XXVI. *Rays of Positive Electricity.*

By Sir J. J. THOMSON *.

[Plate I.]

IN the 'Philosophical Magazine' for October 1910 I described some experiments on positive rays which were made with very large discharge-tubes ; with such tubes it is possible to work at very low pressures without the difference of potential between the electrodes increasing to such an extent as to endanger the tube by sparking through it. At these low pressures I found that the patterns on the phosphorescent screen produced by the positive rays after they had passed through electric and magnetic fields, were separate parabolic curves ; the value of e/m for the particles striking the curve along one of these parabolas is constant. Parabolas giving values of e/m corresponding to the hydrogen atom, the hydrogen molecule, the helium atom, the carbon atom, the oxygen atom, and the mercury atom were observed. I had previously, in 1907 (Phil. Mag. xiii. p. 561), observed the curves corresponding to the hydrogen atom and molecule, and also to the helium atom. In all these experiments the rays were detected by the phosphorescence they produced on a willemite screen ; such a screen, however, does not give a permanent record of the curves traced on it by the positive rays, and accurate measurements of the dimensions and positions of the luminous curves are more difficult than they would be on a photograph. For these reasons I have endeavoured to apply photographic methods to the study of these rays : at first I attempted to photograph the luminosity on the screen, using a very large portrait-lens ; I abandoned this method because I found that to get any effect on the photographic plate exposures lasting several hours were required. Apart from the tediousness of this process, it is difficult to keep the conditions in the tube sufficiently constant for so long a time. I see, however, that Dechend and Hammer (*Sitz. Heid. Ak.* 1910) have recently succeeded in photographing the curves corresponding to several gases in this way.

I find that a much more sensitive and expeditious method is to put a photographic plate inside the tube itself and let the positive rays fall directly on the plate instead of on to the willemite screen. The photographic plate is very sensitive to these rays, and the places where they fall are recorded when the plate is developed. The plate is much more sensitive

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* Communicated by the Author.

than the willemite screen, and an exposure of three minutes shows curves on the plate which cannot be detected on the screen *.

One method I have employed to detect the positive rays by photography is as follows:—The photographic plate is inserted in the lid of a light-tight box, A, fig. 1, so that when

Fig. 1.—Plan.

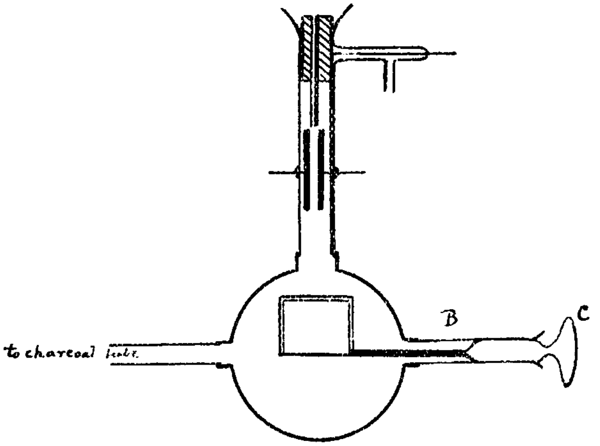
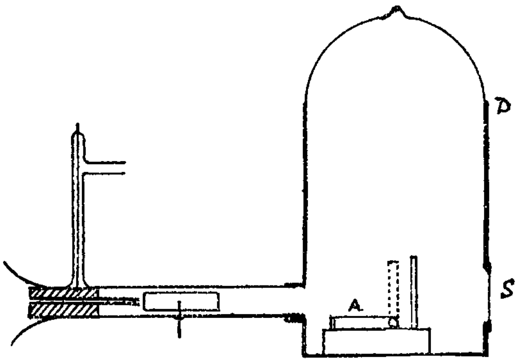


Fig. 1.—Elevation.



the lid is down the plate is protected from light. The bottom of the box is fastened down to the floor of the discharge-tube, while the lid is fastened to a rod, B, which is fixed to a glass tap, C, which rotates in a glass tube; tube and tap are

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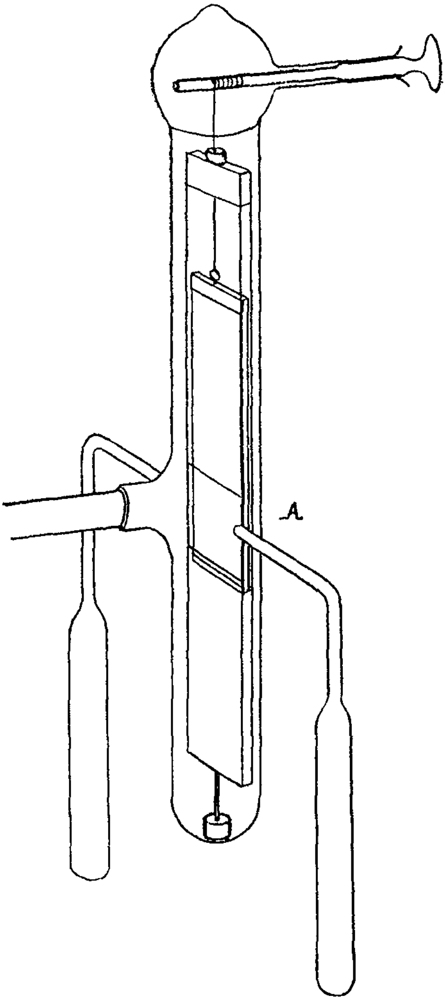
* Since this was written I have seen a paper by Koenigsberger & Kelching (*Verh. Deutsch. Physik. Gesellsch.* xii. p. 995, 1910), who have also used the method of putting the plate inside the tube.

ground so that the tap can be rotated without injury to the vacuum in the discharge-tube. The box containing the plate was placed in front of a willemite screen, S, fastened to the end of the tube; when the lid of the box was down the positive rays could hit the screen; the appearance on the screen showed when the pressure in the tube was such as to give well-developed positive rays and thus indicated when a photograph could be taken with advantage. When this stage was reached the coil or influence machine used to produce the discharge was stopped, the lid of the box lifted by turning the tap, the tap was turned until the lid came against stops placed inside the tube, so that the plate was always in the same position. The tube was surrounded by black velvet so as to prevent light from outside reaching the tube, while the light from the discharge and the phosphorescence of the walls of the tube was prevented from reaching the plate by tightly-fitting stops placed in the neck of the tube. The only way that light could reach the plate was through the long and narrow tube through which the positive rays themselves passed, and this light would produce a small circular patch on the plate coinciding in position with that produced by the positive rays themselves when they were not deflected by electric or magnetic forces.

After the plate had been exposed to the rays for a suitable time the coil was stopped and the tap turned so as to put the plate back again into the box. The lid of the tube, D, which was fastened on with sealing-wax, was taken off, the box taken out of the tube, and the plate developed. The size of the plate was 4 cm. × 4 cm.

