XVI. *On the Sensitive State of Vacuum Discharges.*—Part II.

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Introduction.

IN our previous paper we examined the essential conditions for the existence of sensitiveness in vacuum discharges, and found that sensitive discharges are produced by a rapid succession of discharges of free electricity from one or both of the terminals of the tube, each individual discharge being so small in quantity as to be instantaneous.* The effects which are produced by the approach of a conductor to a tube containing a sensitive discharge were shown to be due to the fact that these individual or component discharges are composed of free electricity, either of a positive or of a negative kind, and that this free electricity during its passage through the tube exercises its ordinary static induction through the space around it; and this, combined with the sudden and instantaneous character of the component discharge itself and the consequent suddenness with which the free electricity appears in any part of the tube, produces impulsive electric action on the sides of the tube and in the space outside it, leading to instantaneous rearrangement of the electricity within the conductor and consequently to discharges from the side of the tube in its immediate neighbourhood, to which these effects are immediately due.

While subsequent researches have confirmed us in our opinion as to the correctness of these conclusions, they have also brought home to us more fully the exact bearing which the examination of the sensitive discharge has upon the general theory of

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* It will be understood that the term "instantaneous" is not used in its strict sense of occupying absolutely no time, but in the sense of occupying so short a time that it may be neglected in comparison with the whole period between two discharges.

electricity. It is neither more nor less than the examination of the electric-spark. Each of the separate discharges was shown to pass through the tube in a time so short that it was negligible in comparison with the interval between two such discharges, so that each may be taken as a separate and absolutely isolated discharge; the effect of the rapid repetition of these individual discharges being only to render visible the phenomena which each of them would have presented had it been possible to observe it separately. Thus we are in reality observing the phenomena of the passage of an electric spark through rarefied gas, under circumstances, it is true, which cause great uniformity of conditions throughout the whole series of sparks, but which do not subject any one of the series to any peculiarity of attendant circumstances which would unfit it to be taken as a representative of such electric sparks.

The interest of the investigation rises still higher when we consider it in relation to the continuous discharge. The latter bears precisely the same relation to the electric arc that the sensitive discharge bears to the electric spark; and when we see that these two types of discharge have such striking resemblance, if not identity, of phenomena, we see that a study of them will probably give to us an insight into the relationship of the electric arc and the electric spark which would otherwise be unattainable. Indeed, it is doubtful whether the real intimacy of their relationship would have passed beyond the stage of conjecture but for the light thrown upon them by observing the modifications which each undergoes when the medium through which it passes becomes rarefied. So closely do these modifications resemble one another that there is no doubt that the careful and exhaustive examination of the electric arc in its process of development into the continuous vacuum discharge which we owe to Mr. WARREN DE LA RUE might without much error be taken as giving the development of the electric spark into the intermittent or sensitive vacuum discharge.

Such being the case, we have in the following paper continued our researches into the phenomena of sensitive discharges with the aim of establishing conclusions as to the structure and mechanism of the electric spark. But before so doing it was necessary to extend the conclusions of our former paper to the case of high vacua, the experiments upon which they were based having been exclusively performed with tubes containing gaseous media at a pressure of from about 1 millim. of mercury upwards. The special peculiarities of discharges in high vacua have also required separate examination in order that the phenomena of vacuum discharges might be viewed as a continuous whole. These matters have necessarily occupied much of our attention, but they have not wholly prevented our arriving at certain general conclusions as to electric discharge which we hope may in the future turn out to be of importance.

As we have seen no reason to alter any of the views expressed in our last paper we shall take them as our starting point. So far as the immediate purposes of this paper are concerned, they may be taken to be as follows: that the intermittent discharges which give the sensitive vacuum discharge pass into the tube under the influence of local tension at the terminal and pass through the tube in the shape of free electricity until they meet with and are neutralised by discharges of an opposite kind, which usually happens at the opposite terminal of the tube. This passage through the tube is not instantaneous, though it is extremely rapid; and the portion of the tube in advance of the discharge is in a state of electric emptiness (or approximately so) while that behind the discharge is filled with the free electricity of the discharge—the discharge spreading out like a pair of lazy tongs and not passing through the tubes in a compact form like a bullet.

The question of the nature and formation of striæ will not here be again discussed; for, in addition to the fact that the explanations given in the previous paper exhaust the subject so far as the authors are at present able to deal with it, the high vacua with which we shall chiefly have to do are not suited to the production of striated discharges. The ideas of positive luminosity and negative dark space will, however, be just as important in this investigation as in the former one, for they are the fundamental elements of all vacuum discharges.

It will be observed that we adhere throughout to the language of the two-fluid theory of electricity. This is done because it not only suffices for our purposes, but is the one that is most naturally suggested by the phenomena. But it must be borne in mind that this is by choice, and for the purposes of clearness and convenience only, and not as expressing any scientific conclusion as to the theory which ought to be preferred. We are not yet sufficiently advanced to be able with any profit to consider the merits of the rival theories.

XIV.—*On the effect of intermittent inductive action of an impulsive type upon continuous vacuum discharges.*

The discharges treated of in our former paper were discontinuous; and the influences whereby the "special" and "relief" effects were produced were more or less directly the outcome of the intermittence of the discharges themselves. In the present section we shall deal with phenomena produced in a different manner. The discharges operated on will be in themselves continuous (using that term in the same sense as in our former paper, *i.e.*, as equivalent to non-sensitive), and the effects will be produced by electrical influences being brought to bear upon them which are due to the intermittence of a wholly distinct electrical system.

The arrangement ordinarily used by the authors for the purpose of examining the phenomena described in this section consists of two large HOLTZ machines, in one of which there are twelve revolving plates of ebonite, and twelve fixed plates of glass, and in the other there are six such plates (Plate 25, fig. 1). The discharge from the larger machine is made to pass through a tube of moderate vacuum, say about 2 millims. pressure, care being taken that no air spark is interposed at any place in the circuit, so that the discharge is neither intermittent nor sensitive. A narrow slip of tinfoil is then placed round the tube nearly midway between the ends, and is connected by a wire to one of the terminals of the smaller HOLTZ machine. The arrangement is then complete. Its electrical effect is easy to comprehend. When the terminals of the first machine are separated (those of the second machine being closed) the discharge from that machine passes through the tube in the form of an ordinary non-sensitive discharge wholly unaffected by the presence of the tinfoil or its connexion with the terminals of the second machine, inasmuch as these terminals—although serving as the channel through which passes the current generated by the second machine—are electrically inert for all purposes of interference. But when the terminals of the second machine are slightly parted a wholly different state of things is set up. Sparks pass from the one terminal to the other, and each such spark represents an impulsive alteration of electric tension in opposite directions at the two terminals. At the positive terminal it causes a sudden downfall of positive potential; at the negative it causes a sudden downfall of negative potential, or as we might better describe it, a sudden rise of potential. And these changes communicate themselves to all bodies in metallic connexion with these terminals in the form of sudden impulses of negative and positive electricity respectively.

We will assume first of all that the tinfoil on the tube is connected with the negative terminal of the smaller HOLTZ machine, *i.e.*, the machine that is used for producing the interfering system. Then in the interval between the passage of two consecutive sparks between the terminals of the machine, the wire to the tinfoil and the tinfoil itself will be charging up with negative electricity. But when the spark comes this will disappear; in other words, there will be a change equivalent to a sudden rush of positive electricity to the tinfoil. This will be repeated every time a spark passes, which may amount to many hundred times a second if the distance between the terminals of the machine be small. Thus we shall have a like number of sudden impulsive positive chargings-up in each second, the intervals between two consecutive chargings-up being occupied by a gradual and continuous (though of course very rapid) in-pour of negative electricity, the two actions neutralizing each other in each complete period. In other words, we shall have reproduced in the tinfoil ring precisely the action that goes on when we place a similar ring round a tube through which is passing an intermittent discharge with the air-spark in the positive, and connect it with the positive terminal.

Since the electrical action within the tinfoil is identical in the two cases, it follows that the immediate consequences of that action will be alike, however much its ultimate effects may be modified by the difference in the electrical conditions in the interior of the tubes. And this is so. Through the influence of induction each one of these positive impulses causes a similar discharge of positive electricity from the inner surface of the glass beneath it, leaving on that surface a like quantity of negative electricity. This becomes gradually freed during the interval which elapses before the arrival of the next positive impulse—an interval which, though actually occupying only a very minute period of time, is yet, in all probability, many times as long as the time occupied by the impulse itself. This is precisely the action which takes place within a tube with positive intermittence when the positive special is being produced; the sole difference being that in the present case there are no equivalent discharges of positive electricity synchronously advancing along the tube towards the tinfoil which get satisfied by the negative electricity left behind at the tinfoil, while the positive discharges that are produced there pass out at the negative terminal of the tube.

What, then, is experimentally found to take place in the present case? It is found that if the distance between the terminals, or as it might be termed the *air-spark* of the interfering system, be properly adjusted, we have exactly the same visible appearances as we have in the case of the most perfect form of the positive relief. There is the same complete separation of the positive column, the same sharp bright termination of the truncated portion of it, the same hollow cone of positive discharge separated from the truncated portion of the positive column by the familiar dark space. Nor is it only when the adjustment is very precise that the resemblance exists. With other lengths of air-spark we have other forms of these positive effects, all equally characteristic, although not so readily recognisable as the typical form above described. Just as in producing the positive special a proper adjustment of the length of the air-spark was necessary to produce the typical form, and any excess or defect from this exact length of spark caused the appearances to deviate to a greater or less degree from the typical form, so it is in the present case. And there is so striking a resemblance between the other forms in the two cases that we may express it by saying that they are substantially the same, differing only in the prominence which they respectively give to certain kinds of variance in the details. We thus see that the presence of the *synchronous* discharges proceeding from the positive terminal is not essential to the formation of these typical forms which we have hitherto associated only with the positive special, and its correlative phenomenon the negative relief.

The explanation of this result is very simple. The electricity of the interfering system rushing in accumulated charges to the tinfoil, drives off equal or at all events comparable charges into the tube. These fly to the negative terminal as the goal most suitable for them, thus, as it were, anticipating a portion of the continuous current that would have passed along that portion of the tube in the succeeding interval. This portion of that current is arrested and satisfied by the negative that is left behind on the inner surface of the tube under the tinfoil; and, inasmuch as this negative proceeds from a fixed region (which therefore acts for the moment as a negative terminal or the negative end of a stria), we have the usual phenomenon of a fixed head of luminosity (or, as we may now term it, stria-head), sharp and bright in outline, indicating its reception, such head being separated from the region from which the negative electricity comes by the accustomed dark space.*

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* See Phil. Trans., 1879, Plate 16, fig. 10.

But it may be objected that this explanation seems to assume that the sum total of the discharges due to the interfering system is equal to the total of the continuous discharge, an assumption manifestly improbable, seeing that the interfering system is produced by a smaller machine, and, in addition, has an air-spark interposed in its circuit, the effect of which is to decrease the quantity, although it greatly increases the tension of the resulting discharge. The answer to this is, that although considerable change in the length of the air-spark is possible without destroying the typical form of the positive effect, yet in extreme cases we do find indications of just such an imperfect action of the interfering system as would be expected from considerations such as these. The truncated positive column and the hollow cone separated from it by a dark space are seen faintly amid the ordinary positive luminosity of the continuous discharge in the tube, giving the appearance of a superposition of two discharges, the positive luminosity of the one being continuous, and that of the other interrupted in the way above described. But even in the cases where the action is perfect and gives to us the pure typical form of positive effect, it must not be supposed that theory requires an equality between the sum total of the inductive discharges in the tube, and the quantity in the continuous discharge. If the relieving system is sufficient to create the structure we have described, and to maintain it for a portion of the interval between two discharges, it may well be that during the remainder of the time the discharge, finding this structure ready to hand, might use it during the remainder of the interval, seeing that it is of precisely the type that vacuum discharges find most suitable for their propagation. For it must be remembered that the experience we have of stria spaces, and above all of the dark space round the negative terminal, shows us that the normal state of discharge under fixed conditions is an invisible discharge through a space of definite length (depending primarily on the degree of exhaust) lying longitudinally along the path of the discharge between a sharp bright luminosity on the side from which the positive comes, and a hazy luminosity on the side from which the negative comes. All these conditions are present in the structure we have described,* and it may well be that in spite of its being due to foreign influences the continuous discharge makes use of it in the same way as it would make use of a stria of its own creation.

Be this as it may, there can hardly be any doubt of the interpretation of the observed appearances so far as the discharge is concerned. But, in corroboration of it, we may add the following facts gathered from an examination of the discharge in other parts of the tube. If the interference be not too violent, it will be found that the discharge in the portion of the tube lying between the tinfoil and the negative terminal of the tube is sensitive, and gives all the signs of positive intermittence, while that between the tinfoil and the positive terminal is either wholly or almost non-sensitive. This shows that the discharge in the former portion of the tube is

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* We shall presently find that this view derives strong corroboration from the behaviour of the continuous discharge when subjected to interference by negative impulses.

carried by bursts of positive electricity, while that in the latter portion is left to go on its even course (Plate 25, fig. 2).

We are brought to the same conclusion if we observe the phenomena produced by placing in circuit with the affected tube two other tubes, one at each end. We then find that the one at the negative end contains a sensitive and the one at the positive end a non-sensitive discharge.* To render the proof quite complete, two pieces of tinfoil were placed on the tube, and were connected, the one to the positive terminal, the other to the negative terminal of the interfering system. When both were so connected it was found that, although they each produced the accustomed effect in the tube, the discharge was not sensitive in the two auxiliary tubes in circuit, but that, if one of the pieces of tinfoil was disconnected from its terminal, sensitiveness appeared in the corresponding one of the tubes in circuit. Thus, when the negative terminal of the interfering system was alone connected with tinfoil on the affected tube, so as to produce positive discharges within the affected tube, it was found that the discharge in the tube at the negative end was sensitive, but this sensitiveness disappeared when the positive terminal of the relieving system was also put in connexion with a piece of tinfoil on the affected tube. The sudden in-rushes of positive electricity from under the one piece of tinfoil were neutralised (so far as the remaining portion of the circuit was concerned) by the synchronous in-rushes of negative electricity from under the other piece of tinfoil, and thus the discharge in the two tubes in circuit with the affected tube remained sensibly uninterrupted.

It is, however, a necessary condition for these latter phenomena that the interference should not be too violent. If the air-spark in the relieving system is increased beyond a certain point, the discharges induced in the affected tube (which we will still assume to be of positive electricity) become so large and violent that they are more than sufficient to satisfy the negative electricity coming from the negative terminal; they consequently no longer go only towards the negative terminal but spread out both ways, and can even be made to pass out at both terminals of the tube. The discharge is then sensitive throughout the whole length of the tube; and the sensitiveness in

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* This experiment is very useful in bringing into prominence the essential difference that exists between the passage of electricity through conductors and its passage through gas. It shows us that a current which in some portion of its circuit has to pass through gas can be rendered intermittent in one part of its course while it remains unaffected and continuous, or approximately so, in the other. This is radically different from OHM's law and the general theory of currents through conductors, for these require that at any instant of time the quantity flowing across each section of the conducting circuit should be the same. It is of course true that, whether a portion of the circuit be gaseous or not, the *average* quantity flowing across each section must be the same, but the equality is only in the *average* when taken over a finite and appreciable period of time, and no longer exists at each moment. The tube acts precisely as the air-vessel of a fire-engine. All the electricity that comes into it passes out again, but no longer with the same pulsations. The tube sometimes contains more and sometimes less free electricity, and acts as an elastic or expansible vessel would act if it formed part of the path of a stream of incompressible fluid.

both directions, having been produced by the same interfering impulses, will be of the same character, and will exhibit the same features; thus in the case described above, viz.: positive impulses, we have a double hollow cone at the tinfoil. But the effects are no longer pure, and would not be specially worth notice were it not that some of them resemble very strikingly some of the positive-special effects obtained in the way described in our last paper, with a very long air-spark. It is probable that this same explanation is applicable in both cases. In the present case the power that we possess of altering independently the interfering system without otherwise altering the current affected, enables us thoroughly to test the truth of our explanation. By slightly increasing the air-spark, the limit of the effect of the induction discharges may be made to advance as slowly as we please towards the positive terminal; and in a well striated discharge the authors of this paper have succeeded in putting out one by one the striæ lying between the tinfoil and the positive terminal. The portion of the discharge that remained striated was still continuous and non-sensitive, while that between the striated portion and the tinfoil (as well as that between the tinfoil and the negative terminal) became highly sensitive, showing positive intermittence.

If the wire from the tinfoil be connected to the positive terminal of the machine in the interfering system, we shall of course have negative discharges within the tube, and all the intermittence will be of a negative type. With this arrangement we are able to produce the well known phenomenon of repulsion of the positive luminosity; and, with proper adjustments, to get excellent examples of what we have called the ring-terminal form of negative effect, and of all the forms with which we are familiar in positive-relief or negative-special effects.* Again, as in the case of the positive air-spark, if the air-spark in the interfering system be long, so that the intervals between the impulses are very considerable, or if in any other way we deviate far from the conditions which give us the best effects, we are apt to find mixed results, belonging partly to the original discharge and partly to the interfering system. This fact makes us incline more strongly to accept the explanation given above of the ease and completeness with which the typical positive effect can be obtained, and the strong resemblance which the results of positive interference bear to those of the positive-special through a great range of air-spark. The negative is very inferior to the positive in this respect, and naturally must be so, since the structure set up by the negative impulses, though suited to the needs of their own circumstances, is wholly unlike the structure that the discharge would shape for itself in order to facilitate its passage through the tube; and hence there is a greater tendency for it to reassert its former shape and appear superimposed upon the visible results of the interference.†

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* See Phil. Trans., 1879, Plate 17, figs. 12, 13, 14.

† This distinction between the positive and the negative effect of an interfering system is so marked that when the interfering system is of small quantity it becomes very difficult to recognise the effects produced at the tinfoil by negative impulses. The best method of showing the effect of these negative impulses in causing intermittence in the main discharge is to place the finger on the tube between the

Before leaving this part of the subject we must mention that this arrangement enables us to obtain striking examples of artificial striæ. The mode of doing so, viz.: by connecting two rings of tinfoil upon the affected tube to the negative terminal of the machine in the interfering system, will be obvious, after the description given in our former paper of the mode of obtaining artificial striæ by means of the positive-special effect. But in some instances it has not been found necessary to employ two rings. So perfectly does the inner surface of the tube beneath the tinfoil and the interior of the hollow luminous cone perform the functions of a negative terminal, that the portion of the discharge between the positive terminal of the tube and the tinfoil has been found to be organised in every way like an ordinary discharge. When the adjustments were suitably arranged, there might be seen standing at the proper distance from the tinfoil a perfect stria of a flat disc-like shape (Plate 25, fig. 3). This stria was the representative of the negative glow, but it took the ordinary shape of a stria because it was not constrained to assume a distorted form by the presence of any rigid metallic negative terminal, but had in place of it a system almost, if not precisely, what any non-terminal segment of a striated discharge in such a tube would naturally have, viz.: a hollow gaseous structure specially framed to receive the positive discharge which came from the bright head of the stria next to it. Behind this stria came a long dark space, the representative of the ordinary negative dark space; and behind this again the positive luminous column starting from the positive terminal.* It will of course be understood that such perfect effects as these are not common; in order to produce them it is necessary that the magnitudes of the interfering and affected systems should have due relation to one another as well as that the air-spark in the former should be of proper length.†

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tinfoil and the positive terminal. The usual indication of negative intermittence will then appear in the form of luminosity proceeding from the inner surface of the tube beneath the finger.

[*] The significance of this last result as bearing upon the general theory of the striated discharge given in our former paper is very great. In the first place we find the bright termination of the truncated positive column (to which our theory assigned the functions of a stria) actually taking the form of a single perfectly formed stria. In the next place we see that this stria, having just the same advantages that a negative glow has in respect of fixity of conditions, and probably also in respect of the readiness with which negative electricity is supplied to it, is like a negative glow, followed by a long negative dark space. It is in fact in much the same position, electrically and in all other respects, as the negative glow of a tube where the negative terminal is a concave metal plate occupying the whole of the tube. This strongly confirms the view that the negative glow and the negative dark space form a physical unit of discharge (following the language of our former paper) identical in nature and function with the unit composed of any stria and its dark space, but modified by local circumstances; since we find that when we produce a stria under the same circumstances under which a negative glow is formed it is attended by a similar long dark space.

[†] In connexion with what has been above stated about the proportion between the strength of the main and the interfering discharges, and also with the experiments described in Section IX. of our former paper (p. 201, and Plate 18, fig. 16), the following fact deserves mention. In some cases where two rings of tinfoil were used, and two striæ corresponding to them were formed by connecting them with

It must not be thought that the arrangement described above is the only arrangement by which these effects can be produced. Instead of the HOLTZ machines, any two sources of high tension electricity giving out continuous currents may be used, providing that it is possible, as must generally be the case, to render the interfering system intermittent, either by the introduction of an air-spark or otherwise. For some purposes it is very convenient to use a current from a large condenser which is filled by a coil for illuminating the tube. Other arrangements might be made to give the rapid impulsive electrical actions which are requisite in the interfering system. But all these modes of arriving at the results would be electrically equivalent, and do not require further mention here.

XV.—*On the standard-tube method of examining intermittent vacuum discharges.*

The results given in the last section have been utilized by the authors of the present paper to furnish them with a new method of testing the intermittence of vacuum discharges, which has been, and promises still to be, of very great utility in the investigation of the mechanism of such discharges. It differs essentially from almost all the modes of testing intermittence described in the former paper in that the luminous effects, by which the nature of the intermittence is recognised, are produced, not in the tube under examination, but in a separate tube which may be chosen on account of its manifesting such effects very readily, and which, being used throughout the whole of the experiments, may be termed the standard-tube. This avoids the great difficulty that otherwise must have been faced in extending the results of our former paper to vacua of a different character to those used in the experiments there described. So long as the nature of the intermittence could only be judged from the appearances in the tube itself, each separate tube presenting phenomena in any way differing from those which had been previously observed and classified, had to be subjected to a separate examination until the observer became familiar with its peculiarities. But with the new method this labour is avoided. Only one tube has to be known thoroughly, and all others, however much they may differ among themselves, are made to express the nature of the intermittence of the discharge that is passing through them in terms of the appearances in the standard-tube.

the negative terminal of the interfering machine, it was found that the formation was rendered more perfect by leading a wire from the positive terminal of the interfering machine to a point on the tube between the rings near the stria due to the first ring (*i.e.*, that nearest the negative end of the tube). This, in fact, supplied synchronous impulses of negative electricity in the manner figured in fig. 16A of the plate above mentioned. The circumstances under which these auxiliary impulses were found useful were doubtless those of an excess of positive thrown in from the surface of the tube below the tinfoil, or as it may also be described a deficiency of negative to satisfy the positive coming up from the second ring.

On the one hand these facts supply an interesting corroboration of what has been said above; and on the other they illustrate the additional power which the present method (viz.: that of an independent source of electricity) furnishes for experiments on interference in general, and especially with discharges not in themselves sensitive.

The way in which this is attained is as follows:—We have seen in the preceding section that rapid electrical impulses of a positive or negative type upon the outside of a tube carrying a continuous discharge, produce within the tube the familiar positive and negative effects respectively; that is to say, the phenomena of positive-special and relief effects. Now it is clearly a matter of indifference in what way these rapid electrical impulses are produced, provided that they have the sharpness and rapidity requisite for producing the luminous effects which are associated with sensitive discharges. Hence, instead of producing these impulses in the manner described in the previous section, it suffices to bring the wire from the tinfoil into contact with the surface of a tube through which a sensitive discharge is passing. If that sensitive discharge be one of positive intermittence, the positive charges that burst through the tube will drive off like discharges of positive electricity along the wire that is in contact with the tube, and we shall have positive effects (that is to say, phenomena of the same class as positive-special effects) in the standard-tube, *i.e.*, the one through which the continuous discharge passes. If, on the other hand, the sensitive discharge be one of negative intermittence we shall have negative effects in the standard-tube, *i.e.*, phenomena of the type of negative-special or positive-relief effects. Thus, the nature of the intermittence in the sensitive discharge will express itself in the appearances in the standard-tube. Nay, it is not only the type of the intermittence in the sensitive discharge that will thus be indicated by the standard-tube. It is clear that the violence of that intermittence will affect the result, and this may be ascertained by examination of the standard-tube; and there is no doubt that all other qualities which a sensitive discharge can possess will in some way or other express themselves in the phenomena which they cause in the standard-tube.

It will be seen from what we have already stated that if the appearances in the standard-tube were thoroughly known it would be possible to read with accuracy the exact nature of the electrical disturbances that are going on in any tube. It is probable that at some stage of the investigation into the mechanism of vacuum discharges it may be necessary to do this, and it will then be desirable to ascertain what form of tube, what kind of gas, and what state of exhaust is best for a standard-tube. But at present this test has only been used by the authors of this paper to establish certain broad fundamental principles; and as this could be done under circumstances very favourable to the action of the test, they have not yet pursued these questions further. They have, however, tried various sources for the continuous discharge that is used in the standard-tube, and on the whole they find that the most sensitive is obtained from a large condenser maintained at a very low state of charge so that the discharge through the standard-tube is not great in quantity. The use of a HOLTZ machine for the source of the discharge in the standard-tube has, however, so great an advantage in the matter of convenience that most of their experiments have been tried with discharges so produced.

The arrangement, therefore, is as follows (Plate 25, fig. 4):—The standard-tube, which is generally a hydrogen or nitrogen tube of very low resistance, but of considerable diameter and length, is placed in circuit between the terminals of a HOLTZ machine, so that the discharge from the machine passes in a continuous manner through it. A narrow strip of tinfoil is placed round the standard-tube and connected by a wire with a flat piece of metal fixed to the extremity of a glass rod which is held in the hand. To test the intermittence of the discharge in any tube one has only to bring this piece of metal into contact with it.* The intermittent discharges in the tube, of whatever nature they may be, drive off from the flat piece of metal and through the wire in connexion with it electricity of a like sign to that of the pulses of free electricity that pass through the tube. This electricity, rushing to the tinfoil upon the standard-tube, produces by induction discharges within that tube, which are of course recognisable. Thus, as we have already said, positive intermittence in the tube under examination produces in the standard-tube what we have termed positive effects, *i.e.*, positive discharges from the interior surface of the tube either in the form of simple positive luminosity, or in the more perfect form of the hollow cone accompanied by the truncated positive column and the intermediate dark space. Negative intermittence, on the other hand, produces constriction of the positive column, and in cases in which the action is more intense it gives the ring-terminal effect.

Used as above described, this test leaves nothing to be desired so long as the intermittence in the tube under examination is positive in type. It would be difficult to exaggerate the sharpness with which all the details of the positive effects that have so often been referred to in this and our former paper come out in the standard-tube so soon as any positive intermittence appears in the other. But with regard to negative intermittence the case is different. It is, for the reasons given in the last section, very difficult to get good negative manifestations at the tinfoil upon the standard-tube. Even when they do appear they are often confused by the superposition of luminosity due to the discharge in the standard-tube. The best way to deal with the difficulty is to observe the nature of the discharge between the tinfoil and the positive terminal by placing the finger upon the tube as mentioned on page 571. We are then examining a discharge composed of a continuous and a negatively-intermittent portion superimposed one on the other. The latter will, of course, cause positive luminosity to appear within the tube beneath the finger, just as much as though the former was not present, and thus the presence of negative intermittence in the original tube will be demonstrated. With this mode of procedure the standard-tube method is probably as delicate a test for the existence of negative as it is of positive intermittence, though it still labours under great disadvantages when it is desired to learn something

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* If it is desired to augment the effect on the standard-tube a piece of tinfoil of tolerably large size can be placed upon the tube that is under examination, and contact can be made with it instead of with the naked surface of the tube. If it is desired to diminish the effect it can be done by allowing the piece of metal affixed to the glass rod to remain at a suitable distance from the tube under examination without coming into actual contact with it.

more about the nature of the intermittence, for we have no longer the power of detecting slight changes in the effects produced in the standard-tube as is the case when the sharply defined positive effects are under examination.

