total set up by the δ -rays on case and gauze together.

§ 4

With the case grounded and with various negative potentials on the gauze cage, readings of the electroscope gave the charge acquired by the source in a given time, usually one minute. It was soon evident that the readings thus obtained varied greatly with the time which had elapsed since the production of the vacuum. Three hours after the liquid air had been applied to the charcoal bulb, a negative potential of 40 volts on the gauze was sufficient to give a slight negative charge to the electrode (the source of δ -rays, B, fig. 2); and larger negative potentials caused a marked increase in this negative current. (See Curve I, fig. 3). As time went on, however, these effects were much altered; positive currents were observed with negative potentials on the gauze greater than 300 volts, and the negative currents at the higher potential were much diminished in magnitude. The results of four series of observations are given in Table I and shown graphically in fig. 3.

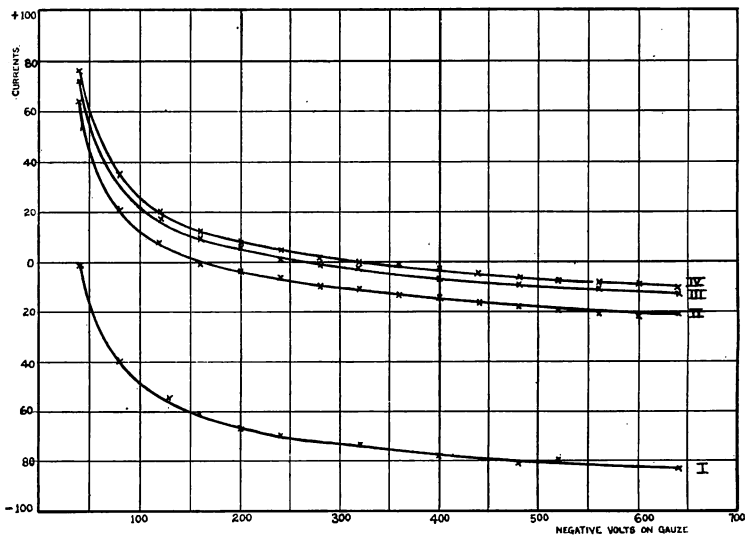
* This method has been several times used to prevent the reflection of slow electrons in experiments upon cathode rays and on the photo-electric effect. v. Baeyer, *Phys. Zeitschr.*, x, 174, 1909.

TABLE I.

| Volts | I (3 hrs.) | II (22 hrs.) | III (46 hrs.) | IV (66 hrs.) | II-I | III-I | IV-I |
|-------|------------|--------------|---------------|--------------|------|-------|------|
| - 40 | - 0.3 | + 63.6 | + 72.7 | + 76. | 63.9 | 73. | 76.3 |
| - 80 | -39.7 | +21.5 | +33. | +34.5 | 61.2 | 72.7 | 74.2 |
| -120 | -54.7 | + 8.3 | +18. | +20.5 | 63.0 | 72.7 | 75.2 |
| -160 | -61.3 | + 1.4 | +10. | +13.5 | 62.7 | 71.3 | 74.8 |
| -200 | -67.5 | - 3.5 | + 6. | + 9. | 64.0 | 73.5 | 76.5 |
| -240 | -70. | - 6.2 | + 1.7 | + 5.5 | 63.8 | 71.7 | 75.5 |
| -280 | | -10. | - 1.0 | + 2.8 | | | |
| -320 | -74. | -10.7 | - 2.8 | 0. | 63.3 | 71.2 | 74. |
| -360 | | -13.4 | | - 1. | | | |
| -400 | -78.4 | -14.5 | - 7. | - 3. | 63.9 | 71.4 | 75.4 |
| -440 | | -16. | | - 4. | | | |
| -480 | -82.2 | -17.8 | - 9. | - 6. | 64.4 | 71.2 | 76.2 |
| -520 | -79.7 | -19.6 | | - 7. | 60.1 | | 72.7 |
| -560 | | -21.4 | -11. | - 8. | | | |
| -600 | | -22.2 | | - 9. | | | |
| -640 | -85. | -21.5 | -13.2 | -10.5 | 63.5 | 71.8 | 74.5 |

In the table, the first column gives the negative potentials applied to the gauze cage; the second, third, fourth, and fifth give the currents (in arbitrary units) observed at 3, 22, 46, and 66 hours, respectively, after the application of the liquid air; the remaining columns give the differences between these currents.