Many photographs have also been taken with an arrangement devised by Mr. F. W. Aston, of Trinity College, shown in fig. 2 (p. 228). In this method the plate is suspended by a silk thread wound round a tap which works in a ground-glass joint; by turning the tap the silk can be rolled or unrolled and the plate lifted up or down. The plate slides in a vertical box of thin metal, light-tight except for the opening A, which comes at that part of the tube through which the positive rays pass; the openings, which are on both sides of the box, are circular and 5 cm. in diameter. When the silk is wound up, the strip of photographic plate in the box is above the opening, so that there is a free way for the positive rays to pass through the opening and fall on a willemite screen placed behind it, so that the state of the tube with respect to the production of positive rays can easily be ascertained. The box is large enough to hold a film long enough for three photographs; by lowering the plate until the bottom third of the plate comes opposite the opening, taking a photograph, then lowering the plate still further until the middle third comes opposite the opening, taking another

Fig. 2.

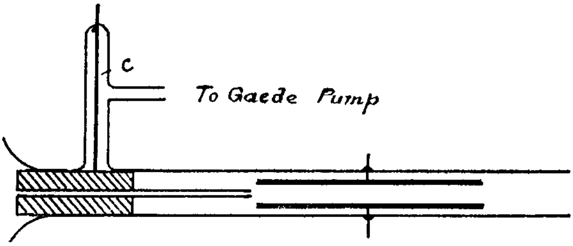


photograph, then lowering the plate until the top third comes opposite the opening, and again taking a photograph, three photographs can be taken without opening the tube. This is very convenient, for the deflexions of the different positive rays vary so much that it is difficult to measure them when they are all on one plate. For example, the magnetic deflexion of the hydrogen atom is about fourteen times that of the mercury one ; thus if the deflexion of the hydrogen atom is within the limits of the plate, that of the mercury atom will be too small to be measured with accuracy. When three photographs are taken, however, we can use a small magnetic force for the first and get the light atoms on the plate, then a larger magnetic field for the second for the study of the atoms and molecules of oxygen and other elements of a similar atomic weight, while we can use a still stronger field for the third for the study of very heavy atoms such as those of mercury.

Method of exhausting the Tube.—The tube was exhausted by a Gaede pump and charcoal cooled with liquid air. The narrow tube through which the rays passed fitted at the end next the photographic plate into a plug of ebonite, and the joint was made air-tight with a little wax, the joint between the ebonite plug and the glass tube into which it fitted was also made air-tight in the same way ; thus the only way gas could get from the discharge-tube into the space through which the positive rays passed after they left the tube was through this long narrow tube through which the gas only filtered slowly ; two large tubes containing charcoal immersed in liquid air led into this part of the apparatus and kept the pressure much lower than it was in the discharge-tube.

The communication with the Gaede pump was made between the cathode and the ebonite plug as shown in fig. 3.

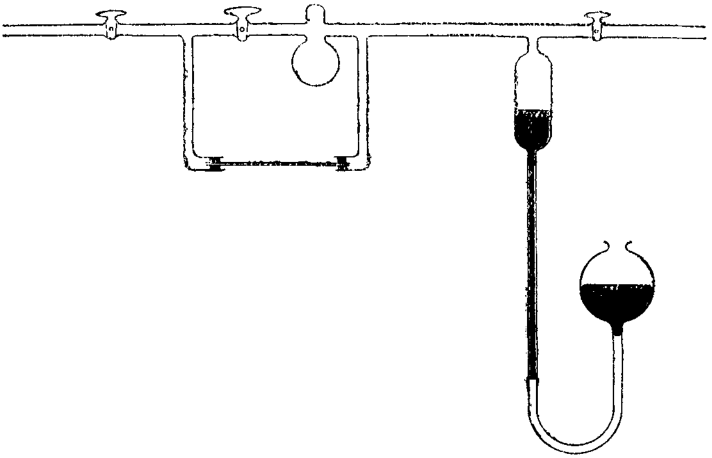
Fig. 3.



The cathode fits fairly tightly into the tube, so that there may be a considerable difference of pressure between the discharge-tube and the space C.

Method of filling the Tube with Gases.—When the rays in some particular gas were under examination a constant stream of that gas was kept flowing through the tube. This was done by fusing on the discharge-tube a glass tube, whose end was drawn out into an exceedingly fine capillary tube, whose end was left open. This capillary was fastened by an air-tight joint into the receptacle containing the gas under examination ; this receptacle was practically the space above the mercury in a barometer tube, and by altering the level of the mercury the pressure of the gas in the receptacle could be adjusted so that when the Gaede pump was kept in continuous action the pressure in the discharge-tube was low enough for the positive rays to be well developed. The details of the connexion are shown in fig. 4.

Fig. 4.



Discussion of the Photographs.—The appearance of a typical photograph is shown in fig. 5 (Pl. I.). In all these photographs the vertical deflexion is due to the magnetic field, the horizontal to the electrostatic. Many of the photographs were taken with the magnetic field in one direction for half the exposure and in the opposite direction for the other half. It will be seen that the curves on the photograph are of two types.

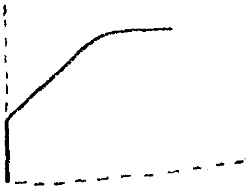
(1) Short parabolic arcs of varying length, having their heads in the same vertical line, showing that the minimum electrostatic deflexion suffered by the particles which produce these curves is the same whatever the nature of the particles may be. The electrostatic deflexion is proportional to e/mv^2, where e is the charge, m the mass, and v the velocity of the particle. Now if the energy of the particle is due to the fall of its charge through a potential difference V,

$$Ve = \tfrac{1}{2}mv^2 \quad \text{or} \quad e/mv^2 = 1/2V.$$

Hence, as the minimum electrostatic deflexion is the same for all the particles, we conclude that the maximum potential difference through which each set of particles has fallen is the same.

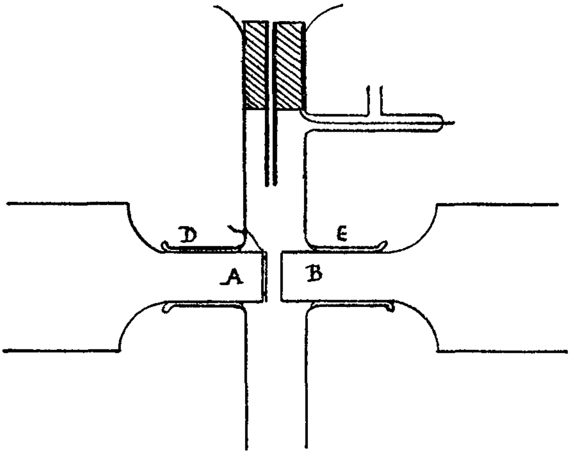
(2) The second type of curve to be seen on the plate are curves which pass through O, the point on the plate struck by the rays when they are not deflected by either electric or magnetic forces. The portions of these curves near O are straight lines when the electric and magnetic fields are coterminous. If the magnetic field overlaps the electrostatic the shape of the curve is that shown in fig. 6. In my paper in the 'Philosophical Magazine' for October 1910 I gave reasons for thinking that these curves represent secondary positive rays produced by the passage of the primary rays through the gas on the way to the plate, and that the parts of the curve near O which are produced by particles which have suffered only small deflexions were produced by rays which had not traversed the whole of the magnetic and electric fields, but had been generated towards the ends of these fields. If this view is right, then, if we shorten these fields, we ought to diminish the intensity of these curves near O. To test this point the magnetic field was reduced from the length of 25 mm., the value it had in most of the experiments, to 6 mm. The arrangement used is represented in fig. 7 (p. 232). The pole-pieces A, B, 6 mm. in diameter and 1 mm. apart, came through sealing-wax joints in the side tubes D and E; the other ends of A and B were screwed into the pole-pieces of a powerful electromagnet. On one of the poles, A, a thin piece of brass was fastened by a thin layer of sealing-wax which insulated it from the pole-piece: the brass was connected with one terminal of a battery of small storage-cells, the other terminal of which was connected with the earth and with the other pole-piece, B. In this way an intense electric field coterminous with the magnetic