It is obvious that if the standard-tube be at a considerable distance from the tube that is to be tested, the relieving system, composed of the tinfoil and the wire, will have considerable capacity, and thus the impulse on the tinfoil will lose proportionally in intensity. It is necessary, therefore, that they should not be too far apart. But there is a certain difficulty in placing them near together, for the tube containing the intermittent discharge acts by induction on the discharge in the standard-tube and makes it behave as though it were intermittent, even when there is no metallic connexion between the surfaces of the two tubes. But this is not of very serious importance, for the effect is of the same nature as that produced by the tinfoil, and differs from it only in being feebler and more diffused.

It is often useful to place a second ring of tinfoil round the standard-tube unconnected with the tube that is being examined (Plate 26, fig. 5). By touching this we shall discover the nature of the intermittence produced in the standard-tube by the inductive discharges which are caused (either through the medium of the tinfoil, or directly as mentioned in the last paragraph) by the influence of the tube under examination. If the intermittence in the standard-tube be of a positive type, then it is clear that such also was the original intermittence, and *vice versâ.* In cases where the electrical disturbances are very violent this is a useful addition to the tests already described, as the results it gives are of a milder type than those produced at the ring of tinfoil which is in direct connexion with the other tube.

This method is not confined to cases in which the electric pulsations in the system under examination are actually in the form of discharges. It enables us to contrast any systems in which there are electric variations of a suitable type. Thus, for instance, we can by its aid compare the relative intensity of the disturbances at the terminals of the tube, at a point on its surface and at an intermediate terminal not in connexion with any portion of the external circuit. The effect at the air-spark terminal is always by far the greatest. But no general rule holds as to the others, save that there is but little difference between the intensity of the disturbance at an intermediate terminal (wherever it be situated) and that upon the surface of the tube. Nor is there, as a rule, much difference between the disturbance at the non-air-spark terminal and an intermediate terminal. On the contrary, it would seem that tube and terminals are all on much of an equality so soon as the electricity has once launched itself into the tube from the air-spark terminal.

XVI.—*On the Leyden-jar effect of vacuum tubes.*

We are about to touch on a subject which merits a much more complete investigation than we have as yet given it, not only because the influence of this property of vacuum tube ramifies in all directions throughout the whole of the phenomena which they present, but also because there is no doubt that an attentive study of it would throw great light on the nature and capabilities of a vacuum tube considered as a system capable of being affected by electrical influences.

It is well known that a vacuum tube after being used to convey a discharge is often strongly charged; the gas within the tube, therefore, or the interior surface of the glass can retain a considerable quantity of free electricity. And further than this, a vacuum tube is capable of giving considerable relief to a sensitive discharge in another tube, just as a conductor would, showing that the inductive discharges which take place within the tube have much the same effect that the displacement of electricity in a conductor would have. This is rendered evident by the inductive discharges that become visible in the neighbouring tube, which must represent relief given to the sensitive discharge. The exact amount of this effect is difficult to measure, but it is plain that the result is to make the tube act for the moment much as a Leyden jar would act in which the inner tinfoil was in connexion with earth, for the superfluous electricity on the inside of the tube, though it cannot be driven out of the tube, is driven off from the inner surface of the jar, and remains for the moment as a charge in the rarefied gas within the tube.

The capacity of a vacuum tube to act as a relieving system is immensely increased by passing a continuous discharge through it. This is seen in experiments with the standard-tube. If we mark the effect produced on the tube under examination by connecting a piece of tinfoil upon it with a piece of tinfoil upon the standard-tube (which is of course a relief-effect) and then suddenly stop the discharge in the standard-tube, we shall see an immediate diminution of the effect. In positive-relief, for instance, we have found the discharge-effect pass into mere repulsion, a change which as we have shown in our previous paper indicates a diminution in the capacity of the relieving system. And in some cases this difference is very marked, showing that the passage of the continuous discharge greatly facilitates the redistribution within the tube of the free electricity which is developed by the action of induction from the discharges that are passing through the sensitive tube. That this should be the case is not surprising when one has regard to the phenomena which have been described in Section XIV.

The attention of the authors of the present paper was drawn specially to the subject of the capacity of vacuum tubes as receivers of electricity by a very peculiar phenomenon. They noticed that on touching tubes containing a sensitive discharge, severe shocks were sometimes experienced, while at other times no such shocks were felt. It was found that this was not due to any greater length of air-spark in the former case, for the two effects would occur with the same length of air-spark. On examination it was found that the severe shocks were felt when that terminal of the machine was connected to earth which was separated from the tube by the air-spark interval, but not otherwise (Plate 26, fig. 6). In other words, we may say that it occurred when the earth connexion was *behind the air-spark,* reckoning from the tube.

A little consideration suffices to explain how this is caused. Let us suppose that the air-spark is in the negative, so that the positive terminal of the machine is in metallic connexion with the positive terminal of the tube, while the air-spark is situated between the negative terminal of the tube and that of the machine. Then, as we have said, the strong shock will occur when the negative terminal of the machine is put to earth, and not otherwise.

Let us consider how the discharge takes place. The negative terminal of the machine and all bodies metallically connected with it are maintained at potential zero by means of the earth connexion. Hence the negative side of the air-spark interval is at potential zero, and would remain destitute of free electricity if free positive electricity did not collect upon the surface of the metallic body forming the other side of the interval. But, as such is the case, free electricities of opposite signs accumulate on the two surfaces until, through their tension and their inductive action upon one another, the discharge is brought about. Now, how has this positive electricity accumulated upon the positive side of the interval? It is not due to the influence of the negative side, for that, as we have seen, would have been inert. It must, therefore, have become charged solely through the accumulation of electricity at the positive terminal of the machine which has flowed from thence into the tube and, passing through it, has emerged at the negative terminal and charged the positive side of the air-spark interval. In this process the tube has become fully charged. When a discharge comes, the tube, like a Leyden jar, will empty itself, and thus the amount of electricity passing will be augmented by the whole of the charge which the tube can hold. The shock, therefore, which is the inductive effect of this sudden discharge of the large stock of accumulated electricity, will be proportionately severe.

Compare this with the case in which (with the same arrangement of air-spark) the positive terminal is to-earth. The tube is now kept at potential zero,—or, more correctly, its positive terminal is. The active cause of the discharge is now the electricity accumulating on the negative terminal of the machine, and, although it no doubt produces a displacement of the electricity in the system on the other side of the air-spark interval, it is clear that it cannot cause the tube to become charged, connected as it is with earth at the positive terminal. Hence, when the discharge takes place, it is only the interchange of the free electricity on the two sides of the air-spark interval, and there is no accumulated store in the tube to take part in the discharge. The shock is accordingly very much smaller.

There are two very interesting experiments which serve to confirm the justness of these conclusions. The first is an application of an experiment described in Section XIII. of our previous paper (Phil. Trans., 1879, p. 220, and Plate 20, fig. 26). In order to ascertain the condition of a tube in advance of the discharge, a piece of tinfoil was fastened to a glass rod which was then laid along the tube, the piece of tinfoil resting upon it at a spot near to the non-air-spark terminal of the tube. A piece of tinfoil was then laid on the tube near the air-spark terminal and connected with the former piece by a fine wire. The consequence of this is, as we know, that the piece near the air-spark terminal derives relief from the other piece; and, in the experiment above referred to, it was shown that the efficacy of the system to give relief was greater as thus arranged than it would be if the glass rod with the tinfoil were moved into a position at right angles to the tube, so that the tinfoil would be as far as possible from the tube. The conclusion deduced from this was that the further end of the tube was in the act of charging up in the contrary sense to the air-spark pulse at the moment that the discharge occurred. Now if this be tried with the Leyden-jar arrangement (*i.e.*, with the earth connexion behind the air-spark) it will be found the effect is intensified, and that the tinfoil gives very much greater relief when upon the tube than in any other position; showing that the further end of the tube is rapidly charging up at the time of the air-spark discharge. Thus if the air-spark is in the positive the relieving tinfoil will supply more negative when on the tube than otherwise; in other words, the negative end of the tube must be receiving a rapidly growing negative charge. And this is exactly what must be the case if the explanations given above are correct.

The other experiment is a very remarkable one. We take a tube of moderately high exhaust through which is passing a discharge of considerable quantity, with the air-spark in the negative, and place, as before, the earth connexion behind the air-spark by connecting the negative terminal of the machine to earth (Plate 26, fig. 7). The consequence of this arrangement is that we get a violent negative intermittence. If we place upon the tube a piece of tinfoil and connect it with earth we shall get the usual negative-relief effects, *i.e.*, positive luminosity on the inner side of the tube beneath the tinfoil. But if we withdraw the earth connexion from the tinfoil, and hold it at long sparking-distance from it, bright phosphorescence will appear opposite the tinfoil. The explanation of this is that during the interval between two air-sparks the tube is rapidly charging-up with positive electricity. Rapid, however, as this charging-up is, it is not of a sufficiently impulsive type to give rise to a relief-discharge from the tinfoil sufficient to produce luminous effects. If, however, we hold a wire connected to earth at such a distance from the tinfoil that the accumulated effects of this charging-up are able at intervals (either once, twice, or even more frequently in each interval of the main air-spark) to draw a spark from the earth wire, we have corresponding to each such spark an impulsive relief-discharge of negative electricity from under the tinfoil which produces the phosphorescence observed.

This Leyden-jar effect is found with all lengths of air-spark and in all kinds of tubes. When we come, however, to tubes of very high vacuum the whole becomes so complicated by other considerations that, though there are traces of the effect, it is so masked as to require special examination to detect it. In fact, the tube represents in many cases a much greater resistance than the air-spark interval, so that the above reasoning would not apply without great modifications. It is true that there is a similar contrast between discharges which give strong shocks and those which do not do so, but that may arise from wholly different considerations, which will be noticed in due time (see Section XXVII.). It is partly on account of the great importance of distinguishing between this latter phenomenon, which is peculiar to high-vacuum tubes, and the phenomenon to which this section has chiefly been dedicated, which is common to all tubes, that has made us examine the latter.

XVII.—*On the phenomenon of phosphorescence in vacuum tubes.*

Before entering into the investigation of vacuum discharges through tubes of high exhaust, it will be advisable to consider from all points of view a phenomenon which is a very marked accompaniment of discharges in high vacua, though, as we shall see, by no means confined to them. We allude to the well-known phosphorescence which appears on the inside of the tube, especially in the neighbourhood of the negative terminal. This phenomenon required only incidental notice in our former paper, not because it does not belong to the sensitive state (for we shall find that it is quite as marked a feature in the case of the intermittent as in that of the continuous discharge), but because it is of comparatively rare occurrence in connexion with the low exhausts to which our researches were there confined. But the remainder of the present paper will be chiefly devoted to the consideration of discharges in high vacua, and it is therefore necessary that we should start with a clear understanding of the nature and laws of this phenomenon.

The immediate cause of phosphorescence in vacuum tubes is ascertained beyond controversy. GOLDSTEIN and CROOKES have shown that it arises from streams of molecules or small particles of some kind which pour off from the negative terminal during the continuance of the discharge. These while moving at high velocities strike against the glass and by their impact impart sufficient energy to the glass to render it luminous, and also to raise its temperature very considerably. The peculiar colour of the light thus generated has been conclusively shown to depend solely on the composition of the glass; it is indifferent to the substance of which the terminal is composed; in fact, as will be seen later, the very glass itself may serve as such a terminal. Its configuration undoubtedly depends upon that of the terminal as well as upon that of the surface of the glass upon which it is actually formed; but as the phosphorescent light has no direct connexion with the luminosity of the gas itself, it gives us no direct information as to what is going on within the tube, save so far as it testifies to the existence of these streams of material particles coming from the negative terminal.

The relation of this to other electrical phenomena seems not to have been clearly understood, and it has been supposed by some to indicate that the gas within the tube is in some special and peculiar state differing widely from the ordinary gaseous state in its physical qualities, and especially in the length of the free path of its molecules and the frequency of the collisions between them. As we are of opinion that there are no sufficient grounds for such a supposition, but that, on the contrary, the phenomena are compatible with the ordinary molecular theory of gases, we shall proceed to state our views upon the subject, and the experimental facts upon which these views are based.

It is by no means an unusual phenomenon to find streams of particles driven off from the surface of bodies highly charged with electricity. The very familiar phenomenon known as the "electric wind" is an instance of this kind. In this case particles of air are driven off from the pointed terminal of an electric machine or a highly charged Leyden jar with such force that they produce a perceptible wind; and their reaction can be made to turn a vane much in the same way as CROOKES' electric radiometer is turned by the electric discharge in a vacuum. This phenomenon is admitted to be due to the repulsion between the highly charged conductor and the neighbouring particles of air which have become charged in a like sense by coming in contact with it.

There are, it is true, many peculiarities of this "electric wind" which prevent our accepting it as an exact analogue of the molecular streams which produce phosphorescence in high vacua. In the first place it is common to both the positive and the negative poles, and is indeed more easily produced at the former than at the latter. Then, again, the velocities of the particles seem to be much less than in the case of phosphorescence, although the whole pressure produced by them is relatively considerable owing to the greater density of the medium affected. But these are not differences which weigh very heavily in the consideration of the matter as a whole. The typical peculiarities of the negative terminal only begin to manifest themselves as the pressure of the surrounding gaseous medium is lessened, and it is only in very high vacua that they attain their full proportions. Moreover, the lower velocity of the particles is exactly what we should expect to find in a medium so much denser than the high vacua in which phosphorescence is usually observed.

These are not the only cases in which, at the ordinary atmospheric pressure, we have phenomena of this nature. It is well known that in the electric arc there is a constant stream of particles of carbon from the positive to the negative pole. And of late a method of coating glass with platinum has, we believe, been invented and carried out, as a commercial process, which depends on a like principle. The platinum is deposited from an electrode of that metal held near the glass and connected with some source of high tension electricity. And doubtless if experiments were made upon the streamers which are seen between the two poles of an electric machine when they are beyond striking distance some very closely analogous phenomena might be observed.

But if these phenomena fail in being strictly analogous to the molecular streams that produce phosphorescence in that they show no special preference for the negative pole, or are even characteristic of the positive pole rather than of the negative at ordinary atmospheric pressures, the analogy becomes much more strict when we come to discharges in rarefied gas. It has long been known that if small metallic particles are lying loose on the negative terminal of an exhausted tube, a strong electric current will drive them along the tube towards the positive terminal. A convenient form of the experiment is obtained by enclosing some platinum black in the tube. If this be shaken down to the negative end of the tube, so as to lie upon the terminal, a shock from a coil of fairly large size will drive it along the tube in spite of the great specific gravity of the particles of which it is composed, No such phenomenon will be seen if the platinum black be placed on the positive terminal.* And all who have used vacuum tubes with platinum terminals will remember how commonly it is the case that the portion of the tube round the negative terminal becomes coated with a thin film of platinum due to the small particles of the metal that are driven off from the terminal by the electric discharge.

In the opinion of the authors of this paper, there are no sufficient grounds for looking upon the molecular streams which produce phosphorescence in vacuum tubes as anything other than or different from the phenomena above referred to.†

The hypothesis that the existence of the molecular streams that produce phosphorescence depends upon some special modification of the gaseous structure of the medium through which the discharge passes, apparently owes its origin primarily to the belief that this phosphorescence is peculiar to tubes of high exhaust, and secondarily to the belief that in the tubes in which it is found to occur the particles which cause it (and which are presumably molecules of the gas within the tube) are exempted from the usual interference which gas molecules exercise upon one another in their motions through the space which contains them. Both these beliefs we consider to be unsupported. So far as our observation goes, phosphorescence can be produced in almost any vacuum tube. The sole condition is that the violence of the discharge from the negative terminal should be sufficiently great, taking into consideration the form and size of the tube, and of its negative terminal and its degree of exhaust. This degree of violence is attained in the case of tubes of very high exhaust without any special arrangements, and a continuous current sufficiently

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* Plumbago, lampblack, and finely divided steel have been used with success in this experiment. Lycopodium and sand, and apparently non-conductors in general, are not similarly affected. These experiments were suggested some years ago by Mr. WARD.

† A very remarkable confirmation of the theory that these molecular streams are identical in their nature with the phenomena above described is obtained from the fact that, as PLÜCKER has shown, the metallic deposit in the neighbourhood of the negative terminal will follow the magnetic curves if the deposit be allowed to take place in a magnetic field, thus showing that the particles of platinum are affected by a magnet in precisely the same way as the particles in these molecular streams. Other experimental facts which in the opinion of the authors of this paper conclusively demonstrate the substantial identity of the two phenomena will be given in a subsequent portion of this paper (see page 648), but it is not convenient to insert them here as it would require us to anticipate in some measure the results of several of the sections that follow.

strong to pass through such tubes appears always to excite phosphorescence to a greater or less distance from the negative terminal. In tubes of a less degree of exhaust this is not the case, but the difficulty can be got over by intensifying the violence of the negative discharge by means of the introduction of an air-spark. This divides the current into isolated individual discharges of great violence; and if the air-spark be taken long enough this process generally results in the production of phosphorescence in the neighbourhood of the negative terminal. If this does not succeed, yet more violent methods must be resorted to; and if even all means fail to produce phosphorescence we trust to be able to show that it is solely on account of the interference of the surrounding gas; and that the absence of phosphorescence is not due to the non-existence of the requisite molecular streams, but to their not travelling with sufficient velocity to enable them to impinge on the glass with the requisite violence. In other words, we hope to establish experimentally that these molecular streams are present in all vacuum discharges, and that their behaviour under various conditions of vacuum and discharge, so far from pointing to any unusual state of the gaseous medium in which they occur, shows a perfect continuity of variation throughout the whole of the wide range of circumstances under which they appear.

It will be convenient in demonstrating these propositions to show first of all that phosphorescence can be produced in vacuum tubes, in which it would not otherwise occur, by increasing the violence of the discharge. By far the best example of this is obtained in the way to which we have just referred, viz.: by introducing an air-spark. If a tube of very moderate exhaust be placed in circuit with a large HOLTZ machine, and an air-spark of considerable size be introduced into any part of the circuit, it will generally be found that phosphorescence appears in the neighbourhood of the negative terminal, even though there was not the slightest appearance of it while the discharge was passing continuously. This is clearly due to the fact that intermittent discharges are necessarily much more violent during the very short period of time which they occupy than are continuous discharges; and hence the velocity imparted to the molecular streams is sufficient to make them impinge on the glass with the velocity requisite to produce phosphorescence. It will be noticed that we have here no change in the degree of exhaustion, but only in the violence of the discharge; and it is further to be remarked that this increased violence can be obtained, either directly as in the case of the negative air-spark, or by way of response to a violent positive discharge in the tube, as in the case of the positive air-spark.*

But it is not only thus that the introduction of an air-spark can be made to produce phosphorescence in a vacuum tube. It is possible to obtain similar phosphorescence in other portions of the tube than those immediately surrounding the negative terminal, and it is by these methods that we can show most clearly that the pheno-

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* This fact alone is a sufficient warning against viewing the emission of these molecular streams as indicating in any way a special direction of the electric discharge. It is, in our opinion, fatal to the idea that these molecular streams prove that an electric discharge in a vacuum tube is a "negative flow."

menon does not depend on the existence of any specially high degree of exhaust. If a strong current be made to pass through any tube of not too poor a vacuum to be capable of giving a positive luminous column, and a considerable air-spark be introduced in the positive portion of the circuit, so as to cause the positive electricity to pass through the whole length of the tube in strong charges, the contact of the finger with the tube will, in almost all cases, cause a bright patch of phosphorescence to appear on the opposite side of the tube (Plate 26, fig. 8). The reason is obvious. The interior of the tube beneath the finger acts as a negative terminal, *pro tem.*, to the advancing positive electricity, and in the act of thus sending off negative electricity it sends off also the streams of molecules that accompany negative discharge, and thus produces phosphorescence in the tube. This will be the case even in tubes which are full of bright luminosity, and the molecular streams will drive through this luminous mist without necessarily dispersing it : a phenomenon which is in itself a sufficient proof that they do not require a specially high degree of exhaust, since we shall find that this is incompatible with the existence of bright luminosity.*

There is yet another arrangement which enables us still further to increase the violence of the negative discharge so as to obtain phosphorescence in tubes in which it does not ordinarily appear. This is the arrangement referred to in our former paper, on page 170 and Plate 15, fig. 2, and is due to Mr. WARD, our assistant. It consists in bringing a wire from the positive terminal of a HOLTZ machine to a small tinfoil patch on the outside of a tube, one of the terminals of which is in metallic connexion with the negative terminal of the same machine. On separating the terminals of the machine to a distance of, say, half-an-inch, a stream of violent sparks will of course pass from the one to the other. Each of these will cause, at the positive terminal, and therefore at the tinfoil of the tube, a sudden downfall of positive tension or rise of negative tension, and thus will be equivalent to an impulsive negative charge there. As we have seen, this will make the inside of the tube act as a negative terminal for the instant, and with this there will be the accompanying molecular streams, and phosphorescence will appear on the opposite side of the tube. Inasmuch as in this way we are able to attain to a much greater degree of violence in the individual discharges, we are by it enabled to demonstrate the existence of phosphorescence due to negative discharge in tubes in which all other methods fail to show it. We shall now give a few experiments to show the very wide range of exhaust through which, by some or all of the above methods, we have been able to obtain it.

We first of all tried the tubes which were most frequently used by us in our former investigation, viz.: tubes of a moderate exhaust representing some 1 or 2 millims.

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* This experiment is interesting also for another reason. It shows that the action to which the emission of these streams is due must take place on the bounding surface of the solid and gaseous matter, for in this case the electricity can only come from the surface of the glass or the gaseous film in immediate contact with it, and not from the interior of the solid body, as is the case with the negative terminals of tubes.

pressure, and giving an amorphous positive column, the exhaust not being sufficiently high to give stratification. Every one of these readily gave phosphorescence under any one of the foregoing methods. As it was of course unnecessary to examine tubes of higher exhaust, we then set to work to examine tubes of lower exhaust. Of these we had but few instances; for if the exhaust be much less than that described above, the special phenomena of vacuum discharges are very imperfectly manifested, and hence such tubes would be useless as vacuum tubes. One, however, was found about an inch and three-quarters in diameter, containing vapour of bromine, in which the exhaust was so moderate that the luminous discharge consisted of a thin red line extending from the positive terminal up to within a very short distance of the negative. This, on being subjected to the last of the tests above described, gave splendid phosphorescence.

By way of a crucial experiment a tube of about 1 inch external diameter was taken which had a cavity at one end filled with potash. In its ordinary state this tube is one of very great resistance, and displays splendid phosphorescence throughout almost its whole length (Plate 26, fig. 9). By heating the potash with a spirit lamp gas is driven out from it into the tube, and thus the degree of the exhaust can be lowered to any desired extent. This was subjected to the method last described, and the potash was heated until it melted, when we were compelled to desist from fears for the safety of the tube. Very bright green phosphorescence was manifested throughout the whole of the time, and it was clear that we had not yet reached the limits of pressure at which it could have been obtained. It was of course difficult to estimate exactly the pressure of the gas in the tube at the termination of the experiment, but from the resistance of the tube, and the appearance it gave when a current was sent through it, we judged it to be equal to at least half-an-inch of mercury.

Feeling the importance of demonstrating conclusively that these molecular streams are not dependent on the existence of any specially high state of exhaust, we next took a tube of about 2 inches diameter which contained nitrogen at a pressure of about 2 millims., and permitted air to enter slowly through the stopcock which closed it. The arrangement for producing the phosphorescence was that last described. We found that it gave marked phosphorescence until air had been entering for a considerable time. When at length the pressure became so great that no phosphorescence appeared, we examined the tube by passing a current through it, and found that it gave no luminous phenomena save in the immediate neighbourhood of the two terminals: an appearance which is well known to signify a very moderate exhaust. The phosphorescence faded gradually as the air entered, and when at last we decided that the phosphorescence had disappeared, it was merely because it had faded to such an extent that we could no longer certainly recognise its presence by the eye. But there was no sudden or discontinuous change marking the exact epoch of its disappearance, nor was there anything to lead us to believe that there had been any sudden cessation of its existence at the moment when it ceased to be visible.

These experiments, which could be multiplied to any extent, show that phosphorescence can be produced in tubes of all degrees of exhaust by sufficiently increasing the violence of the negative discharge. But there is an experimental fact which has been repeatedly observed and should be mentioned here, which shows that it is not essential that there should be any increased violence of the whole discharge, but that a sufficient intensification of the local action at the negative terminal is all that is necessary. When a tube is being exhausted to a high vacuum the phosphorescence always appears first in the neigbourhood of the negative terminal. But it often happens that one of the terminals of the tube is much smaller than the other. In such cases there is invariably a stage in the exhaust in which phosphorescence is visible when the smaller terminal is the negative terminal, but in which no phosphorescence appears when the current is reversed. And similarly when there is this inequality of size in the terminals, a smaller air-spark will suffice to produce phosphorescence when the smaller terminal is negative than when it is positive. Now it is well known that negative discharge is greatly facilitated by increasing the size of the terminal, so that we have a case in which, when all the other circumstances remain the same, we can produce phosphorescence merely by restricting the size of the negative terminal so as to render more violent the local action there.

The above experiments show that the phenomenon of molecular streams can be produced at pressures so considerable as to deserve to be called ordinary gaseous pressures. We shall now endeavour to show, in the second place, that there are no sufficient reasons for supposing that the gaseous molecules which form the discharge are in any way exempt from the ordinary laws that govern gaseous media. It is true that their original projection is an exceptional phenomenon, and that their consequent motion has no analogue in ordinary gaseous media; but there are many phenomena which show clearly that these molecular streams are interfered with in their course by the circumjacent gas, much as other currents (whether of gaseous or solid matter) would be under like circumstances. This is, we think, made evident by the following observations and experiments.

In the first place, when a tube is being exhausted and a discharge is maintained through it, phosphorescence appears first in the immediate vicinity of the negative terminal. This is so well known that it seems to be a matter of course that such should be the case, and yet it is difficult to understand why it should be so, except on the hypothesis that the gas in the tube obstructs the path of the molecular streams, and lessens their velocity. The only other explanation, viz.: that it is due to the greater obliquity of impact on the sides of the tube farther removed from the negative terminal, though of course it has a very decided effect, would not in our opinion be sufficient to account for it.

But we are not left to conjectural explanations to determine that the molecular streams are obstructed by the gaseous media through which they pass. We shall proceed to describe a series of experiments which put this beyond the reach of doubt, and at the same time show how this clogging effect increases with the density of the gas in the tube, just as would be the case if streams of any kind of small particles were trying to force their way through it.

In order to observe the effect of the resistance of the gaseous medium upon the molecular streams to which phosphorescence is due, it was necessary to have an arrangement by which these streams could be examined at various distances from their source without any alteration being made in the other circumstances of the discharge. To effect this the following experiment was devised. A tube was constructed (Plate 27, fig. 10), having loose inside it a second piece of tube, whose external diameter was about 1½ inches, while the internal diameter of the main tube was about 2 inches. When the tube was placed horizontally there was a distance between the two tubes of about half-an-inch on the upper side, decreasing down to zero on the under side, where the two tubes lay in contact. The arrangement adopted for producing the phosphorescence was that due to our assistant, Mr. Ward, referred to above, and with this arrangement we could, by moving the small patch of tinfoil upon the tube to a suitable spot, give to the streams of molecules thrown off from the interior surface of the outer tube any range we pleased from half-an-inch to zero. We then attached the tube to an Alvergniat air-pump and ascertained the maximum range at which relief-phosphorescence could be obtained at different pressures of the gas by moving the tinfoil about until we got to a position where phosphorescence just became visible on the outer surface of the inner tube. This gave us the distance through which the molecular streams occasioned by the impulsive inductive action on the exterior of the tube were able to force their way through the gas without having their velocity reduced below the limits necessary to produce phosphorescence.

A series of precise numerical results would have involved an accurate determination not only of the pressure of the gas and the range of the molecular streams, but also of the quantity of electricity given off by the Holtz machine, as well as the length of air-spark used. But as our principal object was to show the existence of a maximum range dependent on the pressure, it will be sufficient to subjoin a few approximate results, which are, however, derived from a considerable number of actual observations.