FIG. 3.



It will be observed that these differences are constant, and that the four curves of fig. 3 have the same form and are merely shifted vertically on the diagram. It is quite clear that we have here the resultant of two effects, the first independent of the time since the vacuum was made, and depending upon the applied potential, while the second is independent of the potential, but does vary greatly with the time. The first effect is plainly due (at least in great part) to the escape from the source, B, of the swifter δ -rays, thus giving it a positive charge, which is decreased as larger opposing potentials are applied to the gauze. The second phenomenon causes the source to gain negative, or to lose positive, electricity at a rate which is independent of the potential beyond 40 volts; and its variation with the time shows that it must be due to residual gas—either that which occupies the volume of the chamber, or that which is condensed upon its walls and on the electrode.

It seemed desirable first to investigate the nature and cause of the second effect. When the apparatus was in the condition which gave the upper curve (IV) in fig. 3, the liquid air was removed from the charcoal, and a small quantity of air admitted to the chamber so that the pressure rose to 0.2^{mm} . This was allowed to remain for about 15 minutes, when exhaustion was recommenced, while the charcoal bulb was heated in the usual manner. When the pressure had fallen to 0.003^{mm} , the liquid air was again applied. Three hours later a series of measurements was taken, the results of which were between those represented in Curves II and III, fig. 3. This shows that the effect in question is not due to a volume ionization of the residual gas. For the amount of gas in the chamber three hours after the application of the liquid air could not have been very different from that which was present when Curve I was taken. On the other hand, the surface films on the metals might well be different after a brief exposure to a pressure of 0.2^{mm} from what they were after a prolonged exposure to atmospheric pressure. In another experiment, air at atmospheric pressure was allowed to stand in the chamber for two days; upon re-exhaustion, the same behavior was observed as that shown in fig. 3. It seems clear therefore that the effect is due to the presence of surface films which are removed only very slowly in a high vacuum and probably not completely removed in any case.

The next question to be considered was whether the negative charge upon the electrode was due to electrons coming to it from the gas film on the case and gauze or to positive ions lost by the film on the electrode itself. To determine this a magnetic field was employed. The core of the magnet was a bar of soft iron 2 inches square in section, bent so as to form

three sides of a rectangle. One side of this rectangle, 21^{cm} long, was surrounded by the magnetizing coil; the other two sides, 18^{cm} long, embraced the case, as shown in fig. 2, and formed long, narrow pole pieces. Along these pole pieces, from their ends nearly to the magnetizing coil, the field was fairly uniform, not varying more than 10 per cent, when measured by a fluxmeter. In the other two directions at right angles to this, the variation of the field was rapid on account of the spreading out of the lines of force in the large air-gap. With a current of 5 amperes, for example, the field near either pole-piece was 530 gaussses, while half-way between them, and in their plane, it was 250. The field at any one point was nearly proportional to the current in the coil from 1 to 8 amperes. Before using the magnetic field, the brass box which served as the electrode and the source of δ -rays was provided with the brass ring shown in fig. 2 (forming the brim of the "hat"), which had not been present in the preceding experiments. Its purpose was to catch the δ -electrons, originating near one side of the box when they were bent by the magnetic field toward that side. The addition of this ring, by increasing the capacity of the electrode, decreased somewhat the readings of the electroscop.

With the magnetic field, the electrode charged up negatively, the rate reaching a maximum value with a current of 3 amperes on the magnet and not changing when the current was increased to 9 amperes. It was independent of the potential applied to the gauze from -40 volts to -1200, but it did vary with the time after the vacuum was made in the same manner as the results obtained previously. For example, with -40 volts on the gauze, and a magnetic field of 250 units, the following values of the current were obtained at different times after the application of the liquid air to the charcoal:

| | | | | | |
|---------|-------|-------|-----------|-----|---------|
| 1 hour | ----- | 126 | divisions | per | minute. |
| 3 hours | ----- | 72 | " | " | " |
| 24 | " | ----- | 25 | " | " |
| 48 | " | ----- | 12 | " | " |
| 72 | " | ----- | 9 | " | " |

We are, I think, justified in concluding that the carriers of this current are not electrons, but ions of atomic mass. Thus, in a magnetic field of 250 gaussses, an electron whose velocity was as great as that corresponding to 1600 volts would be curled into a circle of only half a centimeter radius, and could scarcely reach the electrode even if it started from the case with that velocity; and there is no evidence that any swift electrons start from the case at all. On the other hand, a

hydrogen ion whose velocity was due to a fall of potential of only 9 volts would move in a path whose radius of curvature is 1.7^{cm} , and might escape from the electrode, while an oxygen atom with a single charge certainly would, as its radius of curvature would be 6.7^{cm} .