Fig. 6.



could be produced between the pole-pieces. Even with these short pole-pieces there was a very considerable production of

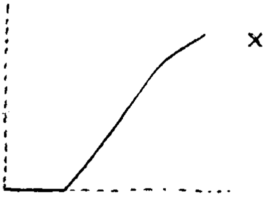
Fig. 7.



secondary rays, as is shown by the photograph reproduced in fig. 8 (Pl. I.). It ought, however, to be mentioned that the pressure in this case was not very low, as by an accident there was a little grease inside the tube which gave off an appreciable amount of vapour. The photograph is interesting as it shows how intense this production of secondary radiation may be. To test the point further, the length of the magnetic field was reduced to 1 mm. ; this was done by replacing the iron rods A and B in fig. 7 by thin iron plates, and increasing the strength of the electric and magnetic fields sufficiently to produce appreciable magnetic and electric deflexions even though the path of the rays through these fields was only 1 mm. long. In this case all the curves of type (2) completely disappeared, and the only curves on the plate were the parabolas of type (1). A photograph taken with this apparatus is reproduced in fig. 9 ; it will be seen that there is nothing on the plate nearer the vertical than the heads of the bright parabolas.

We should also get rays of type (2) if some of the primary rays, after passing through the cathode, lost their charges as they were passing through the electric and magnetic fields. In this case the parts of the curves near O would be due to rays which had lost their charges near the beginning of the electric and magnetic fields, while in the case we have just been considering this part of the curves would be due to rays which had been produced near the end of these fields; by the beginning of the field is meant the part of the field nearest the cathode, and by the end of the field the part nearest the photographic plate. This consideration leads to a method by which we can distinguish whether the curves of type (2) originate in one or other of these ways. For suppose that the electric and magnetic fields, instead of being coterminous, are placed one after the other, let us suppose that the magnetic field is the one nearest to the photographic plate. Then if the curves are due to rays produced by the passage of the undeflected rays through the gas, some of these will be produced after the undeflected rays have left the electric and are passing through the magnetic field, the rays so produced will suffer magnetic but not electric deflexions, and the curve they will trace on the photographic plate will be somewhat like that shown in fig. 6 (p. 231). Curves of this kind can be seen on the photographs reproduced in figs. 5 (Pl. I.). If, however, the rays, instead of being produced between the cathode and the photographic plate, are losing their charges as they travel through the electric and magnetic fields, some of them will lose their charges whilst they are in the electric and before they have reached the magnetic field; these will experience an electric but not a magnetic deflexion, and the curves they trace on the photographic plate will be of the kind shown in fig. 11 (Pl. I.).

Fig. 10.



The concavities of the curves in figs. 10 and 11 are turned in opposite directions, and this criterion will enable us to decide as to the way the rays originate. For example, let us take the most prominent curve of type (2) when the rays pass through helium. Fig. 11 represents the curves for helium when the electric and magnetic fields are nearly coterminous; it will be seen that the curve marked with a ×, which is the one under consideration, is concave to the horizontal axis. When, however, the fields are separated and the magnetic field placed nearer to the photographic plate than the electric, the shape of the curve is as in the photograph reproduced in fig. 13; it is now convex to the origin and of the type shown in fig. 11. The value of m/e for this curve is 12 times that for the hydrogen atom, and we conclude that the ions which produce it do not start between the cathode and the photographic plate, but are complex ions $(He_3)+$, which are formed in the dark space in the discharge-tube and are liable to lose their positive charge on their journey from the cathode to the photographic plate.

The secondary rays present some very interesting features. The following are some of the results obtained by the study of a long series of photographs. We shall for brevity call the ratio of m/e for any ray to the value of m/e for the atom of hydrogen the electric atomic weight of the particle forming the ray.

Secondary rays consisting of the atoms of hydrogen for which $e/m=10^4$ are found in all gases when the pressure is not too low. They occur negatively charged as well as positively, and often there is a bright head at the end of the negatively charged rays corresponding to the head of the positively charged ones; this is shown in the photograph reproduced in fig. 8. It is due, I think, to secondary rays which have been produced before the magnetic field was reached, and which have all, therefore, been exposed to the full magnetic and electric field and, having suffered the same deflexion, strike the photographic plate at the same spot.

Secondary rays consisting of the molecule of hydrogen. Though the primary rays corresponding to the molecule of hydrogen occur on nearly every plate, the secondary radiation due to the hydrogen molecule is generally conspicuous by its absence. An example of this is shown in fig. 5, which represents the appearance when the gases in the tube are the residual gases left after the air which originally filled the tube has been pumped out. The absence of the secondary corresponding to the hydrogen molecule is very marked, while the secondary corresponding to the hydrogen atom is quite distinct. I have found the same thing when the tube contained hydrogen, oxygen, carbonic oxide, marsh-gas, cyanogen, or hydrochloric acid gas instead of the residual gas. When helium is in the tube there is at some pressures, though not at all, secondary radiation corresponding to an electric atomic weight of 2. A photograph of a plate taken with helium in the tube is reproduced in fig. 16, and the secondary radiation of this type is very prominent. I am inclined to regard it in this case as due to an atom of helium with two charges rather than to a molecule of hydrogen with one charge. I had taken so many photographs before I obtained any indication of secondary radiation of this atomic weight when no helium was present, that I was inclined to doubt whether the hydrogen molecule ever did occur as secondary radiation; quite recently, however, a tube which had got contaminated with grease from one of the taps showed the molecule of hydrogen more strongly than the atom in the secondary radiation; a photograph taken with this tube is shown in fig. 14. There must therefore, I think, be some types of compounds of hydrogen from which the hydrogen molecule is liberated to form the greater part of the secondary radiation due to hydrogen, though in hydrogen itself and in numerous other compounds of hydrogen it is the hydrogen atom which constitutes the larger part of the secondary radiation. It is remarkable that, even in a case like that shown in fig. 14, where the positively-charged molecule largely predominates in the secondary radiation over the positively-charged ion, the negatively-charged hydrogen molecule cannot be detected, while the effects of the negatively-charged hydrogen atom are quite distinct.

In many tubes I have observed a secondary radiation for which the electric atomic weight is about 1·4; the curves on the plate due to it are faint, but they occur with a great variety of gases, and with negative as well as positive charges.

Another secondary radiation, stronger than that just mentioned, but not often very conspicuous, is one with an electric atomic weight of 3; it is specially bright when hydrogen is in the tube, while carbon compounds do not exhibit it to any very marked extent. The electric atomic weight would fit in either with a complex ion H_3 with one charge, or an atom of carbon with four charges. Since it seems not to be specially increased by the introduction of carbon compounds, I think the former hypothesis is the more probable. It occurs with a negative as well as with a positive charge. The radiation mentioned in the preceding paragraph may be due to this ion with a double charge.