The pressures of gas (atmospheric air) and the corresponding maximum ranges at which phosphorescence could be obtained with the 12-plate Holtz running at 300 revolutions per minute, and an air-spark of about half-an-inch in length, were as follows:—

Pressure.	Range.
5 millim.	12 millim.
22 ,,	5 ,,
24 ,,	2 ,,
26 ,,	almost contact.

This shows that although these molecular streams exist at a pressure of an inch of mercury, they are unable to force their way through the gas except to a very short distance, and that if the pressure be reduced the distance to which they can penetrate rapidly increases. So far, then, from being exempt from the action of the surrounding gas, they are very highly susceptible to its influence.

Another experiment which shows how completely these molecular streams are subject to the ordinary laws of gaseous resistance was made by us while working with the tube described on page 24, into which air was allowed to enter in order to discover the superior limits of the pressure within the tube at which we could obtain phosphorescence. When the phosphorescence had entirely disappeared it occurred to us to examine the effect of a magnet placed beneath the tube with its axis pointing in the direction of the tinfoil, so that the molecular streams, if any existed, would be moving towards it in directions nearly parallel to its axis. We knew that the effect of a magnet in such a case is to constrict the molecular streams and cause them to move in a more compact body, so that if the disappearance of the phosphorescence was merely the effect of the loss of velocity of the particles through their having to pass through gas of such considerable density, the magnet might have the effect of enabling them to penetrate to the other side of the tube so as to produce phosphorescence. Accordingly when phosphorescence had completely ceased to be visible a strong electro-magnet was placed with its pole near the tube, diametrically opposite to the place where the wire from the positive terminal of the machine rested upon it. The experiment proved the justness of the conjecture, for while the magnet was in action a small bright and well-defined green patch was observed in the place where the phosphorescence would naturally appear, and this disappeared as soon as the current within the magnet was stopped. We then connected the tube with an ALVERGNIAT'S air-pump fitted with a siphon gauge to measure the pressure within the tube, and repeated the experiments while the tube was in connexion with the pump. We found that without the assistance of the magnet we could produce phosphorescence at a pressure of a quarter of an inch of mercury, and with the assistance of the magnet at a pressure of at least three-eighths of an inch. Considering the very large diameter of the tube (something more than two inches) and the moderate magnetic power which we were using, these measurements, as well as those previously given, strongly confirm the estimate of the pressure in the case of the tube with potash mentioned above.

There is another interesting experiment of a different kind which shows clearly how readily the moving particles lose their velocity on passing through the gas in the tube. A tube containing a number of loose films of glass of extreme tenuity was exhausted till it gave very fine striæ, soft in outline, and also gave, with an air-spark, good phosphorescence. A discharge with a long positive air-spark was made to pass through it. On touching the tube with the finger (which, as we have already mentioned, has the effect of causing these molecular streams to pour off from the interior surface of the tube at the spot on which the finger rests) phosphorescence appeared on the films opposite to the finger. These films were moved by the impact of the molecules as in the case of CROOKES' mill; but they were only moved very slightly. If, however, the finger was placed close under one of the films it was moved readily, showing that though the momentum of the molecules after they had crossed the tube was not sufficient to move the films, yet their initial momentum was amply sufficient to do so. The irregular shapes of the films gave opportunities of testing in a variety of ways the truth of this conclusion, and in all cases it was confirmed.

The importance of these results is twofold. They not only demonstrate that phosphorescence can be obtained at pressures so comparable with ordinary gaseous pressures that it is unnecessary, and indeed inadmissible, to have recourse to the supposition of an alteration of the ordinary laws of gases; but they also show that these streams of molecules are strongly under the influence of gaseous resistance, and that they rapidly lose their velocity from its action, so that, even in cases where phosphorescence is not visible, the same molecular streams exist, and may be made to produce it if proper means are taken to prevent their velocities being checked too much by the density of the vapour through which they have to force their way. Thus we may fairly conclude that the above-mentioned pressures by no means necessarily represent the limit at which these molecular streams exist. If it were desired to obtain phosphorescence at still higher pressures, all that would be necessary would seem to be to bring the glass intended to be affected into close proximity to the place of discharge, and still further to augment the violence of the electric impulses. No doubt in this way it would be possible to trace the presence of these molecular streams at much higher pressures; and if the thermal instead of the luminous effects of their impact on the glass were taken, it is probable that the range of pressures might still farther be increased. But it is sufficient for our purpose to show that no special condition of gas is necessary for the genesis of these molecular streams, and that they enjoy no special exemption from ordinary gaseous action in their subsequent path, since our object is not to determine the exact condition under which they occur, but to establish the close analogy between the molecular streams that produce phosphorescence and the other instances to which we have above referred, in which streams of particles are driven off from the negative terminal, and thereby to divest these streams of molecules of the character of an unprecedented phenomenon which would justify the hypothesis of any considerable change of conditions to account for its presence.

It may perhaps be said that it is unnecessary to give experimental proof that these molecular streams are obstructed by the medium through which they pass, so that they may actually exist even when no phosphorescence is manifested. This is in one sense common to all theories respecting them. The experiments of CROOKES with the electric radiometer show that the molecular streams seldom penetrate beyond what is known as the negative glow, with sufficient force to affect the radiometer.* Thus it would appear that all are agreed upon the point. It seems, however, to be thought that the phenomena in tubes of extremely high vacua show a freedom from this retardation. But it must be remembered that these vacua are estimated to be equivalent, or at all events comparable, to one millionth of an atmosphere. Now we have shown that at a pressure of a quarter of an inch or thereabouts we can get bright phosphorescence at a distance of two inches from the origin of the molecular streams. Is it a matter of wonder, then, that at a pressure of ten thousand times less than this we should find that these streams move through a distance of a few inches without appreciable retardation, especially when we consider that we have no certain means of detecting whether they are retarded or not? The conclusion to be drawn from the above is, we think, that whether or not the ordinary gaseous laws suffer any modification in high vacua there is nothing in the phenomenon of phosphorescence in such vacua which entitles us to suppose that they do so.†

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* It must be borne in mind that neither the negative glow nor positive luminosity necessarily bar the passage of these molecular streams. They often (as has been mentioned in connexion with some of the previous experiments) pass through bright positive luminosity for a considerable distance, and very frequently penetrate through a clearly marked negative glow and render phosphorescent the glass behind it. On the other hand, the experiment with the tube containing the glass films shows that it is not necessary that there should be luminous matter in the tube in order to stop the molecules. When a sufficient air-spark was used there was no positive luminosity at many of the places in the tube where the experiments were made, and there was only a very faint haze in the remainder, and yet the retardation of which we have spoken was clearly manifested.

† In a letter published since the reading of this paper Mr. CROOKES has made a further statement of his views on the existence of a fourth or ultra-gaseous state of matter.

We have never expressed any opinion as to the possibility of such a state, and have only dealt with the question whether the phenomenon of "molecular streams" furnishes evidence of its actual existence.

It may readily be conceded that if we could "by some extraneous force infuse order into the apparently disorderly jostling of the molecules in every direction by coercing them into a methodical rectilinear movement," we should fundamentally alter the physical properties of a gas. But our experiments furnish no evidence that any such action as this takes place in the formation of molecular streams. Before the discharge the particles of the gas are moving about in a perfectly irregular manner, and the effect of the discharge is to impress on them a very rapid proper motion in a definite direction. But we see no ground for supposing that the lateral motions, and the collisions consequent thereon, are in any way affected. Every wind furnishes us with an instance of gas the particles of which have an average proper motion, but no one would contend that such proper motion lessened the number of collisions in the gas or interfered with its gaseity. And we can see no reason for regarding a molecular stream as anything else than an exaggerated form of the well-known electric wind, or a mass of gas with an extremely rapid proper motion the magnitude of which is evidenced by the heat imparted to the body on which the gas impinges.

It is shown in the text that molecular streams can be produced with an intermittent discharge in tubes at comparatively high pressures where the gas is certainly in its ordinary state, and it may be added that in an intermittent discharge the periods of action are in all probability very small in comparison with the periods that separate them. Thus in all probability the greater part of the molecular stream would be composed of gas which had not been subjected to the direct action of the electrode, and which, therefore, But there is another point of view from which the results given above are important. They show that no conclusions can be drawn from the length of the path of these molecular streams as to the average free path of the molecules of the gas or the frequency of collisions between them. We know enough of gases to be certain that at a pressure of a quarter of an inch of mercury the ordinary laws of gases are in full force; that the average free path of the gaseous molecules is infinitesimal; and the number of collisions between them in any finite time inconceivably great. And yet at that pressure we can get phosphorescence at a distance of at least two inches.

Although, therefore, we can no longer regard phosphorescence as so exceptional a phenomenon as has been generally supposed, we are far from intending to underrate its importance as a characteristic phenomenon of electric discharge. But this importance is due to the fact that it becomes more and more prominent as the degree of exhaust increases, and not to its specially appertaining to any type of exhaust. And this increase of importance is greatly enhanced by the consideration that the other characteristics of the discharge, such as positive luminosity and the like, become gradually less and less marked as the degree of exhaust increases, till at length almost the sole visible phenomenon of the discharge is the phosphorescence* in the tube caused by the streams of molecules which its passage excites. And in one respect the indications given to us by phosphorescence are more definite than those of any other of the luminous phenomena, because it always speaks to the existence of a negative discharge; and if it is possible, by the method of shadows or otherwise, to determine the direction of the streams of molecules, it tells us with considerable accuracy the position of the source of that discharge. And this renders it, as we shall presently see, of the greatest value in researches which have for their object the discovery of the mechanism of the discharge, and indeed constitutes it the main source from which we derive information in the matter.

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must retain its normal state of intermolecular motion. This gas must be inextricably mixed up with that which has undergone the direct influence of the electrode, so that it is well nigh inconceivable on any hypothesis that there can be anything like order or directed motion in the molecular stream. And yet it is found to produce all the effects of a molecular stream produced by a more continuous discharge in a higher vacuum.

From these considerations and from the entire absence of anything which points to the suppression of the lateral motions, we conclude that the molecular streams furnish no evidence that the gas of which they are composed is in any other than its ordinary state. [July, 1880.]

* It is needless to repeat that the colour of this phosphorescence depends upon the substances used in the manufacture of the glass. The most convenient and easily distinguishable kind of phosphorescence is the green phosphorescence of German glass, and all the experiments for this paper have been performed with tubes of this glass. We shall therefore speak of phosphorescence as being green, although, as we have said, it is not necessarily so.

XVIII.—*The sensitive state*[*] *exists in discharges through tubes of high exhaustion when the current has the sharp intermittence which is the essential condition of its existence in tubes of lower exhaustion.*

When we examine a discharge in a tube of high vacuum which gives phosphorescence, we usually find that there is present an ill-defined column of haze of a greyish or purple colour, extending from the positive end of the tube. This must be taken as the representative of the positive column of the ordinary discharge, and it can be shown experimentally that such is the case by exhausting a tube while a discharge is passing through it, when it will be found that the positive luminosity passes continuously into the haze of which we are speaking.

So long as there is no interruption in the circuit external to the tube, these luminous appearances may[†] be non-sensitive, *i.e.*, may be indifferent to the approach of a conductor to the tube.

But if an air-spark be inroduced, the green phosphorescence becomes decidedly more brilliant, and the haze is found to be highly sensitive. With a positive air-spark the haze behaves on the approach of a conductor in all respects like the positive column in an ordinary sensitive discharge with a positive air-spark, excepting that its sensitiveness is usually more intense. When the air-spark is in the negative it is more difficult to establish the identity of behaviour of the haze and the ordinary sensitive luminous column under similar circumstances, but this does not affect the question of whether it is sensitive or not. As to this there can be no doubt, for the faint luminosity changes its conformation in a very marked way on the approach of a conductor to the tube.

If the vacuum be very high the tube appears almost wholly destitute of the haze of which we have spoken, and of course it then becomes difficult to demonstrate the sensitiveness of the discharge in the manner which we have just described. The very term itself seems to require an extended meaning, inasmuch as the true luminous discharge to which it was originally applied no longer exists. But it is not difficult to decide on the meaning which must now be given to it, for it will be found that the only luminous phenomenon that still remains, viz.: phosphorescence, undergoes changes when a conductor is brought near to or in contact with the tube so that we may fairly apply to it the same term "sensitive" that we have used with regard to luminous discharges in tubes in which the vacuum is not so perfect. It is true that in one class of cases (viz.: those in which the air-spark is in the negative) the sensitiveness of the

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[*] It will be remembered that the definition given in our former paper of the *sensitive state* is "*the state in which the discharge is affected by the presence or approach of a conductor.*" This definition will be adhered to throughout.

[†] We say that the discharge *may* be non-sensitive when there is no interruption in the external circuit because we shall see that it is not necessarily so, just as in the case of tubes of lower exhaust a tube of high vacuum may itself cause the discharge passing through it to become intermittent and sensitive.

phosphorescence[*] when a conductor is brought into contact with the tube is not very strongly marked, and is in fact often difficult to detect; but in these cases it will be found that the phosphorescence is highly sensitive to the approach of a conductor which is in metallic connexion with the negative terminal of the tube, a property which is quite as distinctive of the luminous phenomena of the sensitive discharges of which we have treated in our former paper as is their sensitiveness to the approach of a conductor which is not in connexion with any portion of the circuit. We can thus apply the term "sensitive state" to discharges through tubes of high vacua, even though the phosphorescence should constitute the main or even the only visible portion of the phenomena.

Taking, then, this extended conception of sensitiveness, we find that it appears in tubes of high vacua under precisely the same conditions as in the cases with which we have dealt in our previous paper. A machine giving a continuous current produces a sensitive discharge when an air-spark is introduced; and so does a coil which does not give too much quantity. Indeed, it is in some respects easier to obtain a sensitive discharge in the case of tubes of high vacua than in that of tubes of low vacua on account of the great resistance they present, and the consequent need of considerable violence in the discharge if it is to pass through them. In the case of a coil, for instance, it is only the first and more violent part of the discharge that has force enough to penetrate into the tube, and consequently the discharge within the tube has often the sharp impulsive character necessary for sensitiveness, when in a tube of less exhaustion the discharge from a similar coil would be more prolonged and probably non-sensitive. This property has, however, its disadvantages as well as its advantages. Many of the methods by which we succeeded in obtaining sensitive discharges in tubes of moderate vacua and therefore small resistance, are inapplicable to the case of tubes of high vacua where the resistance is necessarily very much greater. Such a method as the use of the wheel-break with the HOLTZ machine[†] would seldom if ever succeed in causing a current of any kind to pass through a tube in which the vacuum was very high. Before the machine had charged up sufficiently to give a current capable of passing through the tube the next division of the wheel-break would have come into contact with the platinum spring, or would have approached it sufficiently to induce the charge to adopt that path in preference to passing through the tube.

There is therefore no need of an elaborate investigation to show that the sensitive

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[*] A full account of the phenomena due to the sensitiveness of the phosphorescence in the intermittent discharge and of the effects produced on it by a conductor in metallic connexion with one or other of the terminals of the tube will be given in the subsequent sections. It is not necessary here to do more than refer to the fact that changes can be produced in the phosphorescence by the approach of conductors which are either uninsulated or in metallic connexion with some part of the tube. The nature of those changes does not concern us at this stage.

[†] See Phil. Trans. 1879, Part I., p. 170.

state of discharge in high vacua is dependent on intermittence. The arguments in favour of this are precisely identical with those that have been previously adduced in the case of discharges in low vacua, and the evidence is just as conclusive. As in the former case, sensitiveness is never found except in the presence of circumstances which render it extremely probable if not certain that the discharge is intermittent; and on the other hand, whenever the circumstances are such as to cause an intermittence of the proper type, the resulting discharge is found to possess sensitiveness. The telephone gives exactly the same indications of intermittence when placed in circuit between the earth and a piece of tinfoil laid upon a tube containing a sensitive discharge, and the revolving mirror gives exactly the same direct evidence of the intermittence of such discharges. In short, so far as has been observed, the whole of the evidence in favour of the connexion between intermittence and sensitiveness that can be adduced in the case of tubes of low exhaust is equally applicable to the case of tubes of high exhaust, excepting so far as instrumental difficulties or special peculiarities of the discharge (as, for instance, the extremely faint luminosity of the positive haze) make it impossible to apply the same tests. But although the amount of evidence is somewhat diminished by the limitation of our methods of producing intermittence, yet the nature of the evidence remains the same, and it is sufficient to show conclusively that in discharges through high vacua sensitiveness is just as much the invariable accompaniment of sharp intermittence and just as inseparable from it as is the case in the discharges of which we treated in our former paper. And, further, all the considerations which render the examination of the intermittent discharge of importance in the analysis of ordinary vacuum discharges exist and if possible possess yet greater force in the case of discharges in high vacua. There is the same identity of phenomena in the continuous and the discontinuous discharges, and there is the same ground for seeking in the discontinuous discharge the explanation of the various phenomena of the continuous discharge. No excuse will therefore be necessary for subjecting the sensitive state of discharges in high vacua to an investigation of the same type as that which is contained in our former paper.

We shall, for the sake of simplicity of language, assume during the remainder of this paper that the intermittence and consequent sensitiveness is produced in all cases in the simplest and most convenient way, *i.e.*, by an air-spark situated either in the positive or negative portion of the external circuit.

XIX.—*When the air-spark is in the positive the discharge passes through the tube in the shape of positive electricity, and* vice versâ.

It will be seen that this amounts to saying that the general results of our former paper hold good for tubes of high vacua.

The importance of demonstrating this is very great. For it signifies that there is no radical difference between the nature of the discharge in high and low vacua, and it does away with the idea (apparently suggested by the phenomena of phosphorescence) that in high vacua the discharge is only derived from the negative terminal. In addition to this, the establishment of the fact that even in the absence of positive luminosity the positive terminal may be the prime source of the electric discharge, and the negative discharge may be only a response to the positive, sheds important light upon the functions of the molecular streams which accompany the negative discharge, and affords a strong argument in favour of the view that they do not represent in any sense the discharge itself, nor have any necessary connexion therewith, save as being accompanying phenomena of the passage of the negative electricity from the negative terminal, however such passage may be brought about.

There is a good deal of difficulty in applying directly the results of our former investigations to tubes of high exhaustion. The positive luminosity, which in tubes of lower exhaust constitutes the main feature of the discharge, and from the behaviour of which we obtained the indications of the nature of the discharge, fades away, as we have seen, into a thin haze with outlines so vague and shadowy as to be with difficulty discerned; indeed, when the exhaust is very high, the positive luminosity is either so faint as not to be discernible in the presence of the more brilliant luminous effects of phosphorescence, or else is actually absent. But so long as it is present it enables us to obtain evidence as to the character of the discharge which, if not equally convincing with that obtained under the more favourable circumstances of lower exhaust, would at all events suffice to give great probability to the hypothesis that there is no radical difference in the laws of the discharge so far as its capability of possessing either sign is concerned. With a positive air-spark the haze (whenever it is present) is repelled by the finger, and is constricted by a ring of tinfoil which is touched by the finger, just as the positive luminosity would be in a tube of lower exhaust; indeed, the sensitiveness seems rather to increase with the degree of exhaust than otherwise. And if the finger be passed along the tube there is the same continuity in the characteristics of the phenomena, showing that whatever be the nature of the disturbance it is the same from end to end of the tube. If the air-spark be in the negative the appearances are markedly different from those with a positive air-spark, and there is the same continuity of characteristics, but it is more difficult to identify the actual appearances with those which we have been accustomed to see in the case of other tubes. This is not to be wondered at, because we have already had to notice the want of sharpness of the effects with negative air-sparks, and even in our previous investigations we were frequently compelled to work with positive air-sparks in order to ensure good definition. This difficulty can, however, be overcome to a certain extent by having recourse to special rather than to relief effects; and if it were necessary we have no doubt that a great amount of evidence in favour of the proposition at the head of this section might be obtained in this manner.

It is possible, however, even by the use of the methods of our previous paper, to obtain direct evidence of the truth of the proposition in question.* If we place a somewhat broad piece of tinfoil round the tube, and connect two wires from it to the ends of a suitable tube of moderate exhaust, we shall get clear signs of the appropriate double unipolar discharge (Plate 27, fig. 11). The sole drawback of this test is that it is only applicable in cases where the action is of considerable violence, so that it gives no result where the air-spark is very small, or where the tinfoil is very near to the terminal remote from the air-spark. This proof can, however, be extended to cases to which it is not directly applicable, by passing to them in a continuous manner from cases in which it can be used. Thus, where the action is sufficiently violent near the air-spark terminal to enable us to use the unipolar test, but not sufficiently strong at points further removed from that terminal, we can show that the nature of the electrical disturbances at the latter is the same as at the former, by passing the finger along the tube and observing that the appearances at the different points are substantially identical.

There is another method by which we can raise a strong presumption as to the applicability to high vacua of the principles we established in our previous paper. This is by observing continuously the phenomena presented by the discharge during the process of passing from a low vacuum to a high vacuum while the tube is being exhausted. If an intermittent current of either type be allowed to pass through the tube during the whole of the operation, the phenomena observable in low exhausts will pass in such a gradual and continuous way into those which we are accustomed to meet with in high exhausts, that it becomes well nigh impossible to doubt that the *modus operandi* of the discharge is the same throughout. And in the same way we can extend the test from the case of a large air-spark to that of a small one. And if it were not that the direct methods of which we are about to speak render these less direct evidences unnecessary for the establishment of the truth of the proposition in question, such considerations as these would be of the highest value as raising a strong presumption in favour of the radical identity of the modes of discharge in the two cases. As it is, however, we need not dwell on them further, and we have only referred to them in order to show that the methods of our former paper would have enabled us to solve the difficulties of the new subject-matter with which we are dealing had it been necessary that we should have recourse to them.

All the foregoing evidence, though valuable as confirmation of the theory, and interesting in connexion with our previous results, is insignificant in importance compared with the direct evidence afforded by the standard-tube method described in Section XV. A tube of high exhaust is taken, and its terminals are connected with those of a HOLTZ machine. A patch or ring of tinfoil is placed anywhere upon the tube, except in immediate contact with either of the terminals, and a wire is taken from it to a ring of tinfoil upon the standard-tube. No effect will be produced on the standard-tube unless the high vacuum tube is of a nature to cause by its own action

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* See Phil. Trans., 1879, p. 216.

an intermittence in the current—a peculiarity which we have seen may also occur in tubes of lower degrees of exhaustion. But if a positive air-spark be introduced into the circuit which passes through the tube of high exhaust, the standard-tube will at once show positive effects, *i.e.*, the positive luminosity will be severed, and the well-known hollow cone and highly striated termination of the truncated column will at once be visible. This demonstrates conclusively that the action within the tube of high exhaust is such as to cause charges of positive electricity to be driven from the tinfoil upon it in the sudden intermittent and impulsive way that is needed to produce the ordinary sensitive effects in a continuous current; or, in other words, it shows us that charges of positive electricity are rushing through the tube of high exhaust and affecting the tinfoil upon it. And wherever the tinfoil be placed upon the tube of high exhaust (unless, perhaps, in the immediate neighbourhood of the negative terminal, where the results may be somewhat affected by the special circumstances of the case) the same effects will be found to be produced. Thus, in the case of the positive air-spark the discharges pass through the tube in the shape of positive electricity.

The above phenomena present themselves when the air-spark is in the positive, whenever care has been taken that neither the peculiarities of the tube nor those of the discharge introduce a second type of intermittence; and to ensure their appearance it will generally be found sufficient to connect the negative terminal to earth, and to introduce an air-spark into the positive. It happens, however, not unfrequently, that either from the shape or size of the terminals, or their relation to the degree of exhaust, or from some other similar cause, a tube possesses an inherent power of causing an intermittence of a negative type in a discharge even though a positive air-spark has been introduced into it, and in such cases we, of course, get mixed results. And it is of great importance that this should be borne in mind, for when the resistance is very great the danger of results becoming mixed in their character is very much increased, and further complexities are doubtless produced by the escape of large quantities of electricity from different portions of the circuit outside the tube into the air. We shall have to speak of certain types of these exceptional results; but in the meanwhile it is important to remember that such peculiarities as these do not furnish any argument against the conclusions above referred to; they should be looked upon as a kind of instrumental error, and they are only exaggerated forms of difficulties with which we have already become familiar in dealing with ordinary vacuum tubes.*

Conversely, if a negative air-spark be introduced into the principal circuit the effects in the standard-tube will be negative in type, *i.e.*, produced by negative impulses on the outer surface of the glass. If the air-spark be of a moderate size the well-known constriction or "ring-terminal" appearance will often be very clearly manifested; and

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* The only cases of such peculiarities that we have hitherto met with are those of tubes of extremely high vacuum, in which the negative terminal is of small size. These sometimes impart to the discharge a negative intermittence of the most violent type.

if the air-spark be considerable we often shall find phosphorescence produced in the test tube in the neighbourhood of the tinfoil ring that is upon it. In many cases, however, the effects will be less easily recognized, and recourse must be had to the various methods of examining the intermittence in the standard-tube described in Section XV. But these difficulties are common to tubes of all kinds of exhaust when negative effects are being examined. The effects are less sharp than those of positive intermittence, and we must be content with less perfect definition. The result is, however, sufficient to enable us to detect with certainty the existence of negative impulses in the tinfoil upon the standard-tube; and reasoning as in the other case, this shows that the negative charges which burst into the tube pass through it in the shape of negative electricity.

It must not, however, be supposed that in all cases the one discharge passes quite to the other terminal of the tube without exciting a response. If this were the case, high-tension tubes would present a uniformity of behaviour which even low-tension tubes do not possess. It is often very difficult to trace the evidences of the discharges in the immediate vicinity of the opposite terminal, and in some tubes it would seem that the response can come from the opposite terminal a little before the original discharge has reached it. But these last cases are of an exceptional character, and do not at all affect the conclusion that the discharge in general passes through the tube up to the immediate neighbourhood of the opposite terminal before exciting a response. In most tubes evidences of positive relief can be obtained (with a positive air-spark of considerable length) close up to the negative terminal.

The evidence obtained by this method is so direct and so unmistakable in its signification, that it leaves no room for doubt. And just as in tubes of low exhaust we found that these properties of the intermittent discharge rendered possible a variety of other phenomena, all of which were explicable by this theory of the discharge, so also in the case of tubes of high exhaustion all the other phenomena which follow from these properties of the discharge are also manifested, and serve in their turn to demonstrate the identity between discharges in high-vacuum and in low-vacuum tubes. Thus very good unipolar and double unipolar effects can be obtained, manifesting, with certain modifications, the same peculiar phenomena which we are accustomed to see in connexion with them in low-vacuum tubes. So easily are these effects attainable that (as will be seen later on) they afford to us the readiest way of obtaining luminous discharges suitable for an important part of our investigation. And if we recollect how intimately the existence of unipolar and double unipolar discharges in ordinary vacuum tubes is connected with the fact that the discharge at each terminal is independent of the action elsewhere than in its own neighbourhood, we shall see that the existence of similar phenomena in high-vacuum tubes is strong evidence of the substantial identity of the *modus operandi* of the discharge in the two cases.

The various types of evidence which we have already given represent, after all, only a portion of the evidence in favour of the proposition of which we are treating. There are phenomena of the relief and special effects in tubes of high exhaust, which when we come to consider them will afford, if possible, still more conclusive evidence of the truth of the hypothesis. But it is for many reasons desirable that we should not anticipate the examination of the relief and special phenomena of high exhaust tubes, because we propose to deal with them separately as they merit a much more minute examination than we could conveniently give them in this section. Moreover, in our opinion, the tests and other experimental proofs that we have already given, and the complete absence of any phenomena which would lead us to believe in any breach of continuity in passing from the vacua used in our previous experiments to these high vacua, sufficiently establish the proposition that the discharge is in general carried along the tube by electricity of the same sign as that of the air-spark.