Assuming, then, that the negative current is carried by such positive ions from the gas film upon the source, it seems unnecessary to suppose that they are emitted with an appreciable velocity, as any of the electric fields used in the preceding experiments would be sufficient to take them through the magnetic field. It seems more probable that it is simply an ionization of the gas film by the α -rays. When the current in question is reduced to its minimum value by three or four days duration of the vacuum, the charge carried by it is from 5 to 10 per cent of that carried by all the α -rays from the polonium. (See § 6.) If the ions have lost a single electronic charge, this means that only one out of ten (or one out of five) of the α -particles, in its passage through the surface film, produces a positive ion which can get away. When the surface film is not so much reduced by long exposure to a high vacuum, this number may be considerably increased.

It is possible that negative ions of atomic size may also be produced, but the present apparatus is not adapted to decide this question for the following reasons. The magnetic field is by no means parallel to the electrode and some of the lines of force meet the surface of the electrode, though not at very large angles. A small proportion of the δ -electrons from any point of the electrode will leave in paths making only a small angle with the magnetic field and will hence escape. Now when a positive potential is applied to the gauze, the current of electrons leaving the source without a magnetic field is more than 500 times the ionic current under consideration. If a fraction of one per cent of these escape along the lines of force, it will be sufficient to cover up the possible small current due to negative ions. That this is the case will be seen in the following section.

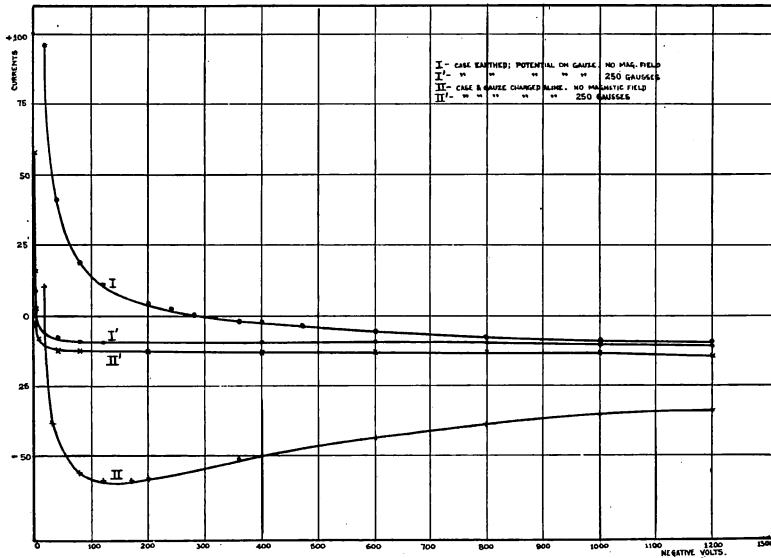
Effects have been observed by other investigators which, I believe, indicate the presence of ions from gaseous surface films. Thus in the recent, very careful determination by Danysz and Duane* of the charge carried by α -rays, the screen which limits the beam of α -rays and the opening of the Faraday cylinder which receives them are both covered with thin aluminium foil, the two foils being parallel and 0.8^{cm} apart. A magnetic field of 8000 units parallel to these foils is used to curl up the β - and δ -rays. Even with this field, the authors found† that a difference of potential of only 2 volts between

* This Journal, xxxv, 295, 1913.

† L. c., p. 302.

the foils increased the charge received by the Faraday cylinder by 2.5 per cent or diminished it by 0.8 per cent according to the direction of the electric field; a potential difference of 1800 volts, they find, may affect the current as much as 8 per cent. It is very difficult to believe that these results can be due to a "drift" of the δ -electrons as the authors suppose; in their magnetic field, the radius of curvature of the path of an electron, moving with a velocity corresponding to 2 volts,

FIG. 4.



would be about 0.005cm ; with a velocity corresponding to 1800 volts about 0.2cm . In neither case does it seem possible that an electron would be able to traverse the 0.8cm between the two foils. In fact, with 2 volts, it appears that it would require a very heavy ion to get through the magnetic field; with 1800 volts, an oxygen ion should get through.

§ 5.