Another type of secondary radiation, much stronger than those just mentioned and especially bright in carbon compounds, is one with an electric atomic weight of 6; both this and the preceding type are shown in fig. 15. I have not observed this unless carbon or some of its compounds are present, and so I regard this as due to a carbon atom with a double charge. It is only found with a positive charge.

In compounds not containing carbon there is secondary radiation with an electric atomic weight very near the last, in fact so near as to make it difficult to distinguish between them, but the measurements I have made of the value of m/e for the radiation in this case have consistently given me values much nearer 7 than 6, and distinctly higher than those with carbon compounds. If the electric atomic weight is 7, it may possibly be the atom of nitrogen with a double charge, though nitrogen is, as a rule, loth to appear in the positive rays. It only occurs with a positive charge, which makes it unlikely that it is an atom of oxygen with a double charge, as oxygen has a great tendency to appear with a negative charge. In some cases this secondary radiation is the strongest on the plate.

In helium the strongest radiation of the type we are considering is one with an electric atomic weight equal to 12; this is indicated by the continuous line passing through the origin in fig. 11. The experiments already described show that this radiation is due to particles which are charged when they pass through the opening in the cathode, but some of which lose their charges as they pass through the electric and magnetic fields. We have thus here a case of recombination rather than that of a true secondary radiation or dissociation such as that which produces the radiation with atomic weights 1, 3, 6. The radiation with atomic weight 12, when the gas is helium, has not been found with a negative charge. Its atomic weight suggests that the carrier of this radiation is the aggregate $(He)_3+$.

In oxygen I have noticed three kinds of radiation of the type we are considering, having respectively the electric atomic weights 16, 48, 96. The first of these corresponds to the atom of oxygen—it is much the strongest of the three; the second to $(O_3)_+$, a molecule of ozone with one positive charge; while the third corresponds to $(O_6)_+$. It is interesting to note that Ladenburg and Lehmann (*Ann. der Phys.* xxi. p. 315) found that a more complex polymer of oxygen than ozone was produced when the electric discharge passed through oxygen at a low pressure. They succeeded in freezing this modification out of the gas with the aid of liquid air, and ascribed to its molecule the composition O_6. The secondary radiation corresponding to O_3 and O_6 is feeble. I have not yet been able to detect any of it with a negative charge. The secondary radiation with a negative charge corresponding to the oxygen atom is extremely well marked; indeed, after H_- it is generally the most pronounced constituent of the negatively charged radiation. In the primary radiation in oxygen the radiation consists of O_+ and $(O_2)_+$. The rays for oxygen are shown in fig. 16.

Another gas in which the radiation is interesting is mercury vapour. We get radiation corresponding to electrical atomic weight 200, *i. e.* to the atom of mercury in both the primary and secondary radiation. In the secondary radiation we have, in addition, two other kinds, one with an electrical atomic weight of 100, which is probably an atom of mercury with a double charge. The liability of the atom of mercury to take a double charge will explain a peculiar appearance which the line corresponding to the mercury atom in the primary radiation often shows. This appearance is represented in fig. 17. In addition to the bright comma α, whose head is in the same vertical line as the heads of the other bright primaries, there is, on the same parabola as α, another bright spot, β, whose horizontal deflexion is only half that of α. Since β and α are on the same parabola, the value of e/m is the same for the particles in β as for those in α, and since the horizontal deflexion of β is only half that of α, the kinetic energy of the particles in β is twice that of the particles in α. This would be just what we should find if the particles in β had had a double charge when they were in the discharge-tube in front of the cathode and exposed to the action of the electric field in the dark space, and lost one of their charges after passing through the cathode and before reaching the electric and magnetic fields.

On some plates there are two bright patches on the parabola corresponding to the hydrogen atom, but in this case the horizontal deflexion of the abnormal spot is twice that of the normal one. The simplest explanation of this spot is that it is due, not to an atom of hydrogen with one charge, but to a molecule of hydrogen with two charges, and that one of these charges has been acquired after the molecule has passed through the cathode. The doubling of the charge, if it arose in this way, would not affect the kinetic energy, but would double the deflexion produced by the electrostatic field, and would put the spot on the curve for which e/m has the value appropriate to the hydrogen atom with one charge. Fig. 17 A shows a spot of this kind.

The other type of secondary radiation in mercury vapour is one with an electrical atomic weight of 800 ; this would correspond to four atoms of mercury with one electric charge between them. The existence of particles of this kind in the secondary radiation, and of O_3 and O_6 with oxygen, and H_3 with hydrogen, is experimental evidence for the existence of aggregates formed round a charged ion. In one theory of the electrical discharge through gases the existence of such aggregates is assumed in order to explain why the velocity of the ions under an electric field is not larger than it is. The smallness of the velocity can also be explained as due to the charge on the ion, so that we could not deduce the existence of these aggregates from considerations of the velocity of the ion. It may be pointed out that the radiation due to these aggregates is in every case faint compared with that due to the simple atom, so that at the low pressures at which the experiments on positive rays are made the number of these complex aggregates is very small compared with that of the simple atom.

In marsh-gas there is a secondary radiation with an electrical atomic weight of 36 ; an aggregate of three atoms of carbon with one charge between them would explain this. In other hydrocarbons, as well as in CO and CN, the strongest secondary radiation is one for which the measurements of the magnetic deflexion give values ranging from 72 to 78. This is the strong secondary shown in fig. 18, the gas in the tube being CO. An aggregate of six carbon atoms, or a molecule of benzene, C_6H_6, with one charge, would give electrical atomic weights agreeing within the errors of experiment with this.

I have tabulated these results for the secondary radiation of the gases I have so far examined in the following Table (p. 239). The first column contains the electrical atomic weight of the particles in the radiation, the second the sign of the charge on these particles (thus + means that they are always positively charged, + and − that they occur with negative as well as positive charges), the third column contains the name of the gas giving the radiation, the fourth the probable composition of the particle, and the fifth whether it is a true secondary, *i. e.* due to dissociation after the rays have passed through the cathode or to recombination.

PRIMARY RAYS.

These are the rays which produce on the photographic plate detached parabolic curves not passing through the origin. The primary rays found in the gases investigated up to the present are as follows :—

Hydrogen.

There are two kinds of primary rays having respectively the electric atomic weights 1 and 2 corresponding to the atom and molecule of hydrogen. The relative brightness of the curves due to the atom and molecule varies greatly with the circumstances of the discharge, in some cases that due

Table of Secondary Radiation.