XX.—*Phosphorescence exists in sensitive as well as in continuous discharges; and when occurring in sensitive discharges it is intermittent in a like manner with the other luminous effects.*

If a tube, which is exhausted to a degree sufficient to produce phosphorescence when a continuous discharge is made to pass through it, be placed in circuit with the terminals of a Holtz machine (Plate 26, fig. 8), and an air-spark be introduced into the circuit, the only effect that is produced upon the phosphorescence is that it grows brighter, and is sometimes slightly altered in its position and distribution. Substantially, the phenomenon remains the same as before the introduction of the air-spark, thus showing that the intermittence of the discharge does not prevent the negative pole from sending off the streams of molecules to which this phosphorescence is due, but, on the contrary, favours its so doing. This is in accordance with what has already been stated in Section XVII.

To the eye the phosphorescence of the intermittent or sensitive discharge is just as continuous as that of the continuous discharge. But this is easily proved to be a mere optical effect, and that the phosphorescence is, in fact, like the discharge itself, intermittent. To demonstrate this, it is only necessary to take a revolving mirror and examine the tube through a narrow slit in the ordinary way. Whether there be a positive or a negative air-spark it will be found that the green luminosity is intermittent. If the air-spark be large a very small velocity of rotation will show the green lines which are the images of the slit clearly separated by dark bands; and with an increased velocity of rotation the intermittence can clearly be shown even when the air-spark is very small.

It might be thought that since phosphorescence is supposed to last for a short time after the excitement which causes it has ceased, the green light would be continuous even though its cause were intermittent. And there are traces of this when the very bright portions of the glass are examined with the revolving mirror, when the air-spark is small and therefore the intermittence very rapid. It is in such cases difficult to decide satisfactorily whether the bright portions are absolutely continuous or not. But this difficulty is in reality of very slight importance, inasmuch as there is no doubt that the other portions of the phosphorescence are intermittent, and these brighter spots do not differ from the rest of the phosphorescence in the origin of their luminosity, but only in their being more favourably situated for the concentration of molecular streams upon them. Hence there can be no reasonable doubt that this apparent continuousness is due to the persistence of the phosphorescence. In the case of large air-sparks the mirror when revolving at a high velocity exhibits a slight haziness on one side of the image of the slit, showing that the dying out of the phosphorescence is not quite instanstaneous, though very nearly so.

It will thus be seen that the phosphorescence produced by the separate discharges of an intermittent current must be very intense, seeing that the periods during which the glass is brightly illuminated by it are extremely short compared with the periods that intervene, and yet the intensity of the apparent illumination of the glass is greater than with the continuous current. This shows that the particles must be driven off at a greater velocity or in greater numbers during the short period occupied by an individual pulse of the intermittent discharge than during the continuous discharge—a difference that would naturally follow from the fact that the electricity in each of these individual discharges represents the total accumulation of the period between two discharges. But it is remarkable that the vanes of a radiometer, when used as the negative terminal of a vacuum tube, as in CROOKES' experiments, revolve very much more quickly under the influence of a continuous discharge than an intermittent one. If an air-spark of increasing length be introduced into the current of a HOLTZ machine that is driving a radiometer electrically, the driving power will gradually diminish, and ultimately cease. This is, perhaps, equivalent to saying that the action upon the radiometer is dependent on the quantity of the discharge, and not upon its tension, since, of course, the introduction of a long air-spark into the circuit must necessarily have the effect of enormously decreasing the quantity of electricity passing, although it similarly increases the tension. But then we are met with the difficulty that the intensity of the phosphorescent illumination in similar cases is increased by the introduction of an air-spark in spite of the diminution of the quantity of the discharge. A possible explanation of this law is obtained by supposing that the effect on the radiometer is proportional to the *momentum* with which the particles leave the terminal while the phosphorescence depends on their *energy.* This would mean that a diminution of quantity diminishes the number of particles leaving the terminal while the increase of tension increases the velocity; such increase being insufficient to prevent the total momentum of the particles from being decreased by the introduction of an air-spark, but sufficing to cause a marked increase in their total energy.

It is a very significant fact that the intermittence of the phosphorescence exists with a positive as well as with a negative air-spark. In the former case the discharge at the negative terminal is of the nature of a response, and is presumably of a much less sharp and impulsive type than it is when that terminal is the air-spark terminal. Yet so brief is the whole time occupied by a single discharge that even the time required for the less instantaneous response is not sufficient to give any perceptible broadening out of the bands in the revolving mirror. It may, however, be said with much justice that it is probable that it is only the first burst of the response that is intense enough to give phosphorescence, and that the absence of continuous phosphorescence in this case is no proof that there is not a gentle continuous discharge from what we have previously called the connected terminal. But even if we allow for this it is clear that the main part of the discharge from the negative terminal in the case of a positive air-spark must take place in an extremely short space of time.

Although phosphorescence is intermittent, like all the other luminous phenomena of the sensitive discharge, there are many reasons which make it desirable to treat it separately from the luminous discharge. It is not, like striæ or the negative glow, a part of the phenomena of gaseous discharge properly so called, but it is the effect of a mechanical radiation which accompanies the discharge. It is a diagram, a projected image of that radiation upon the surface of the glass; while itself, it is the quasi-accidental effect of the fact that glass is the most convenient substance for transparent tubes, and that glass is usually made of substances which will give such phosphorescence when exposed to streams of rapidly moving particles such as those in question. Hence it is only a secondary phenomenon of gaseous discharge, and for clearness it will be well to treat it quite separately, and as in no way a part of the luminosity due to the discharge. But just as the relief and special effects in the luminous discharge are due to interference with the actual main discharge by means of artificially produced discharges of like period, so it is found that the phosphorescence which is due to the main discharge is capable of being affected in a similar way, though, of course, the results are wholly different to those special and relief-effects of which we treated in our former paper, and which relate to the luminous column itself, *i.e.*, to phenomena existing in the gaseous medium through which the discharge passes. And as phosphorescence is the most marked of all the phenomena that accompany the discharge in high-vacuum tubes, we shall, in studying the sensitive state in high vacua, and the nature and circumstances of discharges therein, pay special attention to the phenomena that depend on phosphorescence, and shall in the subsequent sections examine these first, and subsequently proceed to consider those phenomena which are the true analogues of the luminous appearances in tubes of lower exhaustion.

XXI.—*On the relief-effects in tubes of high exhaustion with a positive air-spark.*

I. *Relief-phosphorescence.*

If a tube of moderate exhaust be taken, and a continuous current be passed through it, no phosphorescence will, it is well-known, be visible. But if an air-spark of considerable length be interposed between the positive terminal of the machine or other source of electricity and the tube, the usual green phosphorescent light will be seen near the negative terminal. When this is the case if the finger be placed upon the tube, a bright green patch will ordinarily appear on the further side of the tube immediately opposite the finger. In order to produce this phenomenon, the finger may be placed at any part of the tube, except in the immediate neighbourhood of the negative terminal; but as a rule the green patch will be brighter the nearer the finger is to the positive terminal of the tube. If the same experiment be tried with a tube of high exhaustion it will be found still easier to produce this phosphorescent patch; for the air-spark necessary to produce it in a tube of high exhaust is much shorter than that which would be necessary in a tube of lower exhaustion. There is, however, the correlative disadvantage that it is not so easy to distinguish it, inasmuch as the whole of the inside of the tube of high exhaust may itself be phosphorescent from the action of the negative terminal.

It is not difficult to interpret this phenomenon after the theory of the intermittent discharge is once comprehended. The inner surface of the glass beneath the finger acts as a negative terminal under the influence of the advancing positive electricity that has come from the positive terminal, and the relief-discharge from it is sufficiently violent to send off streams of molecules capable of causing phosphorescence on the opposite side of the tube.

The importance of the phenomenon is much greater than at first sight would appear. In the first place, it affords direct evidence that there is negative discharge from the inside of the tube close to the finger, for these molecular streams only occur as an accompaniment of negative discharge. This alone is a result of great value. The phenomena of positive relief which in the previous paper were attributed to negative discharge could only be identified with the phenomena characteristic of negative terminals by a long and intricate process, and even after this identification had been satisfactorily made it was often difficult to trace the resemblance between the two sets of phenomena so as fully to realise their identity. But here we have no such difficulty. The indication cannot be mistaken; and we are enabled to affirm just as certainly that there is discharge from the side of the tube, and that such discharge is of negative electricity, as if we could test the electricity actually coming from it. And again, the fact that the same indication of negative discharge is obtainable from all parts of the tube (except perhaps in the immediate vicinity of the negative terminal) is direct evidence that the discharge passes throughout the tube in the form of positive electricity, since the response is throughout in the form of negative discharge. And the importance of these considerations is greatly enhanced by the fact that this relief-phosphorescence occurs in tubes of every degree of high exhaust, showing conclusively that when the air-spark is in the positive the discharge is carried in these tubes by bursts of positive electricity, which pass throughout the whole length of the tube just as in tubes of lower exhaust. No stronger confirmation of the results of Section XIX. could be desired so far as regards positive intermittence.

Nor are these the only important conclusions that can be drawn from the appearance of this relief-phosphorescence. It shows that it is not necessary that there should be a discharge actually passing from out of a solid body to cause these streams of molecules. The discharge in question comes from the inner surface of the glass, not from the interior of its mass. This would go to show that the action takes place at the bounding surface of the terminal, or perhaps in the layer of gas that lies immediately upon it, and forms a kind of border-land between the solid and the gaseous, and that it is really an action between the gas and the solid terminal. It would seem clear that it does not lie in the free gas itself, or consist of an action between the particles of the gas merely, as we should then expect to find that there was phosphorescence on the surface of the glass from which the discharge proceeds, caused by the backward recoil of the particles of gas in that layer derived from their violent disruption from those of their fellows that go to form the molecular streams. And there is certainly no trace of this, for as we shall presently see, the spot from which the discharge comes is denuded even of the phosphorescence that it would receive from other sources.

Before we pass on to examine this relief phosphorescence in other particulars we may remark that it is well shown, even in tubes of comparatively low vacua, by the use of the positive unipolar or double unipolar arrangement. By this method we are able to obtain intermittence of a much sharper and more violent type than with an effective current, so that the violence of the relief-effects is proportionally increased. A finger placed on such a tube will give well-marked phosphorescence. This serves, as in the former case, to show the correctness of the conclusions as to the cause of the unipolar phenomena, since it demonstrates that there are sharp periodical bursts of positive electricity into the tube. The relief-phosphorescence with these unipolar discharges is extremely bright, and the whole of the other relief-effects seem greatly intensified. By the use of this double unipolar arrangement we are able to produce phosphorescence in tubes of much lower exhaust than with an effective current, but both of these methods are inferior in this respect to the method described in Section XVII., which is a combination of a unipolar with an inductive discharge.

Another very convenient arrangement for showing the phenomenon of relief-phosphoresence consists in the use of a tube in which the terminals are near together at one end. The introduction of an air-spark will fill the remaining portion of the tube with a luminous discharge or haze (according to the degree of exhaustion), which is in fact a unipolar discharge (Plate 27, fig. 12). If the air-spark be in the positive circuit, this will be in a positive unipolar discharge and it will give relief-phosphorescence and all the other phenomena of positive intermittence.

The phenomenon of relief-phosphorescence supplies us with a very convenient method of determining experimentally the laws that govern the production of these molecular streams and the direction in which they travel. By varying the shape and size of the patch of tinfoil on the tube we vary the negative terminal from which the streams proceed, and by varying the length of the air-spark we vary the violence of the discharge. The opposite side of the tube acts as a very conveniently placed screen on which the effects are shown, so that we are able with a minimum of labour to examine the various phenomena to which these molecular streams give rise. We shall now give the results of this examination so far as we have had time to carry it.

A very cursory examination suffices to show that it is impossible to accept the hypothesis that presents itself to the mind most naturally, viz. : that these molecular streams move in straight lines, or nearly so, starting in a direction normal to the surface of the terminal. Were this the case, then the shape of the phosphorescent patch due to a piece of tinfoil on a tube when employed to produce relief-phosphorescence would be of a shape similar to that of the tinfoil. Experiment, however, shows it to be quite otherwise, and indeed it is at first sight extremely difficult to arrive at precise conclusions as to the law of the distortion observable in this patch, which we may term the phosphorescent image. There are certainly two causes at work in producing this distortion which are of great importance, but it is probable that at least one other cause is present, the existence of which, however, we cannot demonstrate at this stage.

The first cause which is undoubtedly at work to prevent the molecular streams forming an exact image of the tinfoil patch is that they do not all leave normally. It has been assumed rather than proved that such is their natural tendency, but we very much doubt whether even with the continuous discharge this is the case except to the extent that it is approximately true for those parts of the terminal that are not very near its edge. And it is certain that when we come to the intermittent discharge the direction in which the molecular streams which cause relief-phosphorescence can be made to go is inclined at such an angle to the normal that they must possess considerable initial obliquity. A ring of tinfoil connected to earth was placed round a tube in which a current with positive air-spark was passing, and which gave the usual phosphorescent phenomena. A small piece of glass lying loose within the tube was then shaken to such a position in the tube that the line from the piece of glass to the edge of the tinfoil opposite to the place where the glass lay made an angle of about half a right angle with the axis of the tube. A fine sharp shadow of the piece of glass was seen, and its direction was (so far as could be judged by the eye) just what it would have been had it been made by streams proceeding directly to the piece of glass from the tinfoil on the opposite side of the tube. Now had the streams started in a direction more nearly normal to the surface of the tinfoil, and subsequently become deviated to so large an extent as to reach the piece of glass, the shadow must have taken a direction much more oblique than was actually the case; and furthermore, the extreme obliquity of the streams of molecules that caused the shadow renders it very improbable that they should all have started normally.

In this particular instance there was a peculiarity which rendered the experiment very interesting, as showing how completely the relief phosphorescence is independent of that which comes from the negative terminal. The piece of glass was between the tinfoil and the negative terminal, so that the shadow pointed towards the negative terminal instead of away from it.

If a very small patch of tinfoil, connected to earth, be placed upon a tube of considerable diameter and not too high exhaust to permit the details of the relief phosphorescence to be readily distinguished, it will be found that it produces a bright central patch of phosphorescence at the point of the tube exactly opposite to it (Plate 27, fig. 13), and that this bright central patch is surrounded by an annulus of feebler intensity but considerable breadth ending in a fine bright line of phosphorescence serving as its outer edge. The breadth of the whole of this phosphorescent area is such that it subtends a very considerable finite angle at the patch of tinfoil, the semi-vertical angle of the cone of rays being from 20° to 30°. Now in this case the patch of tinfoil is so small that it may in considering the direction of the resulting molecular streams be taken to be a point, and thus we see that the molecular streams from a small elemental area would, if unaffected by any other circumstances than those necessarily present in a tube, pass off in all directions comprised within a solid angle of finite size (depending probably upon the degree of the exhaust and the violence of the discharge), surrounding the normal in an approximately symmetrical way, *i.e.*, forming a right cone of which it is the axis.* We are not able to speak definitely as to the intensity of the streams in the different directions. Those that proceed strictly normally are probably the most intense either from the greater density of the streams or the greater velocity of the particles, for we find that there is a very bright patch in the centre. But this may be partly due, as we shall see, to the fact that the patch of tinfoil has a finite though small area. A more difficult matter to account for is the apparently sharp limit which bounds the phosphorescent area on its outer side. It is difficult to imagine that there can be an abrupt limit to the angular extent of these molecular discharges. The most probable hypothesis is that it is due to a wholly

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* It will probably be objected (and with perfect justice) that we are reasoning as though all the molecular streams that leave the gas beneath the tinfoil arrive at the opposite side of the tube and make themselves visible there. This is of course not the case, and if we were to take a screen situated very much nearer to the tinfoil than is the opposite side of the tube we should no doubt get a wider limit to the directions of the molecular streams. But the general reasoning is not affected by this, although it is most important to bear in mind that our tests do not exclude the possibility of feebler streams of molecules issuing at still greater inclinations to the normal, and that it is only the streams that have a certain intensity that are rendered visible by phosphorescence.

different cause and that it is a result of certain phenomena which are discussed in Section XXIII.

Next take a narrow strip of tinfoil about 2 inches in length and place it longitudinally along the tube. If it be connected to earth we shall find that the relief-phosphorescence produced is in the shape of a broad patch occupying, say, half the circumference of the tube (Plate 27, fig. 14). It is, however, far from being uniform in brightness. Exactly opposite to the strip of tinfoil there is an ill-defined longitudinal band that is brighter than the surrounding parts, and which evidently corresponds to the bright central patch that was observed in the former experiment. From this band there branch out narrow bright streamers all perpendicular to the general direction of the band and giving to the glass a striped or striated appearance. These extend throughout the whole of the phosphorescent area, the spaces between them being less bright, though doubtless they are also phosphorescent, but to a less degree than the striations.

It will be at once seen that no mere superposition of the phosphorescence of the elemental areas composing the strip could produce such a distribution of luminosity in the phosphorescence due to the whole strip. The streams that proceed from the different elements of the strip must therefore interfere with each other. And it is easy to see how this interference leads to the configuration described above. The strong repulsion between an element of the surface of the glass beneath the tinfoil and the particles of gas in contact with it can no longer drive them off at all azimuths, for in the direction of the length of the strip there are equally active elements exercising an equally strong repulsion upon these particles. The only directions in which the streams can spread out are therefore those which are comprised in a plane normal to the direction of the strip through the element under consideration. Any accidental cause creating a difference in the intensity of the local action at any point of the strip (as, for instance, a slightly better contact with the glass) will cause the streams from one element to be rather brighter than those from another, and hence the phosphorescent image of the tinfoil will appear to be striped or striated in the manner above described.*

If the strip of tinfoil be placed at right angles to the direction of the axis of the tube and partially surrounding it, the same striated appearance will be visible in the relief phosphorescence, but the stripes or striations will now stretch along the tube in

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* It is impossible to see this effect without being reminded of the appearances produced by the volatilisation by the electric spark of a fine metallic wire placed upon a sheet of white paper or cardboard. From the general line of the wire there branch out in a direction normal to its length fine lines or striations precisely similar in shape and arrangement to those that appear in the phosphorescent image of the strip of tinfoil, only on a smaller scale. The cause of this striated structure is probably the same. The violent disruptive action that dissipates the metal in the wire is forced to drive it off in normal planes because the particles would be turned back into the plane by the action at the neighbouring elements of the wire were they to commence to move in an oblique direction.

the direction of its axis and not perpendicular to that direction as in the former case, and, similarly, the irregular bright central band will have its general direction along a normal section of the tube. So marked is the extension in the breadth of the image due to these stripes of phosphorescence (Plate 27, fig. 15) that if the strip of tinfoil be a short one its phosphorescent image seems to be long and narrow and to have the direction of its length at right angles to the direction of the tinfoil. The same is the case when a piece of tinfoil is placed longitudinally upon the tube; the greatest elongation of the image seems to be at right angles to that of the tinfoil. It will be understood that there is no actual rotation of the image through a right angle; the effect is solely due to the fact that the spreading out is at right angles to the direction of the length of the tinfoil, and that it is so great as to cause the breadth of the phosphorescent patch which it forms to be greater than the length of the strip of tinfoil.

That the above conclusions as to the law that governs the spreading out of the molecular streams are correct was shown by placing strips of tinfoil in oblique positions, when it was invariably found that the stripes or striations ran perpendicularly to the direction of the tangent to the strip of tinfoil at the point from which they proceeded. In order to test it rigorously, it was determined to place a strip in such a curve that the normal planes to the curve would pass through the tangent at the corresponding point of the *image* of the curve, *i.e.*, the curve on the opposite side of the tube, each point of which is exactly opposite to its corresponding point on the tinfoil. In such a case all the striations must lie along the curve formed by the locus of the central patches of phosphorescence, and the result should be a single bright curved line of phosphorescence without any spreading out or striated margin (Plate 28, fig. 16). The curve in question is evidently a helix, whose pitch is half a right angle. On trying the experiment these anticipations were found to be exactly fulfilled. It also occurred to us that as the striations are in the normal plane to the strip of tinfoil the locus of their consecutive intersections would give the evolute* of the curve formed by the strip of tinfoil, and that as such locus it would probably be represented by an especially bright line. We tried the experiment with a fine copper wire in the form of an ellipse, which was bent round so as to lie on the tube, and it was found to answer perfectly. The four-cusped shape of the evolute was distinctly marked by a bright line of phosphorescence (Plate 28, fig. 17).

It is easy to advance from the case of a strip of tinfoil to that of a patch whose length and breadth are alike considerable. The molecular streams from beneath the elements in the interior of the tinfoil will be hindered from spreading out in any direction by the action of the circumjacent elements, and they will therefore be concentrated and forced to pass off in a normal direction. The elements at the edge of the tinfoil are, however, in a different position, they can still spread out in directions normal to the edge of the patch. They are in fact much in the same condition, so far

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* This term is of course not used in its strict sense, for the wire and the phosphorescence are upon curved surfaces, and not upon planes.

as spreading out in directions outwards from the patch, as they would be if they were separated from the rest of the patch and formed a narrow slip of the same form as its edge. There is, however, the further complication (when the patch is of finite size) that all the normals at the various points of its surface pass through the axis of the tube, and would, if uninterfered with, form a *reversed* image on the opposite side of the tube. In so doing, they doubtless interfere with one another to a greater or less degree. It is not necessary, however, to examine carefully the results of this fresh element of complexity; speaking generally, the consequence is that the phosphorescence assumes the shape of a central bright patch surrounded by a border of smaller luminosity.

The second cause that operates to prevent the streams of molecules from making a perfect image of the patch of tinfoil which excites them is the property that such streams possess of interfering with one another during their passage through the gas. It is no doubt difficult to separate this cause from the last, for the streams only make themselves manifest at their extremities where they strike the glass, so that it is well-nigh impossible directly to distinguish between an initial obliquity and an obliquity that has been acquired during flight in consequence of the interference of other molecular streams. But there is abundant evidence of the independent existence of this latter cause of the obliquity of molecular streams. If we take a piece of tinfoil on a tube of not too large diameter and connect it to earth (the air-spark being, of course, in the positive) we shall, as we have said, produce a patch of green light on the opposite side of the tube. Let the outlines of this patch be carefully observed, and then let another patch be placed on the same section of the tube, but distant, say, a quadrant from the other. If this be also connected to earth, the former patch will be found to have altered in shape, and of course a fresh patch will have appeared corresponding to the second piece of tinfoil. If, now, the first piece of tinfoil be disconnected from earth, it will be found that the second patch has altered in shape. Thus the streams from the two loci of discharge must have interfered with each other, and as there was no community of origin this interference must have taken place during their passage through the gas.*

There is one form of this interference which is so marked, and which is so unmistakably a matter of interference, that it deserves special mention. We refer to the case in which the two pieces of tinfoil referred to in the last experiment are diametrically opposite, so that each is placed where the phosphorescent image of the other would naturally fall. In such a case the streams proceeding from each appear to beat back

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* The existence of this interference has also been demonstrated in the following way. A helix of tinfoil upon the tube connected to earth in the usual way was taken, the pitch being half a right angle. It gave the sharp phosphorescent helix of which we have already spoken. The tube was then touched at a point midway between two threads of the helix of tinfoil, so that the molecular streams from the finger cut normally through the surface formed by the molecular streams from the tinfoil. This was found to cause a distinct shifting of the corresponding part of the phosphorescent helix.

or turn aside those proceeding from the other, for just over each piece of tinfoil there is a patch of glass, of about the same shape as the tinfoil though rather larger than it (inasmuch as it overlaps it a little on all sides), which is wholly devoid of phosphorescence. The best example of this is got by putting a ring of tinfoil on the tube and connecting it with earth. No phosphorescence appears beneath the tinfoil, showing that no streams proceeding normally from the surface of the glass have reached the opposite side. All the phosphorescence is arranged in two rings, one on each side of the ring of tinfoil and parallel to it but separated from it by a space whose breadth is pretty uniform and varies in different cases from one-eighth to half an inch. Here it would seem that the streams that started normally, or nearly so, have interfered with one another with the result either of neutralising one another or deviating one another from the normal course and causing incidence on the glass at some distance on one side or the other of the tinfoil ring.

This capability of interfering with one another possessed by these molecular streams is one of great importance, both as giving us an insight into their nature, and also as an assistance in examining the mechanism of vacuum discharges. But we shall not dwell further upon it now as it belongs more properly to the next section, and is only mentioned here incidentally as one of the causes at work in determining the shape of the relief-phosphorescence.

The third cause which is probably at work to distort the phosphorescent image of the tinfoil is the influence of the position of the exciting positive electricity upon the negative discharge that responds to it. It has been thought that the direction of these molecular streams depends solely on the shape of the negative terminal, and is wholly independent of the position of the positive terminal, that is to say, of the direction from which the demand for negative electricity comes. This may be approximately so in the comparatively mild action that accompanies the continuous current (which may be compared to a case of steady motion in dynamics), but it certainly is not so in the more violent actions which accompany the impulsive discharges of the intermittent current. But, just as in the former case of the interference of molecular streams during their flight, the examination of this point belongs more properly to another branch of the investigation, so that we shall not notice it here at any length.

Leaving the question of the causes which determine the direction of these molecular streams, there is no doubt of their identity of nature with those that accompany the continuous current. They cause shadows in the same manner as do those proceeding from the negative terminal. In this way we can obtain shadows of any loose object in the tube and even of the positive terminal itself. The negative terminal, however, does not ordinarily cast a shadow properly so called, inasmuch as it is itself giving off like streams, and thus the streams that proceed from it turn aside any other streams that would otherwise impinge on it. These shadows due to relief are wholly independent of those that are due to the discharge from the negative terminal. If the object casting the shadow be sufficiently near the negative terminal to cast a shadow in the ordinary way, a second shadow of it can be produced by casting relief-phosphorescence upon it, and these two shadows will in general co-exist without to any great extent interfering with one another. In a similar way two shadows of the same object may be produced by placing two pieces of tinfoil connected to earth on the opposite side of the tube, one a little nearer the positive terminal and the other a little nearer the negative terminal than the object, so that the latter is within the relief-phosphorescence produced by each of the pieces of tinfoil. Two oblique shadows in opposite directions will then be seen, though their definition is not so good as in the former case, since the two systems of molecular streams have under such circumstances a strong tendency to interfere with each other.

XXII.—*On the relief-effects in tubes of high exhaustion with a positive air-spark.*

II. *Virtual shadows.*

If, while a discharge is passing through a tube of high exhaust with positive air-spark, we place the finger on the tube, the green light is seen to fade away from that part of the nearer side of the tube (*i.e.*, the side on which the finger rests) which lies in the direction of the positive terminal, giving the effect of a shadow falling upon that part of the surface of the tube. As the shadows are produced, not by any object actually intervening in the path of the gaseous particles, but by a body affecting them from outside, we have termed them *virtual shadows.* If the air-spark be small the region over which the shadow extends is bounded by a plane almost parallel to the tangent plane at the point where the finger rests and at a little distance from it (Plate 28, fig. 18), but if the air-spark be large the bounding plane is inclined at a considerable angle to the tangent, and cuts the tube obliquely. But it is only in very rare cases that the virtual shadow extinguishes the green phosphorescence from the opposite side of the tube, or from the end of the tube round the positive terminal, although it will often diminish the phosphorescence in that portion of the positive end which lies towards the side upon which the finger is placed.

A virtual shadow has a well-defined outline, the edge of which is generally brighter than the rest of the tube. It starts from the side of the finger nearest the negative terminal, but broadens considerably in the direction of the positive. Sometimes, when the air-spark is very large, it even seems to start from a point a little to the negative side of the finger, leaving that side of the finger surrounded by the outline of the shadow. The area of the shadow appears to be nearly, but not completely, deprived of the phosphorescent light. It is, however, difficult to judge how far the appearance of residual light within the shadow is due to reflexion, and how far to direct illumination. It is probable on theoretical grounds that some phosphorescence remains within the shadow; and this is confirmed by observation, for when the discharge has recently commenced it is often difficult to trace the outline distinctly. It would seem as though the glass needed to lose a little of its sensitiveness to show the full influence of positive relief in producing this phosphorescent shadow.