An estimate of the reliability of the present measurements of the distribution in velocity of the swifter δ -rays will be facilitated by a consideration of fig. 4, which will also serve to give a clearer idea of the somewhat complicated phenomena which appear when α -rays fall upon a metal in a high vacuum. The figure shows graphically the results of measurements, all

of which were made on the same day, after the vacuum had been maintained for eight days. Curve I shows the currents received by the electrode, with the case grounded and with negative potentials between 20 and 1200 volts on the gauze cage. Curve II represents the currents when both case and gauze are charged alike. Curves I' and II' give the currents observed under similar electrical conditions as in I and II respectively, but with a magnetic field sufficient to give its maximum effect. Curve I is similar to those plotted in fig. 3 except for the change in scale due to the altered capacity, and for the fact that it begins at 20 volts instead of 40. According to the views advanced in § 4, an ordinate of this curve represents (with more or less accuracy) the number of electrons whose energies are greater than that represented by the abscissa; these ordinates, however, are to be measured, not from the axis, but from a line below it representing the constant negative current received by the electrode. This corrected zero line may coincide with I', or it may fall below it, since it is not certain that all the carriers of this current get through the magnetic field. Curve II represents the resultant of the current of δ -electrons from the source, and the current of tertiary electrons from the case: at 20 volts the δ -ray current predominates, but at higher potentials the tertiary electrons are in the majority. Their number decreases, however, as higher negative potentials are applied, owing to the decreased number of δ -electrons which reach the case. Their presence can still be detected, however, at 2000 volts. The course of II shows that the gauze cage acts as an entanglement to the tertiary electrons even when there is no field between it and the case; for when the cage is absent the tertiary current reaches a maximum at 40 volts, while with the cage (as shown in II), the maximum occurs at 150 volts.

On the view advanced in the preceding section, the negative ordinates of I' and II' represent the current carried by positive ions generated by the α -rays in the gas film upon the electrode. I have been unable to find an explanation for the difference between the two curves.

Considered as representing the distribution in velocity of the swifter δ -rays, the measurements represented by Curve I (or by the curves of fig. 3), are subject to certain sources of error, of which the following appear to be most important.

1. Some of the δ -electrons, whose velocity is nearly but not quite great enough to get through the electric field, may approach near enough to the gauze to be captured by the auxiliary field between it and the case. A consideration of the electric field in the neighborhood of the gauze shows, however, that to be so captured, an electron must approach fairly

near to the gauze; thus at any given voltage, the electrons improperly captured must lie between narrow limits of velocity and would form a small fraction of the total not returned to the electrode. Moreover, since the shape of the lines of force near the gauze remains the same, this fraction would not vary much for different potentials. The principal effect, therefore, of this error would be to increase each ordinate of the curve in nearly the same proportion, which would not seriously affect its accuracy.

2. Some of the tertiary electrons, set free by the δ -rays which strike the gauze, may be returned to the electrode. In a preceding section reasons have been given for supposing that these will form a nearly constant fraction of all the tertiary electrons from both gauze and case. If this is so, Curve I lies below its true position, each ordinate having subtracted from it a fraction of the corresponding ordinate of II. This would alter the course of I, depressing it most between 100 and 200 volts, and less at higher potentials. This correction, however, cannot be large. The wires of the gauze occupy only 17 per cent of its total area, and certainly most of the tertiary electrons which originate upon it must be captured by the auxiliary field. It is quite improbable that this correction can amount to more than 1 or 2 per cent of the ordinates of Curve II.

3. Some of the δ -rays originating upon the sides of the box-source will cross its opening obliquely, and will be *deflected*, so as to strike the box, by fields too small to stop them. Thus at any given potential, some electrons which should get away will not do so, and the ordinates of Curve I will be thereby diminished. But the number thus improperly stopped at any voltage must be a nearly, or quite, constant fraction of those which should escape, so that the effect would be merely to change the scale of the curve.