Electrical atomic weight.	Sign of charge.	Gases in which they are found.	Remarks.	Nature of radiation.
1	+ and −	All gases.	Hydrogen atom.	Dissociation.
1·4	+ and −	Generally faint; brightest in hydrogen.	$(H_3)_{\pm\pm}$?	”
2	+	In helium at certain pressures; also in certain hydrocarbons.	He_{++} in first case, $(H_2)_+$ in second.	”
3	+ and −	Especially bright in hydrogen; not exceptionally bright in hydrocarbons.	More likely to be $(H_3)_\pm$ than $C_{\pm\pm\pm\pm}$	”
6	+	Especially bright in carbon compounds.	C_{++}	
7	+	Found most frequently when carbon compounds are absent.	N_{++} ?	
12	+	Found in helium; generally the brightest line of this class in that gas.	$(He)_{3+}$	Combination
16	+ and −	In oxygen; one of the brightest lines on the negative side.	$O_\pm$	
26	+ and −	In cyanogen; also bright on negative side.	$(CN)_\pm$	
36	+	In CH_4.	$(C_3)_+$	
48	+	In oxygen.	$(O_3)_+$ faint.	
72-78 ..	+	In most hydrocarbons; also in CO, CN.	$(C_6)_+$ or $(C_6H_6)_+$	
96	+	In oxygen.	$(O_8)_+$ faint.	
100	+	In mercury vapour.	$(Hg)_{++}$	
200	+	In mercury vapour.	Hg_+	
800	+	In mercury vapour.	$(Hg_4)_+$ faint.	

to the molecule is exceedingly faint, while in others it is much the brighter of the two. I have never detected rays consisting of negatively charged molecules, while those due to negatively charged atoms are invariably present unless the pressure of the gas in the discharge-tube is exceedingly low.

Oxygen.

The primary rays characteristic of oxygen have electric atomic weights 16 and 32, and are due respectively to the atom and molecule of oxygen. Rays with these atomic weights and having a negative charge are very conspicuous, their only rival on the negative side being the hydrogen atom. A copy of the photograph taken with oxygen at a very low pressure in the tube is given in fig. 16.

Carbonic Oxide.

The electric atomic weights of the characteristic primary rays for carbonic acid are 12, the carbon atom with one charge, 16 the oxygen atom, 32 the oxygen molecule, and one with an atomic weight about 47, this may be a molecule of ozone which would have an atomic weight 48, or possibly one of carbonic acid which would have an atomic weight of 44. It would thus appear that the molecule of CO does not appear among the positive rays when the discharge passes through this gas. Fig. 18 is a photograph for this gas.

Marsh-Gas.

The electric atomic weights are 16, the molecule CH_4 more probably than the atom of oxygen, as it does not appear on the negative side, and 28. This may possibly be a molecule of acetylene C_2H_2, which would give an atomic weight of 26. It is remarkable that there were no lines with an atomic weight of 12 on this plate, though it was present in the other carbon compounds which were investigated, carbonic oxide and cyanogen. Fig. 19 is the photograph for this gas.

Cyanogen.

The electric atomic weights for the primary rays are 12, the atom of carbon, and 26, the molecule CN. It is remarkable that the latter is also found with a negative charge. Fig. 20 represents the photograph for this gas.

Helium.

The line corresponding to the electric atomic weight 4, due to the atom of helium, is exceedingly strong, and can be detected when there is only a very small quantity of helium in the discharge-tube. The most prominent line on fig. 21 is due to helium, the tube contained other gases in addition.

Hydrochloric Acid Gas.

The primary rays were the atom and molecule of hydrogen, and a very faint one presumably due to the chlorine atom as it had an electric atomic weight of about the right magnitude; it was too faint to admit of accurate measurement. It was, however, stronger on the negative side. The oxygen line was exceptionally strong in this gas.

One very remarkable fact which appears from the study of these rays is the ease with which the atom of hydrogen acquires a negative charge; this does not harmonize well with the usual view as to the electro-positive character of hydrogen. With this exception the negative charge, as far as my observations have gone, is assumed by, and only assumed by, those ions which have distinctly electro-negative chemical properties, thus leaving out H. The gases which appear on the negative side are O, Cl, CN, all well recognised electro-negative ions. It would thus seem that here we have direct experimental evidence that the atoms of the electro-negative elements can acquire a negative charge when under the same circumstances the atoms of the other elements do not do so.

Long and Short Lines.—The length of the parabolas on the photographs varies very much from one curve to another; the least deflected parts are all on the same vertical line, indicating, as we have seen, that the maximum potential difference through which the particles have fallen is the same for all the different kinds of particles which give rise to these lines; this potential difference is probably the potential difference between the cathode and the negative glow. Though the minimum horizontal deflexion is the same for all the curves, the maximum is very different even when the pressure of the gas in the tube is exceedingly low. As will be seen from the reproduction of the photographs, some of the curves are exceedingly short, so that the horizontal deflexion of any one of the particles producing it is not much greater than the minimum, showing that all these particles have practically fallen through the maximum potential difference, and have therefore probably been produced near the confines of the negative glow. On the other hand, there are on the same photograph some curves of great length where the maximum horizontal deflexion is at least five or six times the minimum; the particles which have suffered the maximum deflexion have therefore fallen through a potential difference of less than one-fifth of that between the cathode and the negative glow. Since the electric force increases rapidly near the cathode there will be, at a distance from the cathode much less than one-fifth the thickness of the dark space, a difference of potential amounting to one-fifth that through the whole of the dark space; hence we conclude that the particles which suffer these large deflexions must have been generated quite near to the cathode, so that the production of these particles must be going on through nearly the whole of the dark space. It is rather remarkable that on some of the photographs all the lines are quite long, and there are no indications of any particles which are produced exclusively at the junction of the dark space and the negative glow. The very sharp line of demarcation, which in general characterizes the junction of the dark space and the negative glow, would lead us to expect that this region would be associated with some form of chemical change which does not exist in the rest of the dark space; this, however, seems not necessarily to be the case, as there are several gases in which no short lines can be detected: one of these is oxygen, and this is also one of the gases where the contrast between the negative glow and the dark space is specially well marked.

With some few exceptions which will be considered later, the brightest part of the parabolas corresponding to the primary rays is the part which has experienced the least electrostatic deflexion, these rays which produce this part of the parabola are those which have the greatest kinetic energy and would naturally produce a greater effect than the same number of particles with less kinetic energy; the decay in the intensity as we recede from the head of the parabola seems in some cases to be larger than can be accounted for by the falling off in the kinetic energy, and seems to indicate a considerable diminution in the number of the particles. Now in the dark space ionization is produced (1) by the cathode particles, these move away from the cathode, and (2) by positively charged particles, these move towards the cathode; there are in addition other sources of ionization, such as ultra-violet light and soft Röntgen radiation, which we shall leave out of consideration for the present. The positive particles starting from the negative glow will not at its boundary have acquired any energy from the electric field, and will therefore not be likely to produce ions in that neighbourhood, while this is just the place where the cathode particles are most numerous and most energetic. Now the greater part of the particles forming what we have called the primary rays come from the neighbourhood of the negative glow; we conclude that they represent the ions produced by the collision of rapidly moving cathode particles against the molecules in the discharge-tube. On the other hand, we should expect that the ions produced by the positive particles would show the characteristics of what we have called secondary rays, for these particles would have their maximum velocity when they reached the cathode, and after passing through the cathode would continue to produce rays of the same type while passing through the electric and magnetic fields.