Now we have already established the fact that the immediate consequence of affording relief to any portion of the surface of a tube through which a discharge with positive air-spark is passing is to cause rapid impulsive discharges of negative electricity from the inside of the tube, and we have also seen that these discharges are accompanied in high vacua by the usual streams of molecules. Hence it is natural, in seeking to account for the phenomenon we have described above, to look to these negative discharges and their accompaniments for the solution. And that this is the proper source is shown by the fact that a similar phenomenon appears with negative special where there are also similar impulsive negative discharges, while in positive special and negative relief which give rise to positive discharges there is either no such phenomenon, or it is manifested on so much more insignificant a scale as to point to its being only a secondary effect.

Considering then that the positive relief and the negative special give effects which are as identical in the case of phosphorescent discharges as in that of ordinary discharges, we may fairly consider that we are on safe ground in applying our previously obtained results to them; and we therefore conclude that a negative discharge from the inside of the tube transversely to its length is the necessary condition for the existence of this phenomenon of virtual shadows. We shall now show that it is due to a beating down of the streams of molecules coming from the negative terminal (which would otherwise impinge on the side of the tube and there cause green light), this beating down being caused by the transverse streams of similar molecules coming from the inside of the tube.

In the first place, it is certain that such streams of molecules do interfere with each other when their paths cross. The experiments referred to in the last section suffice to show this. If two patches of tinfoil giving positive relief be so arranged on the tube that their green lines cross, it will be found that they displace each other, and that neither of the green patches produced by the pieces of tinfoil is in the position that it would be were the other not present. It is true that it is difficult to draw conclusions as to the exact nature of this interference from the mode in which they are displaced, for both the patches themselves and their displacements are very irregular, but the experiment is decisive to show the existence of interference between such streams of molecules when they are synchronous and when their paths cross.

In the instance just given the two sets of molecular streams are both due to the relief discharges that come from the side of the tube. We shall now give some instances in which one of the interfering streams is due to the discharge at the negative terminal of the tube.

We have already described relief-phosphorescence, and have shown that it is usually situated exactly opposite the place where the relief is given. But if the finger is placed in the immediate neighbourhood of the negative terminal, a little in front of it, we shall find that the patch of phosphorescence formed by it is no longer immediately opposite it, but some distance farther down the tube (Plate 28, fig. 19). In other words, the streams of molecules that were crossing the tube to form the relief-phosphorescence have been swept down the tube by the streams that were proceeding from the negative terminal.*

A much more striking form of what is substantially the same phenomenon was observed in a tube the negative terminal of which consisted of a straight wire fixed at right angles to the axis of the tube and passing through it to a point about half-way between the axis of the tube and the opposite side (Plate 28, fig. 20). The discharge passing through the tube had a positive air-spark of considerable size. On placing the finger upon the tube the usual relief-phosphorescence appeared. But when the finger was placed upon the tube at the spot where the wire forming the negative terminal of the tube would have, if produced, cut the surface of the tube, it was found that the relief-phosphorescence took the form of an annulus round the root of the negative terminal. The inner boundary of this annulus was well defined and formed approximately a circle round the root of the negative terminal as centre, but the external boundary was of course irregular. This showed beyond a doubt that the streams of molecules from the sides of the negative terminal had caused the streams from the interior of the glass beneath the finger to deviate from their course, and, instead of passing along parallel to the negative terminal, to be inclined at an angle to it, and thus to form the annular patch already described. And the truth of this conclusion was made still more evident when the finger was placed on the side of the tube so as to be at the point on the normal section through the negative terminal at the greatest distance from that terminal. The relief-phosphorescence then appeared to be cut in two by a broad and comparatively black space with roughly parallel sides, showing that the molecular streams from the sides of the negative terminal had diverted the streams that were going to form the relief-phosphorescence.†

We will now describe certain experiments which although they closely resemble the case which we have just mentioned have got an individual value from the remarkable way in which they support the whole theory of the intermittent discharge as put

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* A splendid example of the interference of molecular streams is obtained by the same means when the negative terminal is in the very usual and convenient form of a hollow cone. The molecular streams that proceed from it first strike the sides of the tube at a little distance from the negative terminal, thus leaving a zone quite destitute of phosphorescence. If the finger be placed upon this zone (the air-spark being of suitable length) the whole phosphorescence on the tube is affected. The molecular streams from the finger coming across the cone of molecular streams from the negative terminal cause them to deviate *en masse* from their previous course, and thus throw the phosphorescence upon the other side of the tube. The effect is generally very striking, and this property of the dark zone near the negative terminal in such tubes (and also in a lesser degree in tubes that have their negative terminal in the form of a disc) has led us to give to it the name of the *sensitive zone*.

† It is instructive to compare this with the behaviour of the positive pole under similar circumstances. If relief-phosphorescence be thrown across the positive terminal its shadow is as fine and sharp as though it were a non-conductor. The reason is obvious. If it has at the moment any electrical function at all it is that of receiving and not of giving forth negative electricity. Hence there are no molecular streams proceeding from its surface which could cause those that pass near it to deviate from their course.

forward by the authors of these papers. A loose skeleton-tetrahedron of copper wire was enclosed in a tube of high exhaust. A discharge with a positive air-spark of considerable length was made to pass through the tube and the finger was placed on the tube just opposite to the place where the tetrahedron lay. The shadow of the wires forming the tetrahedron was cast upon the relief-phosphorescence in precisely the same clear sharp way that would have been the case had the molecular streams proceeded from the negative terminal (Plate 28, figs. 21 and 22). A conductor was brought into contact with the outside of the tube exactly at the point where one of the angles of the tetrahedron was in contact with the inside of the tube. Instantly all the shadows of the wires bulged out to a breadth depending on the distance from the glass of the part casting the shadow. This was so precisely the counterpart of the experiment above referred to that it was impossible to mistake its meaning. The conductor permitted negative electricity to pass off from the inside of the tube (and therefore from the angle of the tetrahedron, which was situated there) in obedience to the demand for negative electricity that was created by the positive discharges through the tube. But the whole of the tetrahedron being metallic, a supply of negative electricity to one portion of it enabled the whole to act as a negative terminal, and hence negative electricity streamed from all portions of it in obedience to the general demand for it. With this negative electricity there streamed of necessity molecules, and these streams of molecules diverted from their course the similar streams that were passing by on their way to produce relief-phosphorescence, and hence came the bulging out of the shadows. Those parts that were most distant from the glass diverted the molecular streams at an earlier period of their course than the other parts; and it was in the shadows of the former that the bulging was most conspicuous, showing that the effect was a true diversion or alteration of the direction of motion of the molecules.*

It scarcely needs further discussion to show that the above is the true explanation of the phenomenon. But there are one or two cognate experiments which serve to establish this yet more clearly. A similar experiment having been tried with other pieces of metallic wire with like results, it was then tried with a wire-shaped piece of glass. No such effect followed. The glass being a non-conductor, the electricity could not pass from one part of it to another. The air-spark was then changed to the nega-

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* A slight peculiarity in the phenomenon ought to be here mentioned as indicative of the way in which intermittent discharge is obedient to local circumstances. One of the edges of the tetrahedron chanced to be made of two very fine parallel wires. The sharp shadow of the tetrahedron represented this perfectly, having a narrow green line between the two black lines which formed the shadows of the two fine wires. When the conductor was brought into contact with the tube, as before described, the shadows of these two fine wires bulged on the outside but not on the sides where they were nearest to one another, and thus the narrow green line was left intact. The inductive repulsion of the negative electricity in the two wires prevented any discharge taking place from them towards one another, and hence there were no molecular streams from those sides of the two wires that lay closest to one another, and there was nothing to impede the transverse molecular streams that sought to pass between these wires.

tive and a piece of tinfoil immediately over the tetrahedron was connected with the negative terminal, thus forming the negative special which, as we shall see (and as is otherwise obvious) produces precisely the same phenomenon as the relief-positive. Just as before, the shadow of the wires of the tetrahedron was cast, sharply and clearly, upon the bright patch of phosphorescence which was formed thereby. A conductor was then brought, as before, in contact with the tube at one of the corners of the tetrahedron. No bulging out followed. The relief afforded by the conductor only permitted positive electricity to stream from the wires of the tetrahedron, and as this was unaccompanied by any molecular streams it was powerless to divert those that were passing across the tube.*

Secondly. It is experimentally evident that the shadow is produced by a depression or deviation of the streams of molecules in question which come from the negative terminal. An examination of the appearance is well nigh enough to establish this, for it is easy to see how the rays are bent down, and how the parts upon which they are constrained to fall grow brighter thereby.† But there is an experiment which puts this beyond a doubt. In a tube kindly lent by Mr. CROOKES there is an intermediate terminal, nearer to one end of the tube than to the other, partly composed of a flat piece of aluminium, the flat sides of which are turned towards the terminals of the tube, and in this flat piece of aluminium there chance to be some little holes (Plate 28, fig. 23). When the more *distant* terminal is made *negative*, a bright image of these small holes appears on the side of the tube in the midst of the general shadow of the intermediate terminal. When the tube is touched on the side on which this image appears, but at a point on the negative side of the image, it is found that the image is splayed out, part being thrown down or farther along the side of the tube. If the finger be moved a little to one side the splaying out moves towards the other side.‡ This seems to show distinctly that the effect of the finger is to push away from it the rays going to form the image.

But it is possible to prove in an even more direct way that the virtual shadow is

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* An interesting variation of these experiments is obtained by placing the finger beneath the tetrahedron and casting the shadow of the apex on the opposite side of the tube. If the tetrahedron be a non-conductor a somewhat magnified shadow will be seen; but if it be a conductor this will be splayed out to an enormous extent, for the finger which supplies the negative electricity which permits the production of the relief phosphorescence also enables the edges of the tetrahedron to become sources of negative discharge, and thus to splay out the shadows which they cast upon the relief-phosphorescence.

† This is clearly shown when we form a virtual shadow at a spot that lies within an already existing virtual shadow. If the former would, if it alone existed, extend to any part of the surface beyond the limits of the latter it will still do so, and the bright line that marks the edge of the virtual show will have an angle at the spot where their boundaries would cross and will thereafter follow the outline of the outer shadow. This shows that each relieving system produces its effect independently of the other.

‡ Similar effects are produced upon the edges of the shadow of the intermediate terminal itself, but the phenomenon is best observed in the way described in the text as the displacement or distortion of the small isolated bright spots which form the image of the little holes in the aluminium is more capable of being accurately observed.

due to a turning aside of the molecular streams that come from the negative terminal. A tube was taken in which there were a number of small objects, such as pieces of glass. The tube being of a very high exhaust there was phosphorescence over the whole of the interior of the tube, and all these small objects cast shadows, the pieces of glass also giving out phosphorescence. If the finger was brought in contact with the tube a little on the negative side of any one of these small objects (Plate 29, fig. 24), it was found that the molecular streams that were proceeding down the tube from the negative terminal were so far turned aside by the cross currents of molecules that proceeded from the interior surface of the tube beneath the finger that they no longer struck the object but passed completely over it, so that it gave no shadow at all. And the fact that the molecular streams did not reach it was not only shown by the absence of a shadow but it was also directly demonstrated in the case of the small pieces of glass by the fact that they ceased to manifest phosphorescence ; so that it was established beyond contradiction that the molecular streams that formerly reached them no longer did so.

On these grounds, then, we may accept the hypothesis that the virtual shadow is due to the beating down of the streams of molecules that pass along from the negative terminal. It will be remembered that they are moving at a very slight angle to the sides of the tube, so that a very small deflection would suffice to account for this phenomenon. This last point seems to be an essential condition for the formation of the virtual shadow, for in the case of short tubes, in which the negative terminal is a wire placed axially and projecting a considerable distance into the tube so that the molecular streams would no longer proceed at a slight angle to the sides of the tube, it has been found difficult to get good virtual shadows even with a fairly long positive air-spark.

An experiment ought to be mentioned here which is serviceable in rendering more complete the chain of proof, viz.: the production of a double virtual shadow when the negative is bifurcated. This was done in the tube of Mr. CROOKES, to which we have already referred, which was furnished with an intermediate terminal which was made positive, while the two terminals at the extremities of the tube were made negative (Plate 29, fig. 25). When the finger was placed upon the tube two shadows were clearly seen pointing in opposite directions, showing that these shadows point *from* the negative and not *to* the positive ; a law the truth of which might perhaps have been anticipated, but which, so far as it can, serves to show the correctness of our conclusions.

XXIII.—*On the relief-effect in tubes of high exhaustion with a positive air-spark.* III. *The positive luminosity and its attendant phosphorescence.*

If a tube be watched during the process of exhaustion, and the phenomena be carefully noted which it presents when a current with a positive air-spark is passing through it, the positive luminosity will be found to go through very marked changes of form. As it approaches the high state of exhaustion which is usually associated with phosphorescence, the positive column will be found to diminish in diameter until it is reduced to a small pencil-like column very sensitive to the approach of a conductor, which, on account of the difficulty of keeping the tube free from all disturbing influences, usually stretches along the glass on one side of the tube instead of taking the normal centrical position. Its extreme sensitiveness often causes it to be crooked, and it may sometimes be seen crossing the tube from side to side in a zigzag manner.

This luminosity can be driven against the opposite side of the tube by the approach of the hand or any other conductor to the tube. Contact with the tube is so far from being necessary, that the violent action which it causes entirely masks the phenomena of which we are about to speak. The best effects are got when the hand is from three to six inches from the tube. When this pencil-like column is thus in contact with the tube it will be found that a long streak of the well-known phosphorescence marks its line of contact, and if the hand be brought a little nearer, so as to force the column, as it were, with more violence against the side, this green streak becomes very bright and vivid (Plate 29, fig. 26). It is extremely mobile, for it moves with the positive column, and is beyond all doubt attendant upon it. We shall hereafter see that they can be made to separate slightly by special precautions being taken, but this only serves to prove more clearly how closely they are attendant the one on the other, for it is with difficulty that the separation takes place, and as soon as the disturbing influence is removed they come together again.

But it is not only in this way that the phosphorescence attendant upon the positive luminosity becomes visible. If from any cause the positive column, taking a zigzag course, impinges, so to speak, on the side of the tube, a green patch of phosphorescence appears. And when the finger is placed upon the tube so as to form a patch of what we have termed relief-phosphorescence, although this seems to blot out the feebly luminous positive column, yet its presence is shown by its attendant phosphorescence. If some other conductor be brought near the tube, not on the same side as the finger, it will be found that the true relief-phosphorescence remains unmoved, but that there is an extremely mobile portion of the phosphorescent image of the finger which by its sensitiveness shows that it has a different origin and nature to the immovable relief-phosphorescence. If this portion be traced out, as can be easily done since its mobility enables it to be readily distinguished, it will be found to be in the line of a prolongation of the positive column, and thus it is evident that it is the attendant phosphorescence of which we have been speaking.

Before we proceed to examine in detail this most peculiar phenomenon it will be well to mention that one of the most convenient modes of obtaining it is by means of the positive unipolar or double unipolar discharge. Using this arrangement, the thin pencil-like form of the positive column appears in tubes whose exhaust is not sufficiently perfect, or in which other circumstances are not sufficiently favourable to give it when a current passes through the tube. And just as in less perfectly exhausted tubes each of the two positive columns of the double unipolar discharge assumes a thick tongue-shaped form, the tips pointing towards each other, so in higher exhausts we find two long pencil-like columns each tapering away to a point, and each accompanied by its attendant phosphorescence. Either of these can be used for the purpose of examining the properties of this phosphorescence, and the results will hold good in all cases, however the pencil-like column be obtained. There is no such pencil-like column when a negative unipolar is observed.

The first thing to do in the analysis of this attendant phosphorescence is of course to ascertain the direction and, if possible, the source of the streams of molecules which produce it. This was done by means of a tube into which had been introduced a number of crooked pieces of wire and small bits of glass. When the attendant phosphorescence was brought up to these it was found that (subject to the qualifications to be given later on) *the shadow of each object lay in the same normal section of the tube as the object itself*, and was, roughly speaking, in the position in which it would have been had the seat of the discharge been the opposite side of the tube. This conclusively showed that the streams producing this attendant phosphorescence did not come from the negative terminal, but were due to local action in the tube, and that the *direction of these streams was normal to the axis of the tube.*

Further and more minute investigation has since shown that these results require some modification when the part of the attendant phosphorescence which is being examined is situated at some bend or corner of the zigzag course of the positive luminosity, and that they can only be taken as accurate where the luminosity is not very greatly curved. This result, so far from affording any argument against the theory that this phosphorescence is due to local action, strongly supports it, as showing that peculiarities in the direction of the molecular streams are only found when we should, from the circumstances of the case, expect to find peculiarities of local action. No doubt in such cases the direction of the streams is a resultant of conflicting tendencies. We shall, therefore, neglect such cases for the present, and confine ourselves to the case of a fairly straight positive column where, as we have already said, the streams at each point come to the glass along paths lying in the normal section of the tube at that point.

We see at once that we have here a phenomenon of almost unexampled importance in the analysis of the *modus operandi* of the positive discharge. We find that its passage is accompanied by discharges of negative all along the tube, the molecular streams accompanying which move in directions normal to its axis. Taking as a provisional hypothesis[*] that these start from the sides of the tube, we see that we have a process of relief continually going on. But the most remarkable point seems to be that these streams either start in the direction of or are subsequently directed to the thin column of positive luminosity. This leaves scarcely any room to doubt that

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[*] We shall presently see that there are experimental grounds for believing this hypothesis to be a correct one.

it represents the *locus of the exciting cause of this local action.* We, therefore, have direct indications of this being a locus where the positive electricity (which alone can be the exciting cause of these negative discharges) obtains relief from the negative given off in the tube.

It will here be the place to mention an observation of a very remarkable kind which was made upon the shadow thrown by a crooked wire within the tube upon this attendant phosphorescence. The portion casting the shadow was nearly straight and had a direction lying in a normal section of the tube somewhat inclined to the radius of that section on which its foot lay. As the narrow green line was driven round the tube towards the wire the shadow of the wire appeared upon it, but not crossing it. When it was driven still nearer to the foot of the wire the shadow, instead of remaining fixed, and thus more and more completely crossing the green line, was found to shrink in and grow shorter, and continued only partially to cross the green line, although the latter had moved so much that it would have been completely divided had the shadow retained its original length. When, however, the green line was driven still closer up to the foot of the wire the shadow ceased to shrink below a certain length, and finally passed quite across the green line. The solution of the peculiarities here exhibited will be found, we believe, in the hypothesis that the streams of molecules come off from a considerable segment* of the surface of the tube situated in the region opposite to the green line, and they by their mutual action, or by the direction in which they originally start, stream towards the thin column of positive luminosity without their paths crossing at the axis of the tube or at any other part of their path.

We have said that this thin luminous column with its attendant phosphorescence is sensitive in the highest degree, and is strongly repelled when the hand is brought anywhere in the neighbourhood of the tube. It might be thought, therefore, that it is nothing but a special form of relief phosphorescence, and that it differs from what we have treated of in a previous section only in that it is the portion first formed and not needing actual contact for its formation. But this is by no means the case. The two are wholly different in genesis and in properties. Nothing is easier than to distinguish them. Relief phosphorescence is quite fixed in position unless another centre of production is formed by touching the tube in its immediate neighbourhood, in which case the two systems of streams of course interfere the one with the other. But even when contact is made with the tube it is quite easy to drive this attendant phosphorescence about by bringing other conducting systems into the neighbourhood of the tube, although they do not produce the slightest effect upon the relief phosphor-

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* This is confirmed by the fact that it is impossible to cast a shadow upon this attendant phosphorescence unless the object casting it be very near to the side of the tube where the phosphorescence appears. And even then it has a tendency to be blurred and hazy. This indicates that the molecular streams that cause it do not proceed from any one spot, but that they converge upon it from a considerable region, all their directions being, however, approximately situated in a normal section of the tube.

escence. Then, again, the shadows cast by the two will often be in different directions. Moreover, if an object cast a clear shadow upon the relief-phosphorescence and the mobile portion of the phosphorescence (which we have seen belongs to the attendant phosphorescence) be brought up to it, we shall generally find that it blurs it so completely as to render it difficult to make out its outlines, thus showing that the streams which give rise to it do not take their origin in the same spot as those which occasion the relief-phosphorescence. In short, however we examine the matter we are continually met by fresh proofs of the radically distinct nature and origin of the two kinds of phosphorescence.

Perhaps the most convincing experiment upon this point remains to be described. A tube was taken in which were a quantity of very thin films of glass lying loose in the tube. A spot was selected where one film lay over another with a very shallow interval between them. The relief-phosphorescence was thrown upon the spot of the tube where they were lying. It caused bright phosphorescence on the surface of the upper one, but left wholly unilluminated the one that lay beneath it. The positive luminosity with its attendant phosphorescence was now driven behind the films. The lower as well as the upper was now illuminated by phosphorescence. Now we know that the streams producing this phosphorescence are normal to the axis of the tube. Hence it is clear that the exciting cause of the negative discharges which caused these streams must have been below the upper film (and probably below the lower one also) since it caused streams to impinge on the lower film which could have come from nowhere but the lower surface of the upper film. Thus we see that we have the most cogent evidence for supposing that the thin column of positive luminosity really represents a locus of demand for negative electricity and excites discharge from the sides of the tube, and possibly from the gas, to satisfy it.

In order to establish more firmly the position that this attendant phosphorescence is caused by streams that come towards it in directions normal to the axis of the tube, and principally in directions inclined but slightly to the diameter of the normal section through the point, an electro-magnet was placed with its axis perpendicular to that of the tube and its pole near to the tube, but not near enough to produce relief-phosphorescence. The position of the green line was carefully observed, and then the current through the coils of the magnet was turned on. The instantaneous effect was to twist the green line into the shape of an S. Now if it be remembered that, roughly speaking, the directions of these streams of molecules are diametral, and therefore in the original position were parallel to the axis of the magnet, it will be seen that the effect observed was precisely what should have been expected. Molecular streams parallel to the axis of the magnet would be bent into helices, and accordingly those on one side would appear to be thrown one way and those on the other would appear to be thrown the other way. In order to establish experimentally that this effect would be produced upon a system of molecular streams constituted as described, a broad slip of tinfoil not quite long enough to go round the tube was placed on the tube. It left, of course, an opening along its length, and when it was connected to earth this became phosphorescent from the relief-phosphorescence. The directions of the streams producing this phosphorescence were substantially the same as those to which we have seen reason to believe the attendant phosphorescence is due. An electro-magnet was tried upon this strip of phosphorescence, and it produced similar results to those above described, thus strongly confirming the truth of the theory we have adopted to account for the genesis of the attendant phosphorescence.

One more peculiarity remains to be noticed with regard to this attendant phosphorescence. It is possible, as we have said, to cause it to separate slightly from the positive luminosity with which, as we have said, it is so closely bound up. One way is by bringing the positive luminosity across some piece of wire or other conductor in the tube; but as this phenomenon is obscure and difficult to observe we shall not dwell on it further. The other way is by approaching a conductor to the tube on one side or the other of the position which surrounding circumstances have constrained the positive luminosity to take up. It is often possible by doing this to drive the green phosphorescence a little distance off on the further side of the positive luminosity to that on which the conductor is. It would seem as though the phosphorescence were more strongly repelled than even the positive luminosity. A straight wire in connexion with earth was placed at an angle to the axis of the tube, and made to approach it. The green line assumed a serpentine form, cutting the positive luminosity at its point of inflexion (Plate 29, fig. 28). The solution doubtless is connected with the fact that the presence of the conductor renders negative discharge easier from the part of the tube nearest to it, and that the streams of molecules, in consequence of their inertia, persist in maintaining a nearly diametral path although the direction from which comes the demand for the negative discharge which is inclined at an angle to this.*

We will now return to the excepted case in which the positive luminosity is made to pass in a zigzag direction through the tube (Plate 29, fig. 27). As we have said, the places where it appears to impinge on the side of the tube are marked by patches of phosphorescence. These patches are as a rule exceptionally brilliant. If an object within the tube be situated so that the column of luminosity comes into contact with it on thus crossing the tube, it will be found that it casts a shadow in the direction in which the column strikes it—that is to say, in the direction of the course of the column as we proceed towards the positive terminal. In fact, in such cases the shadow is much as it would be if the column were threaded throughout its whole length by molecular streams coming from the negative terminal and proceeding towards the positive terminal.

Now before we proceed further we must call attention to the fact that it is only

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* If the conductor be brought towards the other side of the tube exactly opposite to where the luminosity and its attendant phosphorescence is situated it often splits the line of phosphorescence into two, one situated on each side of the thin column of positive luminosity.

where the positive luminosity has such a tortuous course as has been described that this phenomenon presents itself. Repeated experiments have demonstrated beyond the possibility of doubt that where the positive luminosity lies along the inner surface of the tube (as is usually the case) the image of a small object lying over it will be cast perpendicularly upon it. Hence the case we are about to discuss must be taken as an exceptional case due to the presence of special circumstances, the nature of which it is one of our aims to discover, but not in any way casting doubt on the conclusions which we have already drawn from observations upon the normal behaviour of the positive luminosity and its attendant phosphorescence.

If the object which is brought into the path of the positive luminosity in its passage across the tube be a non-conductor, there is no special peculiarity in the shadow case. It will be an ordinary phosphorescent shadow, whose direction is defined in the way we have given above. But if it be a conductor, and especially if it be a portion of a conductor of some little magnitude such as the end of a piece of wire, it will be found that the shadow is bulged out to a very considerable extent. And if the finger be placed against the outside of the tube exactly opposite to the other end of the small conductor, this bulging out will become immensely increased.

Now there can be but one possible interpretation of these phenomena. The bulging out must be caused (as we saw in a previous case) by a discharge of negative electricity from the sides of the wire, and such discharge must be in response to a demand for it in the tube. But here we come to a very remarkable peculiarity of the present case. This demand must be intensely local; for while in the case of relief phosphorescence there was no perceptible bulging out of the shadow of a conductor that was partly within the range of the streams that were crossing the tube, such a bulging out not only occurs in the present case but is a most marked phenomenon. Thus we have direct proof that the positive luminosity marks a locus of intense demand for negative electricity.

A very curious variation of this experiment may here be referred to in order to strengthen the conclusions just drawn. The zigzag positive luminosity was made to cut the thin projecting wire that formed the positive terminal. Its shadow gave no sign of bulging out, and behaved as though it was a non-conductor. It is obvious that no negative electricity could be drawn from it as a response, and hence there was no bulging out of the shadow. To test the matter still further, the metallic object that had previously been experimented on was shaken down into contact with the positive terminal, and its shadow was observed. It was found to have no bulging, but to be thin and sharp like the shadow of a non-conductor.

We have thus direct evidence of the intense local demand for negative electricity in the track marked by the positive luminosity.* It seems paradoxical that this can co-exist with streams of molecules proceeding along it. But it must be remembered that we have no evidence that they are (at all events throughout the whole of their course)

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* We shall return to this subject in Section XXVIII.

carriers of negative electricity, and the experiments which we have just described seem to show almost conclusively that such is not the case.

The property which, as we have just seen, conductors within the tube possess of becoming negative terminals and thus giving out negative electricity on all sides, seem to account for a peculiarity in the attendant phosphorescence which merits remark. If the hand be passed along the under side of the tube at a little distance from it, the line of attendant phosphorescence will be seen sharply and clearly defined along the top of the tube until the hand comes to a place where a conducting object is lying in the tube. The line of phosphorescence will there be split in two and become irregular in outline, and will join again beyond the spot where the conductor lies, thus enclosing within it a space with no phosphorescence. This experiment is also of use as showing strong grounds for holding that the streams which produce the attendant phosphorescence come from the opposite side of the tube.

It will now be seen how special is the importance of the evidence given us by these molecular streams. Without the definite evidence which they give of the existence of sources of negative discharge, it would have been left to speculation to determine the nature of the action in the tube which accompanies a discharge. And as we have seen that these molecular streams to which phosphorescence is due are not peculiar to tubes of high exhaust, but probably exist as an accompaniment of negative discharge in tubes of all degrees of vacuum, we see that we have here a fresh step in the analysis of the mode of propagation of vacuum discharges in general.