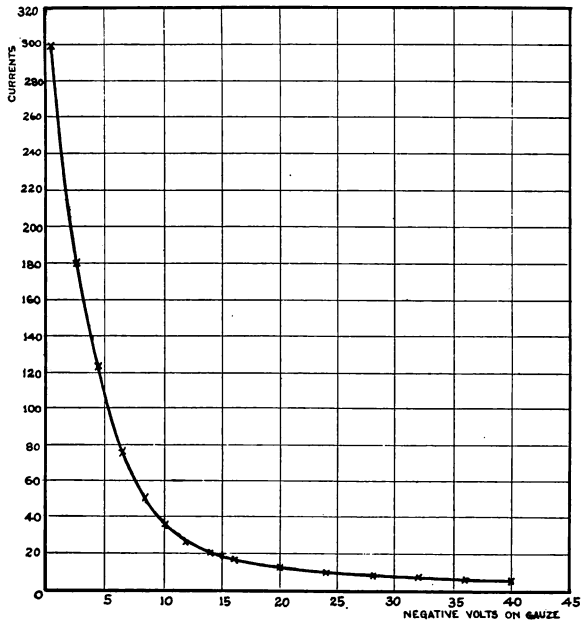
We may reasonably conclude, I think, that the measurements given represent a fair first approximation to the distribution in velocity of the swifter δ -rays. It will probably be possible to improve the accuracy of the determination by using a more intense source of α -rays and receiving a restricted beam of δ -rays in a Faraday cylinder. A suitable source of α -rays for this method is not at present at my disposal.

§ 6.

The preceding measurements have had to do only with δ -rays whose velocities exceeded 20 volts. By reducing the sensitiveness of the electroscopes to somewhat less than one-eighth of its former value, measurements could be taken with smaller negative potentials on the gauze cage. A series of

observations made in this manner is represented in fig. 5. It is within this region that all previous measurements of the velocities of δ -rays have been, so far as I know, confined. Most, if not all, of such measurements have been, I believe, to a considerable extent vitiated by two circumstances: lack of knowledge of the existence of the swifter rays and of the tertiary rays which they produce; and the fact that the α -rays were allowed to pass through the field, thus giving two sources

FIG. 5.



of δ -rays, and of tertiary rays, with much consequent confusion of the results.

Among neither the swifter, nor the slower, rays is there any approach to the Maxwellian exponential distribution; if it were so, the integrated curves (those of figs. 3, 4, and 5) would also be exponential. This is not true in either case;* the diminution in the ordinates is too rapid at the lower potentials and too slow at the higher. If we plot \sqrt{V} instead of V , thus making the abscissæ proportional to velocities

* In the curves of figs. 3 and 4, allowance must be made for the depression of the zero line; but no reasonable adjustment of this sort will bring the curves near to an exponential form.

instead of to kinetic energies, the result is still very far from an exponential curve

The form of the curves, however, for both the swifter and the slower electrons suggests an equation of the form $yx^n = C$. In fact, a very fair agreement between the observations from 30 to 500 volts, and this equation may be obtained by using $n = 0.75$, as may be seen from Table II. In this table the observed currents have been increased by 12 units to allow for the ionic current discussed above.

TABLE II.
 $yx^n = C$ $n = 0.75$

| x (volts) | y (obs + 12) | y (calc.) | Diff. |
|-------------|----------------|-------------|-------|
| 20 | 108· | 89· | 19· |
| 40 | 53· | 53· | 0· |
| 80 | 31· | 31·2 | — 0·2 |
| 120 | 23·5 | 23·2 | + 0·3 |
| 160 | 19· | 18·7 | + 0·3 |
| 200 | 16·7 | 15·8 | + 0·9 |
| 240 | 14·6 | 13·8 | + 0·8 |
| 280 | 11·8 | 12·3 | — 0·5 |
| 320 | 11·4 | 11·1 | + 0·3 |
| 360 | 10·5 | 10·2 | + 0·3 |
| 400 | 9·5 | 9·4 | + 0·1 |
| 480 | 8·5 | 8·2 | + 0·3 |
| 600 | 6·2 | 6·9 | — 0·7 |
| 800 | 4· | 5·6 | — 1·6 |
| 1000 | 2·6 | 4·7 | — 2·1 |
| 1200 | 1·3 | 4·1 | — 2·8 |

The departure of the observations from the equation at the higher voltages may or may not be of significance, since the currents under these conditions were small and could not be very accurately measured, and the placing of the zero line is uncertain. At the lower potentials, however (beginning at 20 volts), the equation does not fit at all. This may well be due to the large admixture of tertiary electrons at these potentials, while above 40 volts there can be few, if any, of these. An approximate representation of the distribution of the slower electrons may be obtained with an equation of the same form, but with a larger value of n , between 1.5 and 2.