Though some secondary rays are probably produced in this way, yet I am of opinion that the rays which produce the curves on the photographic plate arise in a different way, for the ions produced by the impact of one molecule against another would probably start off in different directions; this would make the curves on the photographic plate very fuzzy, while, as a matter of fact, they are very often beautifully sharp. Again, if the ions forming these rays came from the dissociation of the molecules of the gas in the deflexion chamber, we should expect that the brightness of the curves due to the mercury ions, for example, would be much more dependent on the presence of mercury vapour in the deflexion-chamber than in the discharge-tube. Experiments on the behaviour of the secondary radiation due to mercury show that this is not the case; on the contrary, if we abstract the mercury vapour from the discharge-tube by charcoal cooled with liquid air, we produce a much greater diminution in the brightness of the secondary lines due to mercury than we do if we abstract by the same means the mercury vapour from the deflexion-chamber.

The evidence is, I think, in favour of the view that the secondary rays are due to the dissociation of systems in the undeflected Canalstrahlen, rather than to the dissociation of the gas in the deflexion-chamber through which the Canalstrahlen pass. The dissociation of the systems in the Canalstrahlen is produced by the collision of these systems with corpuscles and not with ordinary molecules; for if the collision were with ordinary molecules, the direction of motion of the systems and their velocities would change when the collision took place, and the result would be that the lines on the plate would be very fuzzy and ill defined, a collision with a body having as small a mass as that of a corpuscle would leave the direction of motion and the velocity of a body as massive as a molecule practically unaltered. The corpuscles when struck by the Canalstrahlen may be regarded as practically at rest in comparison with the systems which strike against them; for though in the space between the parallel plates used to produce the electrostatic deflexion of the rays there is an electric field strong enough to make the corpuscles move with very great velocities, yet as the path of the Canalstrahlen is the region where the corpuscles are produced and where they have not had an opportunity of acquiring a high velocity from the electric field, they will only be moving slowly when struck by the Canalstrahlen.

Experiments on the ionization produced by the collision of corpuscles against molecules at rest, or rather moving very slowly in comparison with the corpuscles, have shown that for the corpuscle to ionize the molecule the velocity of the corpuscle must be greater than a certain value: thus, according to the results obtained by Townsend and H. A. Wilson, if a corpuscle is to ionize a molecule of air by colliding against it, the velocity of the corpuscle must exceed that which it would acquire by falling through a potential difference of two volts. It would probably not require so large a velocity to ionize the constituents of the beam of Canalstrahlen, as some of these are probably much more loosely connected systems than a molecule of air; we should expect, too, that the velocity would vary from one constituent to another. Let us suppose that to ionize a particular constituent requires a potential difference of n volts. If now the corpuscle is at rest and the molecule moving, the relative velocity when there is ionization must be the same as in the previous case; but since the molecule has a much greater mass than the corpuscle, the molecule to acquire the same velocity must fall through a much greater potential difference; if it requires n volts to give this velocity to the corpuscle, it will require $w \times n \times 1{\cdot}7 \times 10^3$ volts to give this velocity to a system whose electric atomic weight is w; we have taken the mass of the hydrogen atom as $1{\cdot}7 \times 10^3$ times that of the corpuscle. Thus the greater the electric atomic weight of any constituent of secondary radiation the greater is the potential difference through which it must have fallen in the discharge-tube in order that it should be dissociated in the deflexion-tube. Thus the secondary radiation of least electric atomic weight, that of the atom of hydrogen, would require to fall through a smaller potential difference than any other. This explains why at comparatively high pressures, when the potential difference in the discharge-tube is small, the hydrogen atom is the only type of secondary radiation to be seen; the others are, as it were, latent in the beam of Canalstrahlen, but the potential difference in the discharge-tube was not sufficient to make them move quickly enough to be ionized when they came into collision with a corpuscle.

For the uncharged Canalstrahlen to be dissociated, and thus give rise to secondary rays, they must travel with a velocity greater than a certain critical velocity, and to acquire this velocity they must fall through a potential difference not smaller than the value just found, this gives a minimum value for the potential difference required to produce the secondary radiation. There will, however, be a maximum as well as a minimum value, for the uncharged Canalstrahlen are produced by the combination of a positively charged particle and a negatively charged corpuscle, and in consequence of the small mass of the corpuscle the velocity of the uncharged system will practically be that of the positively charged particle before it combined with the corpuscle. If, however, the velocity of the particle exceeded a certain limit, it could not combine with a corpuscle even though it passed quite close to it, its velocity would be sufficient to carry it far away from the corpuscle, and it would not retain it as a satellite. If A and B represent respectively the particle and the corpuscle, then if when they are at a distance r apart their relative velocity is v, they will separate to an infinite distance of $v^2 > 2 . \frac{e}{m} \frac{e}{r}$, where e is the charge in electrostatic measure and m the mass of a corpuscle. Even with the smallest admissible value of r a corpuscle would acquire a velocity great enough to satisfy the preceding inequality by the fall through a potential difference of two or three volts ; hence it is only exceedingly close to the cathode, perhaps only inside the hole through which the rays pass, that the corpuscles are still enough to allow of any combination with a positive particle to take place. Let us take as the case most favourable to recombination the one where the corpuscles are at rest and the relative motion is entirely due to the positive particles, then if v is the velocity of the positive particle for combination to take place, $v^2 < 2 . \frac{e}{m} . \frac{e}{r}$. The smallest value of r permissible will depend upon the size of the particle : it will be of atomic dimensions. Let it equal $b \times 10^{-8}$ cm.

Putting $e/m = 1{\cdot}7 \times 10^7 \times 3 \times 10^{10}$, $e = 4{\cdot}5 \times 10^{-1}$

we find $$v^2 < \frac{4{\cdot}6}{b} \times 10^{16}.$$

If the velocity is due to the fall of the charged body through V volts, then if w is the electric atomic weight of the particle, the preceding relation is equivalent to

$$v < 2{\cdot}3 \frac{w}{b} \times 10^4.$$

Thus for the secondary radiation due to the dissociation of the uncharged rays,

$$V > w \times n \times 1{\cdot}7 \times 10^{3},$$

$$V < 2{\cdot}3 \frac{w}{b} \times 10^{4}.$$

Thus the velocity of each kind of secondary ray must be between certain limits which do not depend on the potential difference between the electrodes in the discharge-tube. If these limits are very close together the velocity of the secondary ray will be very nearly constant. I have found that this is the case for the secondary rays corresponding to the hydrogen atom.

The curves on the photographic plate which pass through the origin may arise either from the dissociation of the uncharged Canalstrahlen—the change from an uncharged particle to a positive ray, or from the reverse process, the change of a positive ray while in the electric and magnetic fields into an uncharged particle by the coalescence with it of a negatively charged corpuscle ; a method of distinguishing between these cases is given on p. 233. For such a coalescence to take place, however, the velocity of the positive ray must be below a certain value ; if the velocity is greater than this the ray behaves like a primary one. When the difference of potential between the electrodes in the discharge-tube is much greater than is necessary to produce this velocity any secondary ray must have fallen through only a fraction of the potential difference in the tube, and must therefore have been produced near the cathode. Now it is just in this neighbourhood that the positive ions in the dark space have their greatest velocity and are most likely to produce fresh ions by collision. Thus it is probable that among the ions in the secondary rays there are some which have been produced by the collision of positive ions with the molecules of the gas in the dark space, while the primary rays which have fallen through the whole potential difference have been produced by the collision of cathode particles with these molecules.