XXIV.—*On the special effect in tubes of high exhaustion with a positive air-spark.*

We have seen in our former paper that the characteristic peculiarity of the special effect in tubes of low vacua with a positive air-spark is that the luminosity is attracted instead of repelled. If a wire from the positive terminal be carried parallel to the tube, and at a little distance from it, a line of luminosity will appear on the side of the tube nearest to the wire throughout its whole length.

If the same experiment be tried in high vacua precisely the same effect is produced. The thin pencil-like column of which we have spoken in the last section will be found pressed close to the side of the tube nearest to the wire. It follows all the movements of the wire, and takes a curved direction when the wire does so. This alone would furnish a strong presumption of the radical identity of the modes of discharge in low and high vacua, were any further proof needed.

There is, however, an apparent peculiarity in the behaviour of this thin pencil-like column, when the special effect is produced, which must be mentioned. When the piece of metal attached to the wire which is in connexion with the positive terminal is brought close to the tube there is no longer an attraction of the positive luminosity, but a strong repulsion (Plate 29, fig. 29). There is nothing in this phenomenon to invalidate the above conclusions. An exactly analogous phenomenon is observed in the case of tubes of less perfect vacuum. When the body producing the special effect is brought up to the tube, the positive discharge caused by it stretches away towards the negative terminal, and the part of the positive luminosity on the positive side is depressed, owing to the formation of an imperfect negative dark space beneath the wire or tinfoil—a depression which would, if symmetrical all round the tube, cause the positive column to pass into the thin central column which leads up to the termination of the truncated portion. There is no doubt that the phenomenon observed in tubes of high vacua is substantially the same, except that the characteristic feebleness of the positive luminosity in such tubes prevents there being sufficient definition in the positive discharge caused by the special effect to enable the eye readily to recognise the identity of the two phenomena; while, on the other hand, the greater breadth of the negative dark space in tubes of high vacua makes this repulsion of the positive column a more striking phenomenon than its analogue in tubes of lower vacua. That the above is a substantially accurate interpretation of the phenomenon there is no doubt, for if the special effect be produced by a ring of tinfoil we find the well-known truncated positive column; the hollow cone around it being, however, as we should expect from what has been said above, faint and very ill defined.

We see then that positive special causes the positive luminosity to locate itself on that side of the tube along which runs the wire in connexion with the positive terminal. And we have also seen in the previous section that there is a constant discharge of negative electricity towards this positive luminosity from the surrounding parts of the tube. It follows, therefore, that we may expect positive special to be marked by the appearance of phosphorescence at the place where the positive special is being produced, and not, as in positive relief, on the opposite side of the tube; and this has been found to be the case. The thin pencil-like column of positive luminosity that appears along the line of the wire is accompanied by the same attendant phosphorescence that we have discussed in the previous section. Moreover, the inside surface of the tube immediately beneath a piece of tinfoil connected with the positive terminal has been observed to be covered with the well-known green phosphorescence, and even a shadow has been thrown upon it from a film of glass within the tube, the edge of which was over it and very near to it, and also from other small objects lying in similar positions. This completes the proof both that the positive special is in effect the creation of a virtual positive terminal on the inner surface of the tube, and also that where there is such a virtual terminal or centre of instantaneous discharge the portions of the tube near thereto give off negative electricity to satisfy it; and with this negative discharge there are the usual molecular streams. And it further confirms the view that neither the direction of the negative discharge nor that of the molecular streams is independent of the position of the spot from which the demand comes.

The action of the positive special is of course of considerable violence. This enables us in a very convenient way at once to demonstrate the substantial identity of origin of the two forms of attendant phosphorescence described in the previous section, and also to obtain them at will. If a long slip of tinfoil be laid along a high vacuum tube and connected to the positive terminal, and a considerable positive air-spark be used, the thin positive luminosity will be seen to lie along the slip till we arrive at the end of the strip nearest to the negative terminal. Here it will naturally cease clinging to the side of the tube and slant off to a more central position (Plate 29, fig. 30), thus causing an angle in its direction. The attendant phosphorescence can be distinguished under favourable circumstances all along the line of the slip of tinfoil; and the spot where the angle is formed in the direction of the positive luminosity as above described will be found to be covered with bright phosphorescence, precisely as was the case when the positive luminosity was examined by the methods detailed in the previous section. The best arrangement for securing these effects is by the use of the positive unipolar discharge. So clearly are all the details of the phenomenon shown thereby that the attendant phosphorescence is readily distinguished in the shape of two bright green lines running along the two edges of the slip of tinfoil, these edges being doubtless the operative parts of the tinfoil considered as creating a quasi-positive-terminal in the interior of the tube. By this arrangement it is perfectly easy to obtain these effects in a sufficiently brilliant form to permit of the ready determination of the direction of arrival of the molecular streams which cause the phosphorescence. It will be found that the results in all cases are in conformity with the conclusions already arrived at.

But it is not only in the above manner that positive special produces phosphorescence. If we recall to mind the special effect in low tension tubes with a positive air-spark, we shall remember that the hollow cone of luminosity which marked the positive discharge in the tube directly caused by the positive impulses within the tinfoil, was separated from the truncated positive column by a dark space, across which occurred the action by which the advancing positive discharge became satisfied by the negative electricity left behind in the tube beneath the tinfoil. The discharge of this latter from the glass under the influence of the advancing positive electricity is a case of true negative discharge, and accordingly we find that in tubes of sufficiently high tension with sufficiently long air-sparks it is accompanied by the usual molecular streams, and that it produces the usual phosphorescence. This phosphorescence must be due to a negative discharge commencing almost synchronously with that of positive relief, for they both take place through the action of the advancing positive electricity, but it is of much less violence. If a piece of tinfoil be placed on the spot where the positive-special-phosphorescence falls, and then be connected to earth, it will be found that it clears the glass beneath it and for a short distance round its edge from phosphorescence; while, on the other hand, it is able to throw phosphorescence over the glass immediately below the tinfoil that is connected to the positive terminal. This superior intensity of relief phosphorescence will be found to be of importance later on.

Since positive special is accompanied by a negative discharge which commences almost synchronously with that which gives rise to relief phosphorescence and virtual shadows, we might expect that it would also give rise to virtual shadows. And such is found to be the case, although the effects are decidedly more feeble than in the case of positive relief. They are, however, generally present, and under favourable circumstances are clear and distinct (Plate 29, fig. 31). They have not formed the subject of any special examination as yet, but so far as can be determined by inspection they do not materially differ from those due to positive relief in any other respects than would naturally flow from the inferior intensity of the action to which they are due.

Thus we see that positive special effects are clearly distinguished from relief effects by the attraction of the positive luminosity and the appearance of phosphorescence *on* the tinfoil. It is true that they both produce virtual shadows and phosphorescence on the glass opposite to the tinfoil, but these are given only in a feebler degree, and as secondary phenomena, by the positive special. It is worthy of remark that in the latter case we have the phosphorescence both on and opposite to the tinfoil, a phenomenon of which no instance will be found in the experiments on interference which have hitherto been described, and which at first sight appears to contradict the laws of interference of molecular streams already established (see page 609). It is probable that the solution of the difficulty is, that the arrival of the molecules which causes the one is not synchronous with the discharge which causes the other, but the authors of the present paper have been unable to come to any definite conclusions as to the way in which this occurs.

XXV.—*On the relief and special effects in tubes of high exhaustion with a negative air-spark.*

We have already noticed that the main peculiarity of discharges in high as compared with low vacua is the prominence of the special characteristic of negative discharge, viz. : molecular streams, and the comparative insignificance of the special characteristic of positive discharge, viz.: positive luminosity. So much is this the case that while in the tubes of low exhaust we found it necessary to rely chiefly on the effects of positive discharges, as they alone rendered themselves plainly visible, we are, in the case of tubes of high exhaust, compelled to rely chiefly on the effects of negative discharges to guide us in our investigations.

It follows naturally from these considerations that negative-relief is a comparatively uninteresting subject of investigation, for all the impulsive discharges produced thereby being discharges of positive luminosity, are extremely feeble in their luminosity, if not practically invisible. It is in fact exactly similar to positive special, except that the unaffected state of the discharge is different, the luminosity in the case of a negative air-spark being in the form of a diffused haze, and not in the form of a thin pencil-like column. And even this difference contributes to make the phenomena of negative-relief still less impressive and striking.

But, as we have already said, it is not only the negative-relief that has its counterpart in the effects with a positive air-spark. The negative-special presents precisely the same phenomena as the positive-relief. We get perfect virtual shadows and bright patches of phosphorescence on the other side of the tube. Indeed, so perfect is the identity of effects that it would be just as possible to work with one as with the other, were it not that it is so much more convenient to examine relief effects than special effects on account of the simpler character of the manipulation.

There is, however, in all cases a very superior sharpness of action in the positive effects of which we shall have to speak later; but, allowing for this, it would be difficult to overstate the perfect correspondence that there is between the positive-special and the negative-relief, and between the positive-relief and the negative-special. The splendid phosphorescent effect and virtual shadows produced by the two last mentioned are so strikingly alike as to need no further comment; but this resemblance extends to the less striking phenomena. For instance, if we produce the negative-special by the aid of a wire from the negative terminal brought parallel to the tube, and near to it, we shall find that the previously diffused haze is driven into a thin column on the other side of the tube, closely resembling the pencil-like column of the positive air-spark. This can be driven about in like manner, and even attendant phosphorescence has at times been faintly visible. If the negative-relief be produced by a similarly placed wire connected to earth there will be a concentration of the haze on the side of the tube nearest to the wire, as in the case with the positive-special. We have little doubt that further investigation will show that there is here also attendant phosphorescence, though it is difficult to detect it.

The patch of phosphorescence on the glass immediately beneath the tinfoil of which we have spoken in treating of positive-relief has also been seen in negative-relief. The existence of phosphorescence on the glass opposite the tinfoil and that of the correlative virtual shadow are, however, more difficult to determine. We have not obtained the former in a satisfactory manner, and though we have often seen feeble virtual shadows with the negative-relief it has always been a matter of doubt with us as to whether some slight positive intermittence had not crept in and caused it. Our own opinion is that these two secondary phenomena are in the case of the negative-relief too feeble to be generally visible, though the virtual shadows (which require a much less violent action than does the production of phosphorescence on the opposite side of the tube) may occasionally do so.

But although for these reasons we do not find it profitable to examine with special care the phenomena of the discharge with negative air-spark, the importance of the general identity of these effects with the converse effects in the case of the positive air-spark is very great as a proof of the main proposition in the theory which the authors of this paper have put forward with regard to the disruptive discharge in its intermittent form, viz.: that it takes place from either terminal, and that, in general, the electricity passes along the whole of the tube in the form of a discharge of the same name as that of the terminal from which it proceeds, and only meets with a response from the other terminal when it has arrived in its immediate locality. The argument here is the same as that used in the former paper, and therefore need not be repeated, and it is only referred to in order to show that the evidence and the reasoning that sufficed to demonstrate it in the case of tubes of low exhaust are equally applicable and equally effectual here. And it is important to notice how persistently the characteristics of the positive luminosity in the case of the two air-sparks which we met with in tubes of moderate exhaust remain unchanged when the exhaust is pushed further. We know that with a positive air-spark the tendency is for the luminosity to shrink from the sides of the tube into a bright central column, smaller than the interior diameter of the tube, while the tendency of the positive luminosity with a negative air-spark is to spread out through the whole of the interior of the tube (or, at all events, to fill all the peripheral parts of it) and to become hazy in so doing. The pencil-like column of the positive intermittence and the diffused haze of the negative intermittence in high vacuum tubes represent the extreme forms of these peculiarities.

We shall not, therefore, pursue the question of negative discharges any further at present. The general result that they correspond to the converse effect of the positive intermittence, except that the definition is less perfect, and that the feebler and secondary effects are difficult to obtain, will render the remarks in the previous sections applicable to the case of the negative intermittence. The special peculiarities of negative discharge will be dealt with in a subsequent section.

XXVI.—*General conclusions as to the electric discharge.*

I. *The comparative magnitudes of the small time-quantities of the discharge.*

The problem of the physical nature of electricity is so closely bound up with the question of the distinction between positive and negative electricity, that the most hopeful way of approaching the greater problem is by solving the lesser. Now there is no class of electrical phenomena where the differences between the two kinds of electricity manifest themselves so strikingly as in the disruptive discharge, and hence this is the best field for studying the contrasts between the two kinds of electricity, with a view of ascertaining the source of this contrast. The subject is naturally a very wide one, and we do not purpose to deal with it generally in the present paper. Our object is at present simply to record a few conclusions to which we have come bearing upon the *modus operandi* of the discharge.

We have frequently had occasion to remark upon the extremely short duration of the phenomena of the electric discharge. This discharge is, however, not equally instantaneous in all its phenomena. In the present section we shall examine the various small time-quantities of the discharge, in order to get a clear idea of the relative shortness of the periods which they occupy, for the purpose of guidance in our future speculations as to their relationships one to another.

These small time-quantities are as follows :—

1. The period occupied by a discharge.
2. The interval between two discharges.
3. The time occupied by the discharge of the positive electricity from its terminal.*
4. The time occupied by the discharge of the negative electricity from its terminal.
5. The time occupied by molecular streams in leaving a negative terminal.
6. The time occupied by positive electricity in passing along the tube.
7. The time occupied by negative electricity in passing along the tube.
8. The time occupied by the particles composing molecular streams in passing along the tube.
9. The time occupied by electricity in passing along a wire of the length of the tube.

To these there might be added the time that electric induction occupies in traversing a finite space. This we have taken to be zero, for we have not been able to discover any symptoms of its being durational; or perhaps we should rather say that we have considered it either negligible in comparison with any of the above quantities, or included in them so as to be indistinguishable in order of magnitude from the shortest of them.

Taking, then, the small time-quantities which are enumerated above, we know, in the first place, that the interval between two discharges is incomparably greater than any of the other small quantities to which we have referred. This is shown by the revolving mirror. For although this instrument easily separates the intermittent flashes, it never shows any splaying out in the luminous phenomena of the individual discharges; for the haziness which it sometimes shows as attendant on the phosphorescence does not testify to any durational character in the period of arrival of the molecular streams, but only to the power of the glass to retain phosphorescence for a short time after the exciting cause of it has ceased. We may therefore take the interval between two discharges as by far the largest of all the small quantities of which we have spoken.

This conclusion is what we should naturally have anticipated. For although we are not at present in a position to say whether a discharge through a vacuum tube occupies a greater or smaller period of time than an electric spark in air, yet they are phenomena of a like nature, and they probably occupy periods which are to some degree similar in point of duration. Now it is well known that the time occupied by an electric spark in air is almost inconceivably small. However fast a wheel be rotating, it will appear to be at rest when illuminated by an electric spark. And

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* It will of course be understood that under the term "terminal" are included all sources of electrical discharge, whether effective terminals or quasi-terminals.

although the interval between two of the discharges considered in this paper may seldom exceed a thousandth part of a second, it is not surprising that it should be out of all proportion greater than the time actually occupied by the discharge. It is to this fact that we owe the isolation of the individual discharges of the sensitive discharge, which has formed the basis of the present investigation: an isolation which renders the examination of this type of discharge equivalent, as we have already mentioned, to the examination of the electric spark itself.*

We need not examine the magnitude of the period occupied by the whole discharge. It would be obtained by adding together a proper selection of the other small time-quantities with which we are dealing, and which are in reality the component parts of which the whole discharge is made up. And, further, it would possess no scientific value so far as the investigation of the mechanism of the discharge is concerned, for it is the relative duration of the various processes which go to constitute the complete discharge that it is important for us to learn.

We shall next consider the magnitudes of the periods occupied by the positive and negative electricities in passing along the tube, by which we mean the interval that elapses from the instant of their emission from one terminal to the instant of their arrival at a point situated in the neighbourhood of the opposite terminal. And we shall first show that *the time occupied by the passage of either electricity along the tube is of a greater order of magnitude than the time required for it to pass along an equal length of wire.*

The experiments given in Section XIII. of our former paper suffice to demonstrate this proposition. For when a piece of tinfoil near the air-spark terminal was connected by a wire with a piece near the opposite terminal, the former derived at least as much relief from the latter as if it had not been on the tube, while the special effect was manifested at the latter. This showed conclusively that at the time the electric disturbance arrived at the former piece of tinfoil the latter was unaffected by it; and further that there was time for the impulsive electrical action which was exerted upon the former piece of tinfoil to be communicated along the wire to the latter, and to affect it and the tube near it before the electricity itself passed up within the tube to the place where the latter lay. A similar phenomenon was presented when a long strip of tinfoil was placed along the tube. In that case there was a gradual shading from the relief to the special effect. It will be remembered that in this way we got perfect examples of the typical positive effect near the negative terminal by means of impulses from a piece of tinfoil laid on the tube near the positive end (the air-spark being in the positive), showing that the positive impulses had had time to run along the wire, to form the hollow cone of positive luminosity by means of the positive dis-

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* In our previous paper an experiment was described in which the luminous phenomena of a single discharge from a coil were observed, such single discharge having the characteristics which an individual discharge of a sensitive vacuum discharge must have. It was found to exhibit all the phenomena of sensitiveness.

charge that was created by their arrival at the second piece of tinfoil, and to leave the corresponding negative electricity free to meet the advancing positive discharge before that discharge had time to come up. And similar results were obtained, *mutatis mutandis,* when the intermittence was of a negative type.

We have no means of comparing directly the velocities of positive and negative electricity in a tube. But in some experiments* which we described in our previous paper, in which the discharge was due to the action of a small coil, it was found that when all the circumstances were alike at both terminals the two electricities met about the middle, and that the neutral zone was situated there. Further, it was found that the neutral zone could be shifted toward one end or the other by the use of a thunder plate or small condenser which was hung on the terminal, the discharge from which it was desired to retard. These phenomena point clearly to the theory that the velocities of the two electricities are the same in such a tube, and we have seen no phenomena which would lead us to imagine that such is not the case generally.† At all events, in the absence of any evidence to the contrary, the most probable view is that their velocities do not differ largely, or in other words, that the times they respectively take to pass along the tube are small quantities of a like order of magnitude.

The next question is the comparison of the times that the discharges take to pass along the tube with the times that are occupied by their emission from the terminals. And here we are met by a difficulty in defining what is meant by the period of emission of a discharge. It may well be that if the discharge contains only a certain quantity its emission may be very rapid, while if it is greatly larger in quantity it may be durational, and the degree of exhaust may similarly affect it.‡ Something of the sort is pointed at by the contrast between the experiment last referred to and those about which we are about to speak. The former seems to point to considerable equality between the two electricities both as to velocity and rapidity of discharge. The latter will be shown to point to great inequality in rapidity of discharge, the positive having by far the advantage. The difference may probably be accounted for by the fact that in the former case the discharges were of a very gentle character and in a tube of low exhaust, while in the experiments to which we are about to refer the discharges are sufficiently violent to produce phosphorescence.

A further question arises here as to the time occupied by molecular streams in

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* Phil. Trans., 1879, p. 210.

† It is true that the experiment has only been made in tubes of low exhaust, and that it is not safe to conclude that relations which exist in low exhausts between the properties of positive and negative discharges will hold good also in high exhausts. For example, we shall hereafter see that the degree of exhaust has a marked effect on their relative rates of emission. But in the present case we have direct experimental evidence that the velocity of negative electricity along the tube does not participate in this change, but that, on the contrary, negative electricity in tubes of high exhaust continues to behave as though its velocity were the same as that of positive electricity, or at least of the same order of magnitude as it. Hence we shall take such to be the case.

‡ We shall return to this question in the next section.

leaving a negative terminal. Now it is very difficult to imagine that these molecular streams can commence to leave the terminal before the negative discharge begins, or that they can continue after it has ceased; so that in the absence of anything pointing to an opposite conclusion, we are justified in assuming that the period of emission of the molecular streams is included within that of the negative discharge. There is not the same justification for assuming that these molecular streams continue to be emitted during the whole of the period during which the negative discharge is leaving the terminal, but we think it probable that such is the case, though it may be that they are not of the same intensity throughout so as to be equally capable of causing phosphorescence. Seeing, then, that it is probable that the two periods of emission are identical, and that this supposition will not in any way affect the validity of the argument, inasmuch as the period of the emission of the negative discharge is undoubtedly as long as that of the molecular streams, we shall treat these two periods as the same.

In order to compare the periods of time occupied in the actual emission of the two discharges respectively, we shall commence by showing *that the negative discharge occupies a period greater than that required by the particles composing the molecular streams to go the length of the tube but comparable with it.*

This proposition is placed beyond doubt by the various phenomena depending upon the interference of the molecular streams and especially virtual shadows. It is quite clear that if we give relief to a portion of the tube near the positive terminal during the progress of a discharge with positive intermittence, the streams of molecules from the sides of the tube must start before those from the negative terminal do so. It is true that the difference may be infinitesimal, but at all events it exists. Now we find that the streams of molecules that come from the negative terminal are interfered with and diverted by streams from the side of the tube. Hence these latter streams must have continued to flow at least as long as it has taken the molecules from the negative terminal to arrive at the point of the tube where relief is given. It may be that the main portion of these relief streams has passed across the tube before the arrival of the streams from the negative terminal, but the relief streams must be still continuing, or they could not interfere with the others. This last remark may serve to explain the fact that relief phosphorescence is usually diametrically opposite to the place where the relief is given, so that the streams that form it are not perceptibly swept downwards along the tube towards the positive terminal by the streams from the negative terminal.* The main body of the relief streams has had time to cross the tube and impinge on the glass before the streams from the negative terminal can reach the spot. But when we attempt to produce relief effects in the immediate neighbourhood of the negative terminal the case is far different. The two streams are then on equal terms,

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* It would not be wise to attach too much weight to this. The interference of two molecular streams at right angles is not very great when it does not take place in the immediate neighbourhood of the source of one of them.

and the relief-phosphorescence is found to be swept downward along the tube, while the interference between the two streams is greatly increased for the reason that the main parts of both come into collision with each other.

Two other experiments in connexion with interference should also be considered in dealing with this matter. If a shadow of a small piece of conducting material, such as a piece of wire enclosed within the tube, be cast on the side of the tube by relief-phosphorescence and a conductor be brought in contact with the tube near to one end of the wire, the shadow of the whole wire, including the other end of it, will bulge considerably. This bulging is exceedingly black, showing that the whole of the streams that passed close to the wire on their way to produce the relief-phosphorescence have been diverted from their course. Thus the discharge from the wire must have continued during practically the whole of the time that the relief molecular streams were passing it. Now the discharge from the wire must have commenced at the same time as that from the side of the tube, for they were both in response to the advancing positive electricity, and they will presumably last for an equal time; hence the time required for the molecular streams to cross the tube and arrive at the wire is not an important part of the period during which the discharge lasts, for otherwise the relief molecular streams that passed after the discharge from the wire had ceased would probably have shown themselves in the form of phosphorescence on the bulged part of the shadow.

The indications derivable from the second experiment to which we are about to refer are yet more distinct. In the experiment described in Section XXII., in which a phosphorescent image was formed of a small hole in an intermediate terminal (the air-spark being in the positive), it was found that this image was *splayed out* by the finger being placed on the tube. Now a magnet displaced it as a whole without any splaying out (Plate 28, fig. 23). This, then, pointed to a variation in the relative strength of the interfering stream and the stream interfered with, and such variation must have occurred during the period that they were encountering one another, and were moving in the ordinary way of such streams, for it showed itself in a variation in the extent to which the streams from the negative terminal were diverted. We may hence conclude that the time requisite for the molecules to move the length of the tube was decidedly less than that occupied by the discharge, but was sufficiently comparable with it to allow the diminution of intensity of the streams from the side of the tube to make itself visible before the streams from the negative terminal experienced a similar diminution.

Thus far we have only been dealing with positive relief. But the phenomena of negative-special are equally important in the demonstration of the truth of this theory. In that case we know that the impulses that cause discharge arrive at the negative terminal of the tube and at the tinfoil synchronously, for the difference (if any) in the time required to pass from the machine along the wires to the two places is incomparably smaller than any of the quantities with which we have to deal.* And yet we

* This can be seen by the fact that no difference is produced by making the path to the tinfoil longer

obtain the most splendid virtual shadows. Now the discharge from beneath the tinfoil will certainly not last longer than that from the effective negative terminal of the tube, and yet we find that the negative discharge from beneath the tinfoil and its accompanying molecular streams are still in full vigour when the molecular streams from the negative terminal arrive at that part of the tube where they are situated, for they interfere with one another. We need scarcely repeat that there is every evidence that this interference continues for a substantial portion of the period during which these streams respectively last.

These experiments suffice to show that the duration of the negative discharge is not less than the time occupied by the passage of molecular streams along the tube, but is comparable with it. We shall now proceed to show that *the time occupied by the passage of either kind of electricity along the tube is incomparably shorter than that occupied by the emission of these molecular streams, or* (*which is the same thing*) *than that occupied by the negative discharge.*

The truth of this proposition, so far as the positive discharge is concerned, is shown by the following experiment:—If a piece of tinfoil be placed near the positive end of a tube through which a discharge with strong positive intermittence is passing, and be connected by a wire along the tube with a similar piece of tinfoil near the negative terminal, we shall obtain, as we have already said, positive relief-effects at the former piece of tinfoil and positive special at the latter. The relief-effects will not be increased by raising the latter piece of tinfoil from the tube and placing it as far from the tube as possible, keeping it at the same distance from the other piece of tinfoil. But a very remarkable exception presents itself. If the tube be of sufficient exhaust or the air-spark sufficiently long to cause the relieving system, formed by the tinfoil and the wire, to give rise to relief-phosphorescence when at a distance from the tube, it will be found that this disappears when the system is again lowered down so as to rest along the tube. The relief-effects, so far as luminosity is concerned, will be unchanged, or, if anything, increased. But the relief-phosphorescence which should have accompanied them will be found to have disappeared.

Extraordinary as this phenomenon appears at first sight, it will become perfectly intelligible if we accept the hypothesis that the electricity, on its discharge into the tube, spreads along it with a rapidity which enables it to pass to the other end in a very small fraction of the time required for a negative discharge, or its attendant system of molecular streams, to pass off from their source. The positive electricity, on bursting into the tube and arriving at the place where the first piece of tinfoil is situated, produces an impulsive electric tension upon it, which makes it summon from the more distant piece a supply of negative electricity. This summons passes along the wire in so short a time that, as we know, it arrives at the further piece of tinfoil before the discharge has arrived at the part of the tube in its immediate neighbour-

or shorter than that to the terminal. Moreover it has been demonstrated in the former part of this section.

hood. It accordingly causes the negative electricity that is desired to be supplied to the first piece of tinfoil, and thereby causes an impulsive electric tension in the second, which causes a positive discharge within the tube beneath it, showing itself in positive luminosity. The negative that rushes to the first piece of tinfoil forms the usual *blank space*[*] beneath it, and would, in the ordinary state of things, cause a negative discharge within the tube. But before such discharge has got beyond the inchoate stage, the discharge in the tube has arrived at the place where the second piece of tinfoil is situated. Its arrival causes a sudden recall of the negative electricity that had left it previously, thus producing a sudden positive impulse at the first piece of tinfoil, and neutralising the tension there which would otherwise have caused the negative discharge and the accompanying molecular streams. Thus before the molecular streams can start they are revoked through the revocation of the negative discharge that would otherwise have caused them.

That the above must be the explanation of the phenomenon is rendered evident by the consideration that the same relieving system when in a position not more favourable to granting instantaneous relief to the first piece of tinfoil (*i.e.*, when extended at right angles to the tube) is found to cause relief-phosphorescence. The only difference between the two cases is that the relief granted in the one case is subsequently revoked, while in the other it is not. And as we find that such revocation is effective in stopping relief-phosphorescence, it is clear that the streams that were to produce it could not have left the side of the glass beneath the first piece of tinfoil before the revocation came. Hence the time occupied by the positive electricity in passing along the tube is of a higher order of smallness than the time occupied by the negative discharge in passing off from the inside of the tube beneath the tinfoil.