In order to get an idea of the relative magnitudes of the currents observed under various conditions, a rough series of comparisons was made by altering the sensitiveness of the electroscope, and introducing a small mica condenser. The results were as follows :

| | |
|--|-------|
| Electronic current at - 40 volts..... | 43· |
| “ “ “ - 20 “ | 100· |
| “ “ “ - 2 “ | 1700· |
| “ “ “ 0 “ | 2700· |
| “ “ “ + 40 “ | 5800· |
| Current carried by α -rays..... | 200· |
| Minimum ionic current..... | 10· |

It will be seen that the swifter electrons with which we have been principally concerned form only a small part of the total number which leave a metal when it is struck by α -rays. But the fact that α -rays can cause electrons to be projected with such speeds is undoubtedly a fact of considerable importance, whether these electrons be few or many; it must have some bearing upon the theory of ionization by α -particles and of their passage through matter. It is not altogether surprising that α -particles should cause electrons to be projected with velocities corresponding to some hundreds of volts. According to the theory of Einstein, the energy of electrons projected under the influence of ultra-violet light is a linear function of the frequency of the light. This theory has been extended with some degree of success to the electronic emission caused by Röntgen rays, taking, instead of the frequency, the time occupied by the pulse in passing over an electron, and estimating this as well as can be done in the present state of knowledge. If we assume that the effective field about an α -particle has the diameter of an atom, 10^{-8}cm , then, since its velocity is about $2 \times 10^9 \frac{\text{cm}}{\text{sec}}$, its time of passage over an electron will be $\frac{1}{2} \times 10^{-17}$ seconds. The frequency of ultra-violet light is about $\frac{2}{3} \times 10^{16}$ seconds, so that we might expect the maximum energy of the δ -rays to be of the order of 100 times that of photoelectric electrons.

It has been shown that the number of slow δ -electrons varies with the speed of the α -rays in much the same manner as the number of ions produced in a gas. I have not yet been able to determine whether this is so with the swifter δ -rays, nor how their distribution in velocity varies (if at all) with the speed of the α -rays. Knowledge of this sort might throw considerable light upon the relations between the electrons of various speeds, and upon the mechanism of ionization by α -rays, about which very little is known at present.

Summary.

1. When α -rays fall upon a metal, electrons are emitted with velocities varying continuously from a very small value to more than $2.7 \times 10^9 \frac{\text{cm}}{\text{sec}}$, which corresponds to a potential differ-

ence of 2000 volts. It is proposed to include under the name "δ-rays," all the electrons which owe their origin to the direct action of the α-rays,—the swifter ones as well as the slower ones previously known.

2. Evidence is given for the view that, in addition to the δ-rays, positive ions are also produced when α-rays impinge upon a metal in a very high vacuum; these ions appear to come from the layer of adsorbed gas upon the metal. By maintaining the vacuum for several days, the current carried by these ions may be reduced to a small value,—from 5 to 10 per cent of that carried by the α-rays themselves. The present experiments do not determine whether or not these ions leave the plate with an appreciable velocity in the absence of an electric field; but there is some evidence that the velocity is, at all events, small.

3. When the swifter δ-rays fall upon a solid it emits electrons of slow speed which, in the present paper, are referred to as tertiary electrons. Their number is considerably greater than the δ-rays which produce them. The existence of the tertiary electrons makes it difficult to determine with accuracy the distribution in velocity of the δ-rays. A large number of tertiary electrons come from the source of δ-rays itself, and their presence in the beam of δ-rays makes it impossible to draw valid conclusions as to the number of true δ-electrons of slow speed (less than 10 or 20 volts).

4. The distribution in velocity of the δ-rays between 20 and 1200 volts has been determined, and reasons are given for believing that the measurements represent a fair approximation to the true distribution. The number of electrons having a given kinetic energy is not an exponential function of either the energy or the velocity. Between 30 and 500 volts, the results are approximately represented by an equation of the form $yx^n = c$ where y is the number of electrons whose kinetic energy is equal to or greater than x , and $n = 0.75$. It is impossible to say whether or not the departure of the measurements from this equation at potentials higher than 500 volts is significant; the quantities measured are small and their values are rendered somewhat uncertain by the presence of the positive ions and of the tertiary electrons. On the other hand, the fact that the slower electrons (under 20 volts) do not follow the same law of distribution in velocity as the swifter ones is to be expected; the presence of tertiary electrons from the source, in the beam of δ-rays, should greatly increase the numbers of the very slow electrons, as is, in fact, found to be the case.

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