There are a few, but only a few, ions which occur both as primary and secondary ; the positive atom of hydrogen with one charge is the most conspicuous example of this class ; others are the atoms of mercury and oxygen and the molecule of hydrogen. In most cases, however, the ions are quite distinct. On looking at the list of ions due to secondary radiation given on page 239 it will be seen that, with the exception of the hydrogen molecule, there is not one in which the molecule is intact, while many molecules are found among the ions in the primary rays; for example, the molecules of hydrogen, oxygen, marsh-gas, not to mention those of the monatomic gases like helium and mercury vapour. Again, the ions in the secondary rays carry in many cases more than one unit of charge; thus, for example, we have C_{++}, N_{++}, Hg_{++}, He_{++}, suggesting that the positively charged particles when they collide with a molecule in many cases detach more than one corpuscle from it.

It is very interesting to find that in the primary rays several different types of ions are found even in elementary gases like hydrogen or oxygen, for, as we have seen, we find both the atoms and the molecules amongst the primary rays in these gases. These ions are supposed to be due to the bombardment of the molecules by the cathode rays. How is it, then, that when we expose the molecules of a gas to bombardment by cathode rays we get two types of ions, atoms as well as molecules in the gases we have just mentioned? It is true that in the dark space next the cathode we have cathode rays with very different velocities; and one way of explaining the two types of ions would be to suppose that when the energy of the cathode rays exceeds a certain value, they split the molecule into atoms when they impinge against it, while the slower cathode rays only succeed in knocking a corpuscle out of the molecule without impairing the cohesion between the atoms. On this view the charged atoms would be produced by the fast cathode rays, the charged molecules by the slower ones. If this were the case, however, we should expect that the lines corresponding to the atom would be shorter than those corresponding to the molecule, as the minimum energy required to produce them is greater than that required for the molecule, and the place where the atoms are produced would therefore be further from the cathode than the corresponding place for the molecules; as a matter of fact, the lines for the atom are often, though not invariably, longer than those for the molecule.

Another way in which the different kinds of ions might arise is as follows:—Let us suppose that a diatomic molecule is made up of two atoms A and B, and that A is positively and B negatively charged. When the cathode rays pass through the gas they may strike either A or B, and detach a corpuscle. If A is struck, then, after the collision, A has two positive and B one negative charge, together they form a system with a total positive charge of one unit; the attraction, however, between A and B due to their electric charges has been increased, so that the system AB is less likely to break up into atoms than it was before the collision took place. Suppose, however, that B and not A is struck by the cathode particle, then after the collision B will be uncharged, while A has one unit of positive charge, the total charge on the system is again one unit of positive electricity; but as B has been deprived of its charge the electrical attraction between A and B is very much less than it was before the collision took place, so that the system will be much more likely to break up into separate atoms and supply us with a charged atom A. The negatively electrified atom B will be a little less likely to be struck by a negatively electrified cathode particle than the positively electrified one A. On the other hand, when a collision did take place, it would be easier to detach a corpuscle from the negatively electrified B than from the positively electrified A.

Similar considerations would apply to compounds as well as to elements. We might in certain cases get some of the atoms of a compound molecule liberated and not others. Thus, if the hydrogen atoms in marsh-gas CH_4 are negatively charged, and if one of them is struck by a cathode particle, it would lose its charge and be easily detached, the other hydrogen atoms which retained their charge would cling to the carbon atom.

The photographs hitherto described were made with discharge-tubes whose volume was considerably greater than 1000 c.c.; I have also made some photographs when the tube was very much smaller, the diameter being about 2 cm. The feature of these photographs is, that unless the pressure is reduced very low, when the potential difference between the electrodes is very large, almost the only thing to be seen on the plate, whatever gas may be in the tube, is the secondary radiation, negatively as well as positively charged, corresponding to the hydrogen atom; the negative portion is not infrequently almost as bright as the positive.

When the tube is filled with air, a very faint curve corresponding to the oxygen atom can with difficulty be detected on the plate; it is, however, much too faint for reproduction from a photograph. Though this line is so faint, it is remarkable that it is generally the first to appear when the photograph is developed; the hydrogen line, though so much stronger in the end, takes a much longer time to develop. It appears as if the hydrogen atoms had penetrated much more deeply into the film than the oxygen ones, but that close to the surface of the film the oxygen atoms produce more effect than the hydrogen ones. The relative intensities on the photographic plate do not always seem the same as on the willemite screen.

I find from the photographs that the slope of the straight part of the curves corresponding to the secondary radiation due to the hydrogen atom, negative as well as positive, for the slopes of the two are the same, does not vary appreciably with the potential difference between the electrodes in the discharge-tube. I have taken photographs with the tube in states for which the equivalent spark gap in air varied from ·7 to 4 cm., and found only very slight alterations in the slopes of the curves. As the velocity of the particles in the rays is proportional to the tangent of the angle of slope, this implies that the velocity of the particles in the secondary rays is almost constant, a result I had previously arrived at by the willemite screen.

I wish to express my thanks to Mr. F. W. Aston, of Trinity College, and Mr. E. Everett, for the assistance they have given me with these experiments.

XXVII. *Focal Isolation of Long Heat-Waves.*

By H. Rubens *and* R. W. Wood *.

THE isolation of very long heat-waves, which is usually accomplished by selective multiple reflexions (Reststrahlen method) can be accomplished also by selective refraction. It was shown in 1899 by Rubens and Aschkinass that it was possible to separate very long heat-waves from the radiation of an incandescent source by means of quartz prisms of small angle *. This method, involving the use of a spectrometer, did not however prove to be very efficient, on account of the large loss of energy, and the isolated radiation disappeared almost entirely if a quartz plate of any considerable thickness was interposed in the path of the rays.

The method which will be presently described is free from these objections, and has enabled us to obtain heat-waves of greater wave-length than any hitherto observed and with sufficient intensity to make accurate measurements of their properties possible. Like the other method, it depends upon the selective refraction of quartz, the separation being accomplished by means of lenses however.

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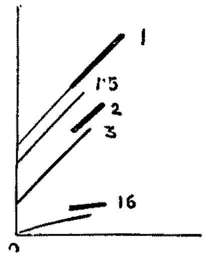
* Communicated by the Authors.

† H. Rubens and E. Aschkinass, Wied. *Ann.* lxvii. p. 459.

Fig. 5.



Key to fig. 5.—The figures represent the values of m/e relative to the hydrogen atom.

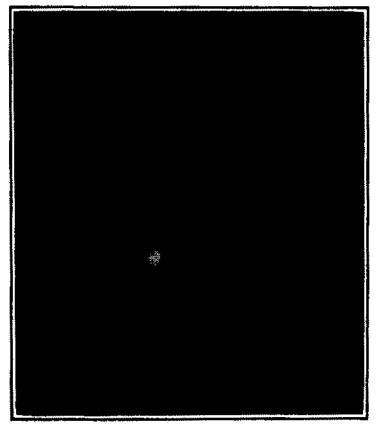


Fig. 8.