It may be suggested that the streams might have started, but have been stopped on their course by the subsequent action. No doubt, as we shall see, some small portion of them may have started, but certainly not all. For as the phenomena of virtual shadows and the bulging of the shadows of conductors within the tube shows, these molecules are capable of passing through the whole length or breadth of the tube, and probably could go much farther during the time occupied by their emission. Hence it is clear that they, or some portion of them, would have got across the tube, or at all events to a finite and considerable distance from the tinfoil, before the revocation came, if it did not arrive until the whole of the streams had started. Under such cir-

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[*] We have greatly felt the need of a word to describe the dark area which is formed round every source of negative discharge. In a striated column it is called "CROOKES' space," the "negative dark space," or a "stria space," according as it is in the first, second, or a later segment (or physical unit) of the discharge, counting from the negative terminal. But in considering the structure of the discharge generally it is necessary to have a term which denotes it whatever be its position, and whether it occurs in a striated discharge or not. We have therefore adopted the term "blank space." It will be found to be as characteristic of a negative terminal as positive luminosity is of a positive terminal, however such terminal be formed.

cumstances it is clearly impossible that the revocation of the relief could be effective in stopping them, and preventing them from producing phosphorescence, seeing that they consist of material particles moving at high velocities; leaving out of consideration the fact that in all probability the largest portion of them would have actually arrived at the opposite side of the tube before the revocation arrived.

It must not be supposed that this theory requires that absolutely the whole of the negative discharge at the first piece of tinfoil (*i.e.*, the one that is nearest to the positive terminal) should be prevented by the revocation. This would not be in accordance with what the luminous phenomena would lead us to expect, and is not countenanced by the theory itself. There has been a discharge of positive electricity from beneath the further piece of tinfoil, and this has left a quantity of negative electricity free on the surface of the glass there. This in itself must render the impulse of the revocation less than that of the original demand. But the two are sufficiently nearly equal to prevent the negative discharge at the first piece of tinfoil having the violent character which would be necessary to produce relief-phosphorescence and to cause the negative discharge there to become a differential effect, and pass off in a gentle and continuous manner.

The existence of this revocation and its efficacy in preventing the emission of molecular streams in the ordinary way is further shown by there being no virtual shadow formed at the first piece of tinfoil. Now the absence of a virtual shadow is a very much sharper test of the absence of molecular streams than the non-appearance ot relief-phosphorescence on the opposite side of the tube, for in the one case the molecular streams produce their effect close to the spot whence they proceed, while in the other case they have to force their way across the tube and must then possess sufficient velocity to produce phosphorescence. In order to show the effect of the revocation on the production of a virtual shadow, one end of a narrow slip of tinfoil a few inches in length was cemented to the side of the tube (through which was passing a discharge with positive intermittence) a little way from the positive terminal, and the slip was allowed to hang downward. A clear virtual shadow appeared, starting from the point where the tinfoil was in contact with the tube. The strip of tinfoil was then laid along the tube, stretching towards the positive terminal, and the virtual shadow disappeared. Now we know that, so far as the effects on luminosity at the cemented end were concerned, the two positions must have been practically equivalent. But in the one case there was a revocation which, though it did not come in time to stop the effects of the relieving system upon luminosity, was yet in time to prevent the emission of molecular streams so that no virtual shadow appeared. This experiment, though very interesting, is not so conclusive of the truth of our theory as is the one first given, for it might be objected that the virtual shadows could not be formed until the discharge in the tube had reached the negative terminal and obtained a response in the form of negative discharge, and a sufficient time had then elapsed to permit the molecular streams which accompanied that response to arrive at the first piece of tinfoil. This would be necessarily later than the revocation which would take place when the discharge arrived at the further piece of tinfoil, *i.e.*, before it arrived at the negative terminal, and *à fortiori* before the molecular streams that issued from the negative terminal in response to it had returned to the first piece of tinfoil so as to suffer interference there.

We have used the above experiments for the purpose of supporting our proposition, both on account of their great interest and the remarkable way in which they illustrate the whole theory of the discharge, and also because of their analogy with an experiment by which we shall prove for the passage of the negative discharge along the tube the same proposition that we have proved above for the positive discharge. But so far as the positive is concerned, the phenomenon of virtual shadows suffices of itself to prove the proposition; for the response from the negative terminal occurs later than the relief-response at any point by a period equal to that taken by the positive discharge in passing to the negative end of the tube. The molecular streams that pass up the tube from the negative terminal find, on their arrival at the place where the relief is taking place, that the molecular streams there are still continuing, for they indicate this by being deflected by them, and thus forming the molecular shadow. Hence the time required by the discharge to pass to the negative end of the tube must have been less than the time during which these relief-molecular streams were being emitted. Simple as this proof is, however, it is inferior to the experimental proofs that we have previously given, inasmuch as it does not point so clearly to the great contrast in magnitude between the two small time-quantities under consideration as does the complete extinction of the relief-phosphorescence in the experiment first described.

So much then for the velocity of positive electricity along the tube. It remains to demonstrate a similar proposition as regards negative electricity. This was done in the following way :—A piece of tinfoil of some considerable size was laid on a high vacuum tube near to the negative end, the discharge being one of strong negative intermittence. A smaller piece of tinfoil was placed near the farther end, and they were connected by a wire as before. We know that this arrangement must give us negative special effects at the farther piece of tinfoil—*i.e.*, negative discharges there. These would, if strong enough, be accompanied under ordinary circumstances by molecular streams, which would cause phosphorescence on the opposite side of the tube. But no such phosphorescence appeared. In order to test whether this was due to the weakness of the negative impulses from the first piece of tinfoil, the second was placed upon a similar tube in an independent circuit (as in the standard-tube arrangement), the distance between the two pieces being retained unchanged. It gave most brilliant phosphorescence, showing that the negative impulses were abundantly strong enough to have caused phosphorescence had they not been prevented from doing so. And it is clear from our previous remarks that the cause which prevented their doing so was the arrival of the negative discharge in the tube at the farther piece of tinfoil before the negative discharge there with its attendant molecular streams had had time to leave the surface of the glass.

The above conclusions are strongly fortified by an experimental result which at first sight appears to be inconsistent with them. We were engaged in producing the above-described effects in a tube of only moderate exhaust. They were very well manifested, showing that even in such a class of exhausts the durational character of a negative discharge which is violent enough to give phosphorescence is strongly marked. But to our great surprise we found that when we were working with a positive air-spark, the tinfoil nearest to the negative terminal of the tube gave a small but distinct patch of phosphorescence. Now the effects at that piece of tinfoil were positive-special effects—that is to say, there was first a positive discharge, and then, after the discharge within the tube had come up, the negative left behind by the former positive discharge passed off to meet it. This latter discharge, therefore, must have had all the essentials requisite to produce phosphorescence, and that which was produced was a true case of positive-special-phosphorescence. But we have already shown that the phosphorescence of the positive-special is very decidedly weaker than that of positive relief, for the latter can extinguish it and cause phosphorescence on the very spot of the surface of the tube at which the positive-special takes place and from which its molecular streams are pouring. How, then, is it that we can produce the weaker phosphorescence when we fail to produce the stronger? The reason is that, in the case we are now considering, the requisite time is allowed for its production. It is true that the negative discharge at the further tinfoil is far less than the relief-discharge which originally occurred at the nearer tinfoil, but there is no revocation in the case of the former. It is allowed to pour off during the whole of the time that the tube remains charged with positive electricity—that is to say, until the negative electricity pouring in at the negative terminal has reduced the tube to an electrically inert state, or approximately so. This is clearly a duration of the right type, since it suffices for the production of phosphorescence both in the case of relief and in the case of the discharge from the negative terminal. Thus we see that the presence of the requisite time-element will enable a negative discharge to produce phosphorescence in cases where its absence was a sufficient bar to the production of phosphorescence by a discharge of far greater initial violence.*

These experiments reveal to us the necessity of considering two other time-quantities which, but for the information derived from the consideration of the phenomena of

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* We may add that all question as to the phosphorescence in this case being due to positive-special was set at rest by slightly raising from the tube the piece of tinfoil nearest the air-spark terminal. This caused the phosphorescence to fade, because when the tinfoil was in that position the positive-special effect was produced by a much feebler inductive action than when the tinfoil was on the tube. As the tinfoil was raised higher the phosphorescence continued to fade for a short time, and then grew bright again, the system having got so far from the tube that it had ceased to produce positive-special effects and had become a relieving system. The effects upon the luminosity bore witness to this series of changes taking place.

revocation, might very easily have been confounded with those of positive and negative discharge. These additional time-quantities are the periods required for the formation of the positive luminosity, and its correlative, the blank-space. These two cannot be considered separately, for they are really two parts of the same phenomenon. Where positive luminosity ends, there the blank space begins; not that there is necessarily a sharp division between them (though such is ordinarily the case), for they may appear to shade into one another, but that they represent the two states in which the effective* electrical field can exist during a discharge; and these two states are mutually exclusive, however sharply or gradually their boundaries may change. It is the time required for bringing the space within the tube into one or other of these states that we are now about to consider.

We are here approaching one of the most difficult problems connected with the electric discharge, and at the same time one that, above all others, is needful to be solved if we would get at the real secrets of its mechanism. In these two phenomena lies the most important portion of that electric dissymmetry from which we may chiefly hope to get light as to the nature of electricity. We do not feel that we are at present sufficiently advanced to treat these questions in so satisfactory a manner as we could wish, but we hope to be able to throw some light upon them even at the present stage.

Taking, first, the question of positive luminosity, it is clear that its formation along the tube cannot be more rapid than the velocity of the discharge itself—of the positive discharge itself. For although no doubt static induction outruns the discharge so much that, as we have said, we treat its advance as absolutely instantaneous, yet the distance by which it effectively precedes the front of the discharge does not increase during its progress. It is not by the rapidity with which static induction moves that the impulsive character of the action of the discharge both within the tube and upon the surrounding space is caused, but by the rapidity with which the free electricity, carrying with it its static induction, is brought locally into the neighbourhood. Thus an inferior limit of the time required for the advance of the positive luminosity is the time required for the advance of the positive discharge.

But this is only the less important part of the matter. The real question is whether this luminosity is produced immediately on the discharge, or whether it is separated from it by an interval of time comparable with the small quantities of which we have been speaking. As to this we think that we must come to the conclusion that it is cotemporaneous with the discharge that causes it. When we get positive-special effects in the way to which we have so frequently referred in the present section, we find that we can form the typical hollow cone and truncated positive column. Now it is clear that this hollow cone must mark a discharge that has really taken place, either

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* We use the phrase *effective electrical field* to denote that part of the tube that is really affected by the discharge, and that undergoes the rapid alterations of electric state which accompany it. We shall presently see that it is quite possible for a portion of the tube to be outside this effective electrical field, and thus to participate in no way in the discharge.

wholly or to a considerable extent, before the main discharge has in its passage along the tube arrived at the tinfoil; as there would be otherwise on such arrival a revocation of the impulsive electrical action in the tinfoil, that is the cause of the very discharge that forms the hollow cone. But we are able to get quite clear and typical effects by this method, so that we are entitled to assume that the positive discharge has actually left the quasi-positive terminal beneath the tinfoil and proceeded along the tube with a velocity which we have already considered, forming the positive luminosity on its path.

The phenomenon which shows in the most striking way the rapidity with which positive electricity leaves its source is the production of positive-special in a high tension tube. Attention has already been called to the wide sweep which the thin positive column takes to avoid the spot at which the positive-special is being produced. Now this avoidance is due to the fact that there is negative electricity there which has been left behind by the positive discharge caused by the positive impulses within the tinfoil. Thus the side of the tube beneath the tinfoil behaves precisely as a negative quasi-terminal, showing that the positive must have wholly passed away from the place at the time the advancing positive discharge arrives at the tinfoil, and has left the corresponding negative electricity free to produce its full effect.

The evidence is strengthened if we consider the case of negative relief produced, by the use of a similar arrangement, at the piece of tinfoil that is nearer to the negative terminal. Here we are able to compare directly the two cases of the relieving tinfoil being on the tube, and at a distance from it. And we find that there is no difference in favour of the latter in the luminous phenomena of relief thereby produced. Hence we are fairly entitled to conclude that the positive discharge passes off in a time shorter than that required for positive electricity to advance along the tube, and that in so doing positive luminosity is formed by it as it goes.*

So far we have nothing that would lead us to draw a distinction in time between the emission of electricity and the formation of the luminous phenomena which accompanies that emission. But when we take the correlative phenomena for negative discharge, *i.e.*, the blank-space, a difficulty arises. It not only must, from its nature, be formed in the same time as the positive luminosity which it limits, but all the phenomena of revocation testify to the fact that it is so. But we have already shown that negative discharge does not take place with a rapidity at all comparable with that of positive discharge, so that we can no longer view the formation of the blank-space simply

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* It is doubtless owing to this extreme rapidity of discharge and propagation that there is so much luminosity and so little heat in the vacuum discharge. It has been experimentally shown that the temperature of striæ is not greater than 100°. But all measurements of temperature are measurements of average effects, and such a result would be quite consistent with the hypothesis that they are in a state of intense heat for a very small fraction of the total period, and such a hypothesis would account for so large a proportion of the energy imparted to the gas passing off in the state of light inasmuch as the proportion of rays of high refrangibility to those of low refrangibility increases with the temperature.

as a phenomenon cotemporaneous with the negative discharge (for that is a durational phenomenon) in the same way that we have taken the formation of the positive luminosity to be cotemporaneous with the emission of the positive discharge. We are left then to choose between two hypotheses as to the formation of the blank-space; first, that this is formed at the very initiation of the negative discharge, and that although the discharge itself may be durational, it is initiated sufficiently to produce the blank-space in a time which is no longer than that required for the positive discharge; or, secondly, that it does not owe its existence to actual discharge at all but merely to what may be called a state of readiness for discharge—*i.e.*, the presence of a quantity of negative electricity ready and eager to be discharged, but by its nature compelled to pass off slowly.

These two hypotheses are not mutually exclusive, and may be, and probably are, both true. The best conception at which we have been able to arrive is that the blank-space represents a space which is sufficiently near to a source of negative discharge to prevent the presence in it of the peculiar action which causes positive luminosity. Whether or not this means that it is a space whose dimensions are such that it permits of some operation taking place for relieving electric tension in a gaseous medium—some transfusion, as it were, of the two opposing electricities that are gathered on its opposite sides—we are not yet prepared to assert. But its existence between consecutive striæ and round the negative terminal point to its representing *a space through which an operation equivalent in its results to the passage of electricity can take place without causing luminosity;* nay, we may say that they actually demonstrate that such is the case, for in these instances the blank space actually severs the luminosity into segments, the luminosities in which have no connexion one with another.

Leaving this question for future consideration, when our knowledge of the subject shall be more complete, the important conclusion to be drawn from the experiments last referred to is that there is no reason to regard the formation of this blank-space as a phenomenon connected with the emission of molecular streams. On the contrary, it is of a higher order of instantaneity, for while they can be affected by revocation, it cannot. They are, as we have seen, of a decidedly durational character, while it seems to belong at least to the order of instantaneity to which the passage of electricity along the tube belongs, inasmuch as it shapes and modifies the positive luminosity that attends that passage. However we form impulsive negative discharges of the proper type upon the side of a tube, the blank-space appears, showing that it was formed in time to control the positive luminosity of the discharge.

There is a well known phenomenon which will doubtless be thought by many to make strongly against these conclusions. It is that if the molecular streams be turned aside from passing down the tube, either by means of a magnet or by shifting the direction of the face of the negative terminal, the positive luminosity comes up into closer proximity with the negative terminal, as though the molecular streams had been driving back the column of luminosity until they were diverted. But we think that this is only in appearance, and not in reality; and that no comparison can be made between the portions of the luminosity in the two cases, as the discharge has been affected by the alteration. Moreover, the same effect is produced by a magnet on discharges in low exhausts where there can be no question of molecular streams proceeding right down the tube. We think that the mistake arises from the effect upon the imagination produced by the view of the well-known negative dark space. This seems to separate the region of the negative terminal from that of the positive terminal, and anything that affects this dark space is thought to do so by directly affecting the action of the negative terminal. But in reality the region of the negative terminal is bounded by the negative glow which is the positive end of the physical unit of discharge, of which CROOKES' space is the blank-space and the negative terminal is the negative end. The negative dark space is only the blank-space of the second physical unit of discharge, and the apparent advance of the positive luminosity shows only that this second physical unit of discharge has been affected in some way by the altered circumstances of the discharge. And when we consider that its exceptionally long blank-space is due to its peculiarities of situation and the fact that its gaseous negative terminal (*i.e.*, the haze at the back of the negative glow) is so unlike the gaseous negative terminals of the other stria spaces, it does not appear strange that an alteration which produces a great modification in these matters should affect the length of this exceptionally extended blank-space.

We now come to the question of the time required for the emission of the positive discharge. This we have, in effect, dealt with already, when we considered the question of the dispatch of the positive discharge in positive special before the arrival at the tinfoil of the discharge along the tube. It must be of an order of magnitude not superior to that of the time required for the discharge to pass along the tube, and is probably of a lower order.

The time required for the passage of the electricity along the wire outside the tube is, as we have seen, so short that it cannot be detected by the aid of any of the other phenomena of the discharge. As it is a case of conduction, it is, of course, the same for both electricities.

The order of the small time-quantities of the discharge is therefore as follows; the groups being arranged in descending order of magnitude:—

A. The interval between two discharges.

B. The time occupied by the discharge of the negative electricity from its terminal.

The time occupied by molecular streams in leaving a negative terminal.

The time occupied by the particles composing molecular streams in passing along the tube.

C. The time occupied by positive electricity in passing along the tube.
The time occupied by negative electricity in passing along the tube.

D. The time occupied by positive discharge.
The time required for the formation of positive luminosity at the seat of positive discharge.
The time required for the formation of the blank space at the seat of negative discharge.

E. The time occupied by either electricity in passing along a wire of the length of the tube.

The period occupied by the whole discharge must be of the order B, since it includes a complete negative discharge. The evidence which shows that the time-quantities in D are greater than the time-quantity in E is much weaker than in any of the other cases, but this defect is not of great importance, as there would be little information to be derived from a comparison of them on account of their difference in nature.

XXVII.—*General conclusions as to the electric discharge.*

II. *In vacuum discharges the durational character of the negative as compared with the positive discharge increases with the degree of exhaustion and becomes very marked in extremely high exhausts.*

We have seen in the previous section that the negative discharge occupies a longer time than the positive in leaving a terminal, whether that terminal be one that is formed on the glass by relief or special action or be an effective terminal of the tube. In the case of the positive discharge the time occupied is less than that required for electricity to pass along the tube; while in the case of negative electricity it is longer than the time required by the comparatively slow-going molecules to do so, and is so much longer than the time required by the electricity to pass along the tube that a revocation caused by the arrival of the electricity at a spot near the other end of the tube is to all appearances in time to stop the negative discharge and its accompanying molecular streams before they have fairly commenced. In the present section we propose to show that this durational character of the negative discharge, as contrasted with the positive discharge, increases with the degree of exhaustion of the tube, and becomes very marked in high exhausts.*

It may fairly be remarked that the experiments upon which the proof of this comparatively *durational* character of the negative discharge was based were made in

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* This character of the negative discharge was already noticed by Messrs. DE LA RUE and MÜLLER, see their paper, Phil. Trans., Part I., Vol. 169, p. 90, and also p. 118, where some very interesting details are given.

tubes of a sufficiently high exhaust to give virtual shadows,* so that it can hardly be said to have been proved to exist in tubes of ordinary exhaust. This cannot be denied, and we are not prepared with any equally rigid proof that it does so exist in tubes of low exhaust, although there are many circumstances which point to such being the case. In the first place, we have the fact that all the phenomena obtained with positive intermittence are sharper in character than the corresponding ones that are obtained with negative intermittence, pointing towards a less instantaneous action in the case of the negative discharge. This is a very well marked phenomenon, which will be found to have been noticed by us in our previous paper, and is manifested by tubes of every class of exhaust. Another circumstance pointing in the same direction is a peculiarity that has long been observed in the negative discharge, viz.: its preference for a surface as compared with a point of discharge. This, and its analogue, the possibility of bifurcating the negative current, seem to point to the discharge at a negative terminal being a continuous process, which is facilitated by its having a large number of places from which it can go on at the same time.†

These general considerations are but poor substitutes for the definite experimental proof which we were able to give for the case of tubes of fairly high exhaustion, and it is hoped that they may be supplemented at some future day. But one reason for this is that the contrast between the character of the two discharges is not a strongly marked phenomenon in low exhausts, though we have no doubt that it exists in some degree. The change that we shall in this section prove to take place as we pass from tubes of fairly high exhaust to tubes of extremely high exhaust takes place also as we pass from tubes of low exhaust to tubes of fairly high exhaust. In the former, the two kinds of discharge are not very markedly different in their duration character. As the exhaust increases, the positive discharge becomes more nearly instantaneous, and the negative discharge becomes more durational till we come to the class of exhaust treated of in that portion of the previous section which deals with that question. We shall now proceed to examine the case of tubes of very high exhaust, and consequently very great resistance, and show that the contrast there becomes very much intensified.

The first class of experiments showing that such is the case consist of observations with the standard-tube. A ring of tinfoil was placed round a tube of very high exhaust with a negative air-spark, and a wire was taken from it to a ring of tinfoil round a tube of moderate exhaust carrying an independent continuous current. Negative effects were of course produced. A supplemental ring was placed round the latter tube, and when touched it was expected to give (in accordance with the

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* It must not be thought from this that these tubes were all tubes which gave phosphorescence in any marked degree with the continuous current. It was necessary to use an air-spark in most cases if it was desired to produce phosphorescent effects throughout the tube. But they were tubes in which the blank-space was of considerable breadth, and ought fairly to be considered tubes of high exhaust.

† See De La Rue and Müller, Phil. Trans., Part I., Vol. 171, p. 108, and Plate 10, figs. 27 and 28.

usual rule) negative relief-effects. These, however, were not very clearly manifested, but the remarkable peculiarity was observed that when the wire from earth to the latter tinfoil was not allowed actually to touch it, but was held at short sparking distance from it, these negative relief-effects were very marked and clear. It is difficult to interpret this in any way other than by supposing that the negative discharge in the large tube went on accumulating for a certain time instead of instantaneously flashing into its full intensity as in the case of the positive discharge. This rapidly rising negative charge in the tube of high exhaust would of course drive off negative into the other tube in the ordinary way, but this (if the above law be true) would be done with less sharpness than in an ordinary negative discharge in such a tube. We should thus have a discharge in the latter tube which, though intermittent in its nature, yet partook of a continuous character, and the relief-effects would therefore be poorly defined. If, however, the relief were only permitted to be given at the exact moment when the accumulation of negative reached its height, and was then given impulsively (as would be done by allowing positive electricity to spark into the tinfoil from the earth wire), the relief would be given with the requisite sharpness, and would produce definitely marked relief-effects.

It will be seen that this explanation requires that the negative should accumulate in the original tube. In other words, it shows that it is a difficult (but not necessarily a slow) process for negative to get out of the tube as well as a matter of time to get in. This will no doubt be found to be the case, and when the law is perfectly formulated it will probably include some such statement. The present form is taken only as an approximation.

The second set of observations bearing upon this matter is intimately connected with the difference of sharpness of effect which we have already noticed as existing between positive and negative intermittence, even in low tension tubes. In high tension tubes this difference becomes in some respects immensely exaggerated. If the intermittence be positive and the negative terminal be put to earth and the hand placed on the tube, strong shocks will be felt. If, however, the intermittence be negative and the positive terminal be put to earth the shocks are so much more feeble as hardly to be sensible. And the same difference may be made evident in another way. If an earth wire be held near to a piece of tinfoil placed upon a high vacuum tube it will be found that the sparks will stream between them when the intermittence is positive even though they are a considerable distance apart. But if the intermittence be negative it is difficult to get any but the very shortest sparks to pass between the tinfoil and the wire. And if contact be made, the contrast (if the air-spark be considerable) is equally striking. While in the case of the negative intermission no special phenomena are observed, in the case of the positive intermission the electricity streams from all sides of the tinfoil and evidences the most violent alternations of tension. It is difficult to see any explanation of these peculiarities other than that the impulsive change of tension is very much greater in the positive than in the negative intermittence—for we know that this, like all the other phenomena of intermittence, depends on sudden changes of tension and not on the absolute tension at any moment. And if the impulsive change of tension is less violent with the negative than with the positive intermittence, it would seem to be a necessary conclusion that it is due to the more durational character of the former discharge.

There is a cognate class of experiments which, when taken in connexion with those we have just described, adds very great force to the conclusions we propose to draw from them. If we try the special effects we shall find the characteristics reversed. While the positive intermittence which gave such very violent relief-action only gives very slight action at the tinfoil, the negative intermittence causes the most violent disturbances there. Just as previously in the case of the positive-relief, so now with the negative special; the sparks stream between the wire and the tinfoil if they are made to approach one another, while if contact is made the electricity streams from all the edges of the tinfoil in the most violent manner. This must, we think, be because the negative pulses that arrive at the terminal can only get relief there slowly by pouring into the tube. They therefore press with all their force at the tinfoil seeking and finding like relief, through the inductive discharges to which they give rise. And it is a considerable time before the rise of tension in the tube, rapid though it be, is capable of balancing this pressure of the negative from without in its endeavours to get relief either by entering the tube or otherwise.*

We shall not dwell further on these experiments. It is difficult, we think, to account for the phenomena they present in any other way than by accepting the truth of the theory that is given at the head of this section, viz.: that the contrast between the two types of discharge, as far as the time required for their emission is concerned, becomes greater as the degree of exhaustion increases.

XXVIII. *General conclusions as to the electric discharge.*

III. *On the positive column.*

We purpose in the present section calling attention to some experiments which throw light upon the function of the positive column, and give us a clue to the action which is going on where it appears, and of which it is doubtless the result. A portion of the experimental evidence relating to this has been already given in Section XXIII., and has to some extent been interpreted there. We shall now give further evidence in favour of the views there advanced.

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* Lest it should be thought that these phenomena were due simply to the high resistance of the tube, we took a tube whose vacuum was so low (we estimated it at about 2 inches of mercury) that the resistance was even greater than in the high tension tubes. No perceptible difference was found between the sensations caused by discharges of positive and negative intermittence, nor in the sparking distance between the earth wire and the tinfoil.

The fundamental experiment in this matter was made by us in our experiments with the standard-tube. We had found in working with positive intermittence that there is but little difference between the variations of electric action undergone by a piece of tinfoil upon the tube, an intermediate terminal projecting within the tube, and the non-air-spark terminal, so that it was comparatively a matter of indifference to which the tinfoil on the standard-tube was joined. It then occurred to us that we would try the case of a unipolar discharge. Accordingly a tube was taken in which there was an intermediate terminal situated very near to one of the ends of the tube. The other terminals were in the usual position at the two ends of the tube. The two terminals that were very near together were joined to the terminals of the machine, so that the current only traversed the very short portion of the tube lying between them. A positive air-spark was now introduced into the current. As has been described in the previous paper, this caused a pointed tongue of positive luminosity gradually to advance into the unoccupied portion of the tube, forming a positive unipolar discharge. The terminal at the other end was then joined to the tinfoil on the standard-tube. No effect was, however, produced until the air-spark was lengthened (and with it the unipolar column) so much that the unipolar luminosity came up to that terminal and formed the usual blank-space around it. Instantly the most perfect positive effects appeared in the standard-tube. The air-spark was then decreased so as to make the unipolar luminosity retreat from the terminal, and at once the effect ceased. This was repeated several times, and the result was always the same, showing that so local is the effect of the free electricity discharged into the tube that it is only across a true negative blank-space that it exercises upon another terminal any decided influence of the type required to produce interference. The experiment was repeated, a ring of tinfoil round the tube being substituted for the distant terminal. The result was the same. So soon as the tongue of luminosity got within a like distance of this ring so that the blank space was formed either completely or partially the effect appeared in the standard tube, but not otherwise.