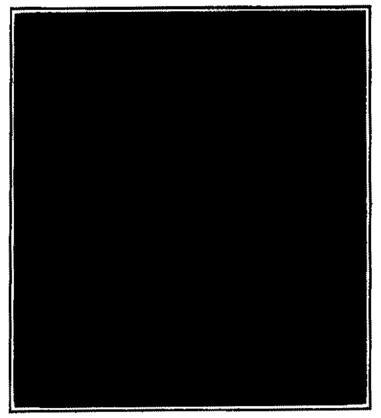


Fig. 9.

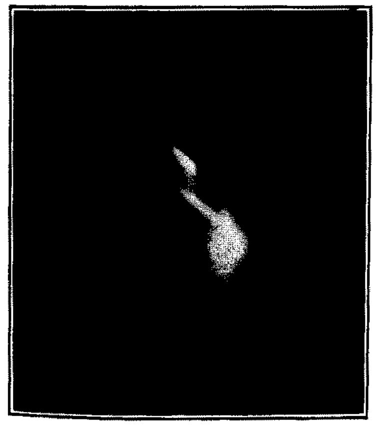
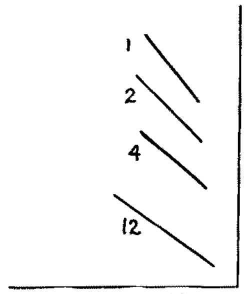


Fig. 11.



Key to fig. 11.

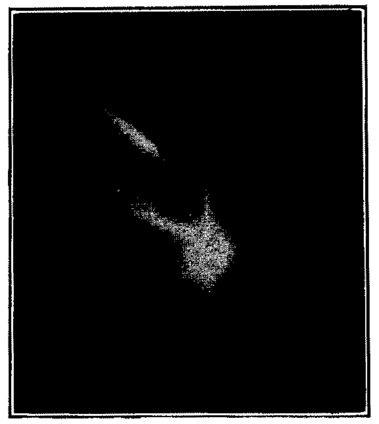


Fig. 12.

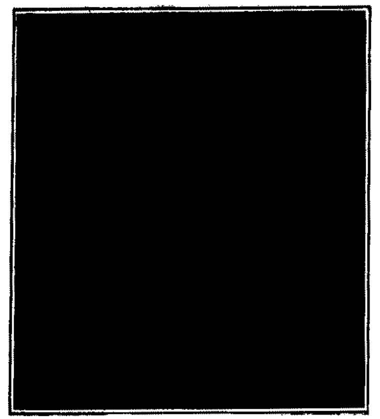


Fig. 14.

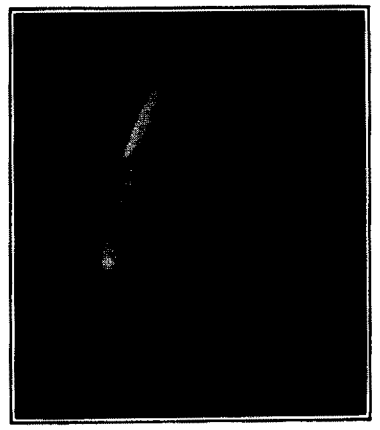
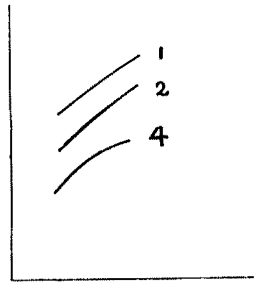


Fig. 13.



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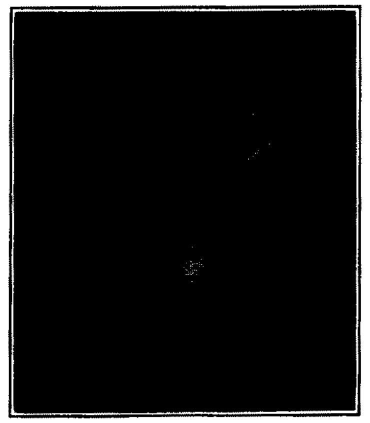
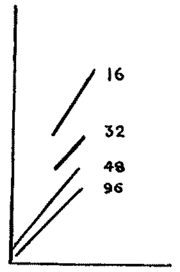


Fig. 16.



Key to fig. 16.

Fig. 15.

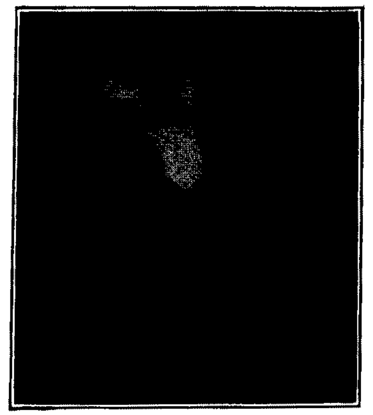


Fig. 17 a.

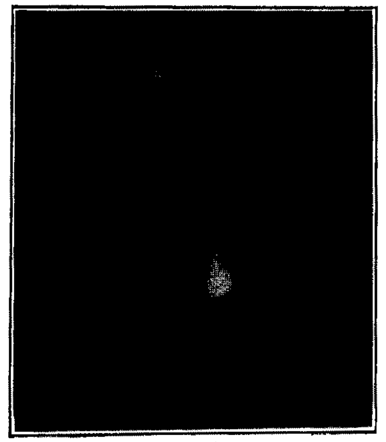
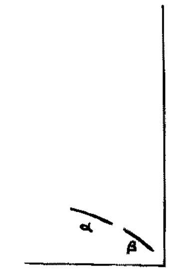


Fig. 17.



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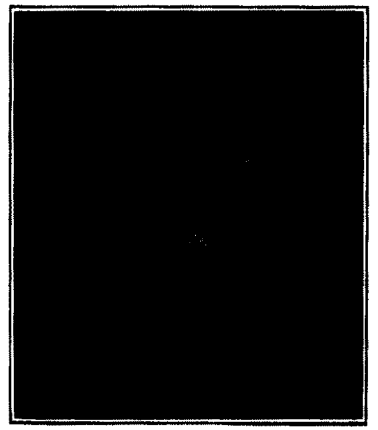

Fig. 18.

Fig. 19.

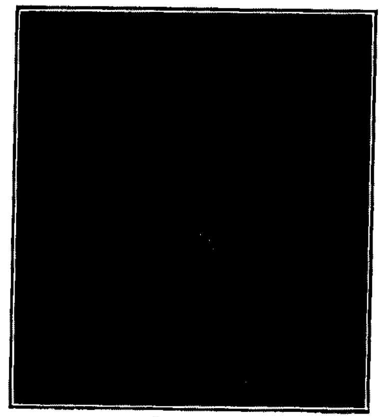

Fig. 20.

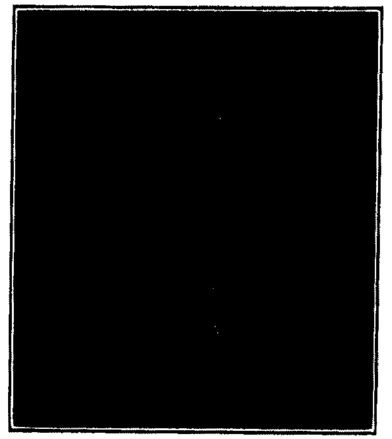

Fig. 21.