We need not point out how strongly this supports the theory suggested in the previous section as to the signification of the blank-space. We wish rather to point out its bearing upon the question of the significance of the positive column. The luminosity in the unipolar discharge is in reality a positive column which doubles back upon itself when it does not find any negative terminal to which it can discharge. It thus may be taken for our present purposes as a representative of an ordinary positive column, and it becomes strictly a positive column when it reaches the further terminal and forms a blank space round it. Regarding it as such, we see that it is unable to produce interference in the standard-tube through the medium of the further terminal, unless it extends to within the breadth of the ordinary blank-space from that terminal. The effect produced upon the standard-tube could only be caused by the presence of free electricity in the immediate neighbourhood of the terminal. This seems to show that the luminosity marks much more clearly the local situation of the free positive electricity of the discharge and the locus of demand for negative electricity than we could have predicated independently of this experimental evidence. It will be noticed that this experiment showed that the positive luminosity, plus an enveloping shell of the breadth of a blank-space, was the limit of the effective electric field. The rest of the tube was not used in the discharge.

A tube was taken of tolerably good exhaust enclosing a spiral of wire. There was a positive column in the tube sufficiently nearly filling up the whole section of the tube to make it pass through the coils of the spiral, so that the spiral was, as it were, bathed in positive luminosity. So long as the tube was not touched, the wire did not act in any way upon the positive luminosity, but if the finger were brought in contact with the side of the tube at a point where it was touched by the spiral, a blank-space appeared surrounding the wire of the spiral whenever it had been touched by the positive luminosity. This shows that throughout the luminosity there was a demand for negative electricity, which caused the formation of a blank-space around the wire and negative discharge therefrom so soon as the relief afforded to the wire from the finger permitted it to part with its negative electricity.

The drawback to this experiment was that it was not possible to test whether there was negative discharge equally from all parts of the wire, or whether it was only from those parts which were in the midst of the positive luminosity. The only test of the existence of negative discharge in such a tube being the appearance of a blank-space, it is obvious that no conclusive evidence could be obtained of its existence where there was no luminosity out of which the blank-space could be cut and by which it could be bounded. But this want is supplied to some degree when we come to tubes of higher vacua, for the negative discharge is there accompanied by molecular streams; and by projecting relief-phosphorescence upon the conductor within the cylinder, and observing the bulging out of the shadow, we can detect negative discharge even when no luminosity is visible. These experiments have been referred to in Section XXIII., and they show that the thin positive column in high vacua indicates the local presence of a very intense demand for negative electricity greater than that which is experienced generally throughout the tube, since the result of the positive column passing across the end of a wire within the tube is to cause a very considerable bulging out of the shadow even when no relief is given to the wire from without the tube, and therefore when the wire is subjected throughout its whole length to the ordinary electric tension produced by the presence of the discharge in the tube.*

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* Since the above was written these conclusions have received striking confirmation from the following experiment. A long tube of high exhaust was taken in which there was a loose wire of considerable length, and straight in its general direction, but bent in one or two places into sharp angles. With a positive air-spark the tube gave the long, thin, pencil-like column of positive luminosity of which we have spoken. When this did not come in contact with the wire no special appearances presented themselves, but when by the approach of the hand or otherwise it was made to move up to and come in contact with one of the angles in the wire, which rested on the inner surface of the tube, a bright patch of phosphorescence of an oval contour appeared, commencing at the angle and extending from it, evidencing incon-

Another proof that the positive column marks an intense local demand for negative electricity is the attendant phosphorescence. We have already remarked upon this in Section XXIII. It assimilates the positive column to a line of centres of positive discharge.

This seems to throw much light upon the meaning of the blank-space surrounding centres of negative discharge. It marks the area through which the centre of negative discharge is capable of exerting such an influence* as to prevent that intensity of demand for negative electricity arising or continuing, which is the condition of the existence of positive luminosity in that particular gaseous medium. We are not as yet able to define what is the nature of this influence, or how it is exercised, but there seems to us to be clear evidence of its existence. In this way we can understand the existence of the blank spaces between striæ. They show the space which is, as it were, protected from intense need of negative electricity by the influence of the gaseous negative terminal composed of the hollow hazy surface of the next stria.†

We have said that the positive column is like a line of centres of positive discharge, and it is attended by phosphorescence in high vacua, just as such a line of centres would be, supposing them to lie close along the surface of the tube. But the positive luminosity can be attracted to the side of the tube by a wire connected with the positive terminal and passing along near the surface of the tube—the air-spark being, of course, in the positive. The true significance of this phenomenon is worthy of remark now that we know the exact meaning of the thin pencil-like column of positive luminosity. The course of reasoning given in Section XXIII. has shown that there is a continual discharge of negative electricity directed towards this positive luminosity from the surrounding portion of the tube, and that it is thus the locus of the centres of excitation throughout the tube. The presence of the wire parallel to and near the tube has, we see, the property of fixing this locus of centres of excitation on the side of the tube nearest to itself. Now we know that all that it can do is to excite by induction

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testably the presence of a negative discharge from the angle of the wire. In other words, the presence of the positive luminosity at the angle had caused there so strong a local demand for negative electricity that it caused a discharge to take place from the angle; the remainder of the wire (although subjected to the general demand for negative electricity) that must exist throughout the tube only serving as a reservoir from which the discharge was drawn. [July, 1880.]

* It may be objected that inasmuch as the breadth of the blank-space ordinarily increases with the degree of exhaust, this hypothesis would make the extent of the negative influence greater in tubes of high exhaust than in other tubes: a result which seems startling in view of the enormously greater difficulty that electricity finds in passing through the former. But it must be remembered that it is much more difficult to produce luminosity in such tubes, and it may well be that this more than counteracts the other effect, and enables the influence of the negative terminal in preventing the formation of luminosity to extend through a greater range than in low vacua where a much less intense need suffices to cause it.

† It will be understood that this is not intended to be a further explanation of the genesis or structure of striæ and the blank spaces between them. It leaves the matter where it was left by our previous paper. It is only intended as an illustration of the application of the present theory of the blank-space to a particular and well-known case of its occurrence.

positive discharges from that part of the tube inwards. Not only can it do this, but it certainly does so, for the effect of the impulsive variations of potential in the wire must of necessity produce such discharges. Hence we see that the effect of producing a locus of such discharges in the tube is to cause the original locus to shift till it coincides with the new locus. Thus the *creation of the new locus has made the first unnecessary*, or, in other words, the discharge does not require any special series of positive centres of discharge along its course, but it is content with one series ; but this it must have.

Now if we compare this with the phenomenon of positive-special-effect when a ring of tinfoil is used, we shall gain a valuable insight into the mode of propagation of the discharge. In that case we know that the inductive discharge at the tinfoil takes the place of the original discharge, and the latter is satisfied by the negative that is left behind by the former. If we suppose this effect to be more imperfectly produced and spread along a line, passing along the tube longitudinally, instead of surrounding it, we shall get an idea of how the discharge is effected when we use the special-effect in the way described above. And the knowledge that we now have of the identity of the phenomenon presented by this special effect, and the ordinary discharge (save so far as regards the side of the tube which the luminous column prefers) in high vacuum tubes, seems to point to something like the above mode of propagation of the discharge in all cases.

XXIX.—*General conclusions as to the electric discharge.*

IV. *Molecular streams.*

There are a few questions relating to molecular streams which we are in a better position now to consider than we were before the phenomena of phosphorescence in the sensitive current had been examined by us. These we shall shortly indicate.

In Section XVII. we stated that it was our belief that there was no essential difference between the molecular streams of particles of gas which go to produce phosphorescence and the phenomenon of the driving off from the negative terminal of small loose particles of conducting matter, which also occurs in rarefied media. In order to settle this point, we took a tube of fairly good exhaust containing a little of a mixture of sand and lamp-black, the sand being put there to assist in removing the lamp-black from the sides of the tube in case it should adhere thereto. The tube was placed vertically with the negative end downwards, and a current from the large 12-plate HOLTZ machine was passed through it. In a few seconds the sides of the tube were covered with a coating of lamp-black for about two-thirds of its length. The experiment was then varied by the introduction of an air-spark into the circuit. Whether this was placed in the positive or negative portion of the circuit, the effect was the same, the lamp-black was driven with such violence against the sides of the tube that it became caked in some places, so that it was a troublesome matter to get it off.

Seeing, then, that these particles of lamp-black behaved in the same way as particles of gas would have done (save that they remained fixed to the glass instead of bounding off and causing phosphorescence), we determined to see whether they could be made to show the sensitive effects which we had observed in phosphorescence. Accordingly, a narrow slip of tinfoil was placed round the tube near its middle point, and connected to earth, and a discharge with a sharp positive intermittence was sent through the tube for a very short time. On examining the tube it was found that there was the usual thick coating of lamp-black over the sides of the tube, except where the tinfoil had been. This remained bare of lamp-black. Thus the relief-molecular streams from under the tinfoil had swept away the particles of lamp-black that would otherwise have lodged on the sides of the tube under the tinfoil.*

We next joined the tinfoil metallically to the positive terminal so as to produce positive special. The result was that the deposit was thicker beneath the tinfoil than elsewhere, corresponding to the appearance of phosphorescence on the tinfoil in a like case. Negative relief gave a similar effect, while negative special kept the surface of the tube beneath the tinfoil clear of lamp-black. Thus, in all four cases the streams of lamp-black behaved in all respects as molecular streams would have done.†

Seeing, then, that any small light particles of a conducting substance are capable, under the action of negative discharge, of forming streams similar to the molecular streams that produce phosphorescence, and governed by like laws, the question naturally suggests itself whether these molecular streams have any necessary electrical function to perform in the discharge, or whether the particles of the gas are not driven off, like the particles of lamp-black, just because they happen to be there and are capable of being so driven off. This is a most important and difficult question to decide. At present we have come to no definite conclusion upon it, but we cannot say that we are aware of anything that conclusively shows that they have any definite electrical function to perform in the discharge, while on the other hand there are many things that point to an opposite conclusion.

In the first place, neither the telephone nor the standard-tube recognises their existence. A piece of tinfoil will cause no louder sound in a telephone nor produce any greater effect on a standard-tube with which it is connected because it is on a spot where there is brilliant phosphorescence. Nor do they take notice of its total or partial absence. It makes no difference whether or not the tinfoil is situated in an absolute or a virtual shadow, and therefore protected from the impact of these streams.

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* In order to ascertain that it was an electrical effect and not merely the effect of something being placed round the tube which might have the effect of deadening vibration, or producing some other mechanical effect, the experiment was tried with a ring of tinfoil unconnected with any relieving system, and also with an india-rubber band. In neither case was the coating of lamp-black affected.

† It is necessary that the discharge should be brief in duration, for otherwise the whole surface has a tendency to get coated. It must be remembered that the lamp-black accumulates on the surface, so that it is only by so doing that the conditions resemble those under which phosphorescence is produced.

In the next place, it seems abundantly probable that they are quite left behind by the negative discharge when it is in the tube. The time they take to pass along the tube is of the same order of smallness as the time that is occupied by the emission negative discharge that produces them. But the time that negative electricity takes to pass along the tube is, as we have seen, of a higher order of smallness than this, for when the intermittence is negative the discharge can pass along the tube in time to stop the production of phosphorescence at a piece of tinfoil near the positive terminal, which is connected with a piece near the negative terminal. Thus it appears that it out-runs these molecular streams, and cannot depend on them for its propagation.

Further, we now know that a discharge may be effected by positive passing through the tube and deriving its satisfaction by a response from the negative terminal. Or it may be effected by the negative passing throughout the tube and meeting with a response at the positive terminal. Now, on the supposition that these molecular streams are the carriers of the discharge, or that they have any special function to perform in its propagation, it is very difficult to understand the first of these modes of effecting the discharge. Moreover, it is admitted that there is not the slightest necessity that any of these molecular streams should strike or even pass near the positive terminal, so that the latter of the two modes of effecting the discharge seems equally incomprehensible on the above theory.

The most attractive hypothesis relating to their functions is that they officiate at the birth of the discharge and enable it to get into the gaseous medium, where it has modes of propagation which are independent of these molecular streams.

There is much to recommend this theory which views molecular streams as a necessary attendant phenomenon of negative discharge, but having no share in its propagation. We are not in a position to pronounce upon this hypothesis. The fact that resistance rises higher with increased degree of exhaust, after a certain point is passed, seems to favour it, as this law would then admit of the simple explanation that the resistance was greater because of the lack of carriers to carry the electricity into the gaseous medium. But this increase of resistance may come from other causes, and this single consideration does not seem to be sufficient ground for assigning to the molecular streams such a special function in the absence of other evidence that they possess it.

On the whole, then, we are inclined to doubt whether molecular streams have any necessary function in the discharge. This does not, of course, imply that the molecules that compose them are not charged. On the contrary, it seems very probable that they are, as it would otherwise be difficult to account for their being shot off at so great a velocity or for their obeying a magnet. But the fact that in this way some small portion of the negative discharge is convectively carried along the tube would no more entitle them to be looked upon as having a function to perform in the discharge than it would entitle the particles of lamp-black to be looked upon in that light.

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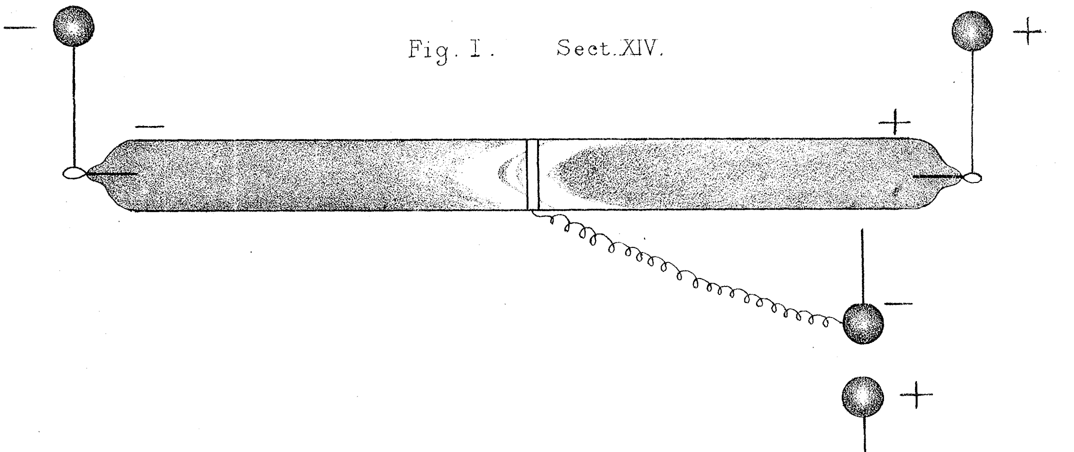
Fig. I. Sect. XIV.



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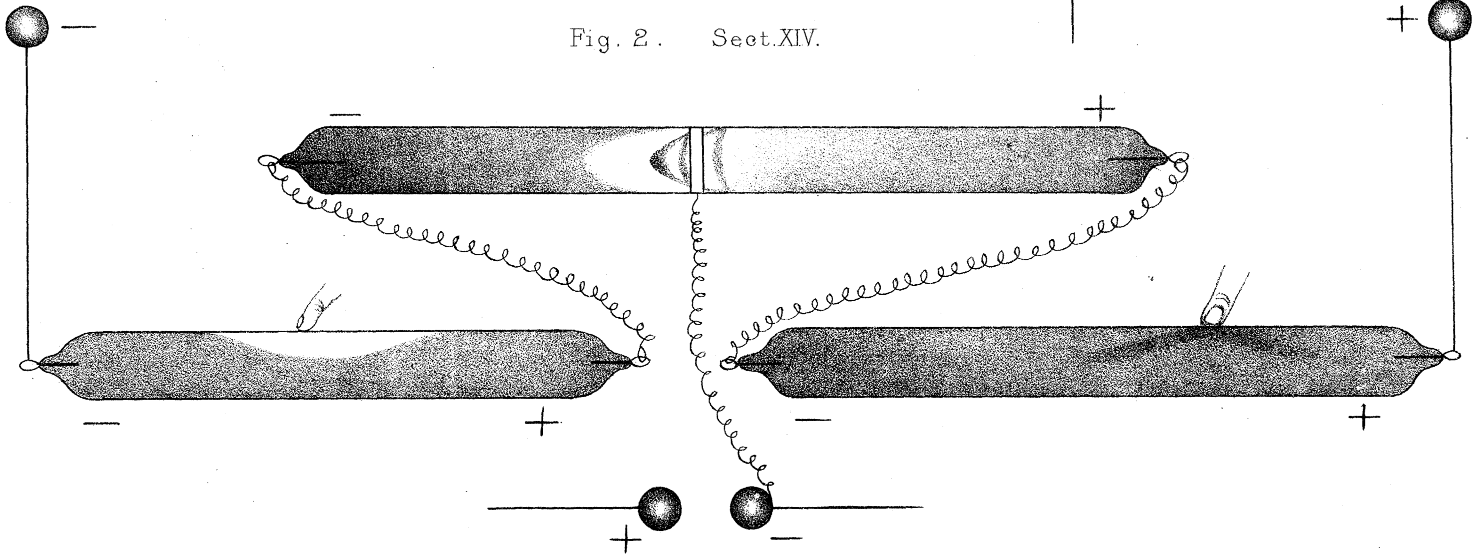

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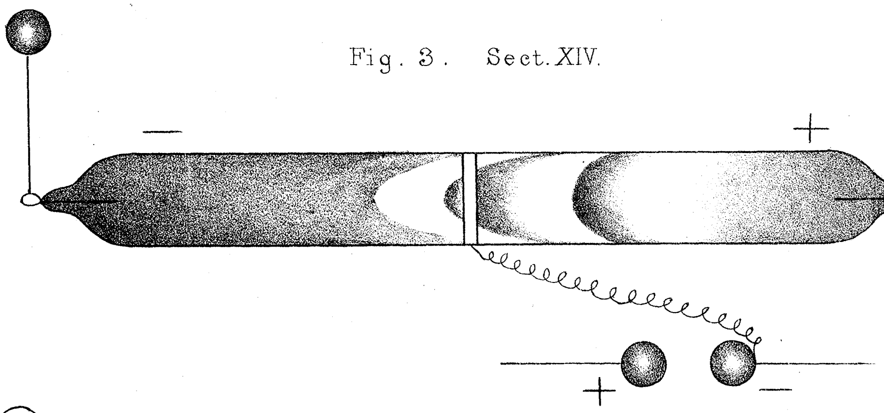

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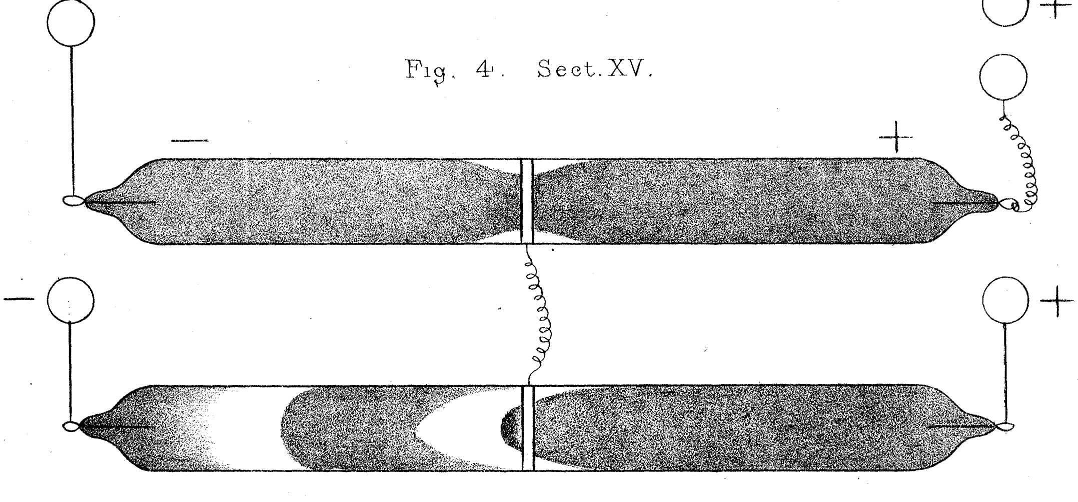

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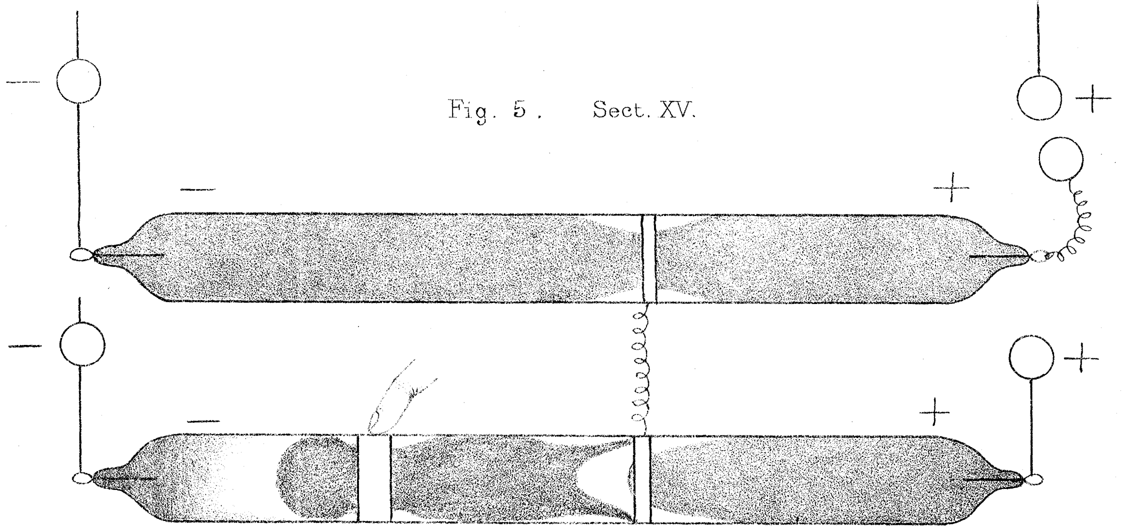
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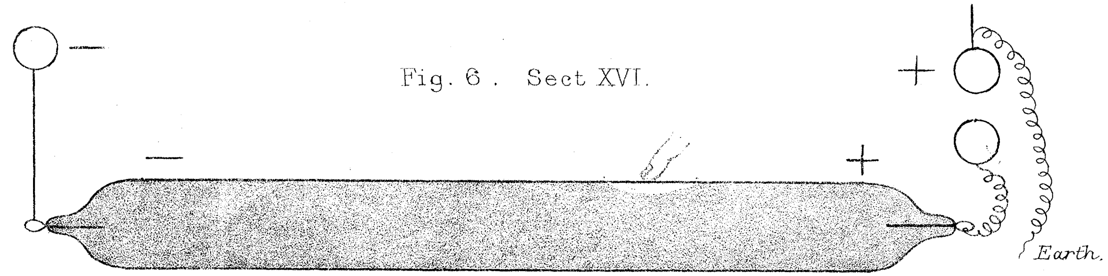
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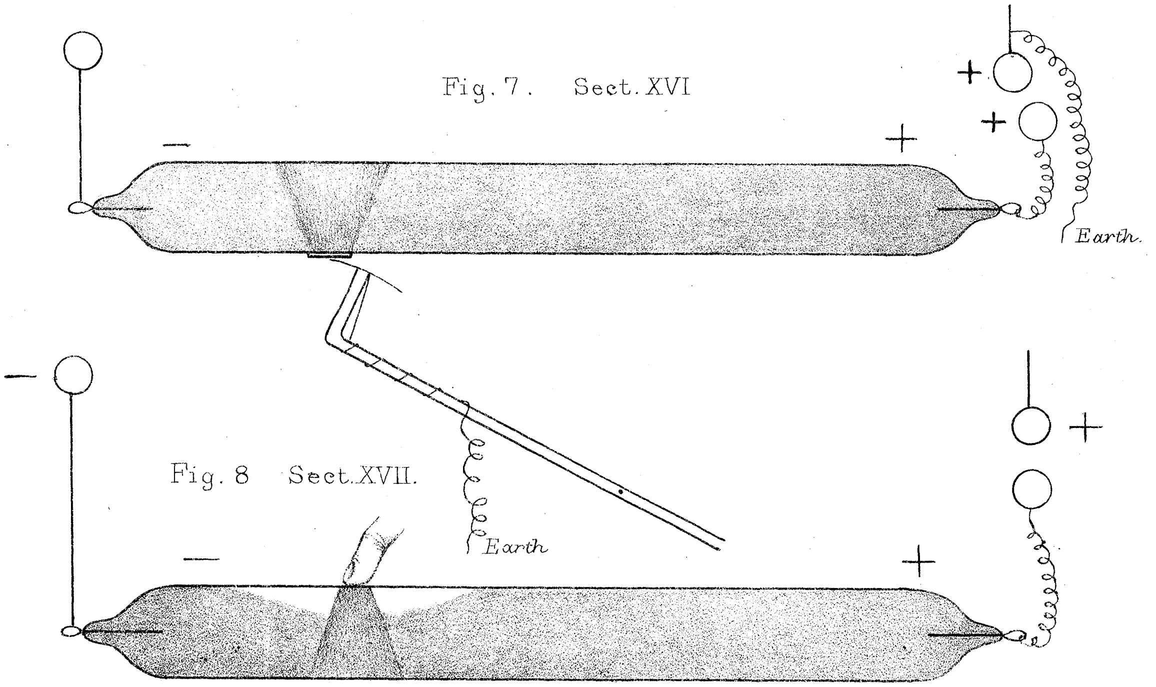
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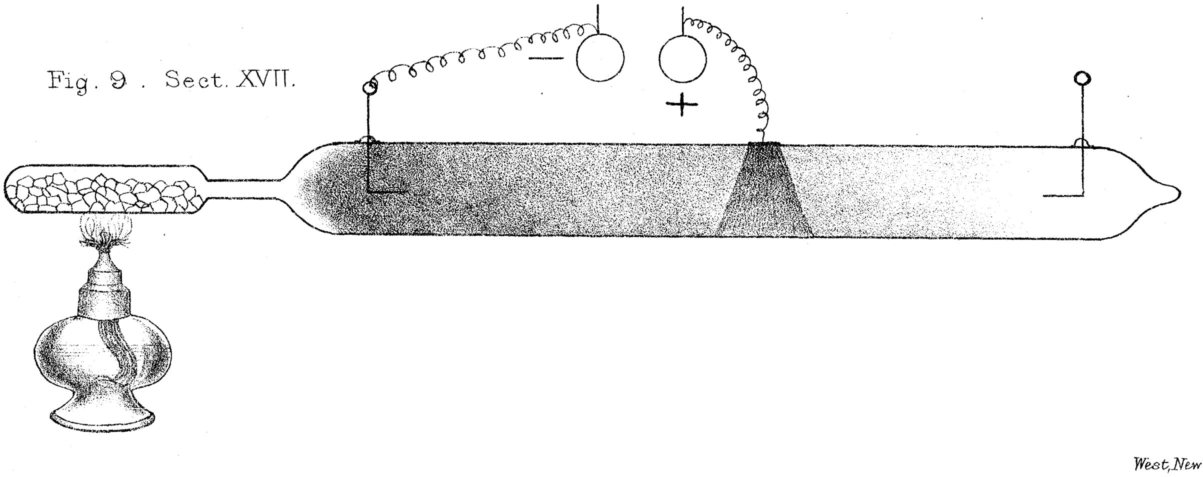
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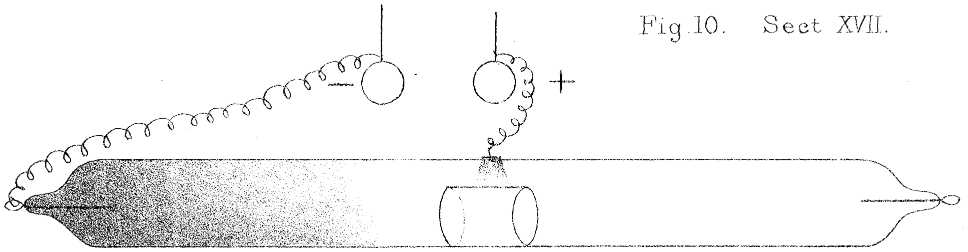

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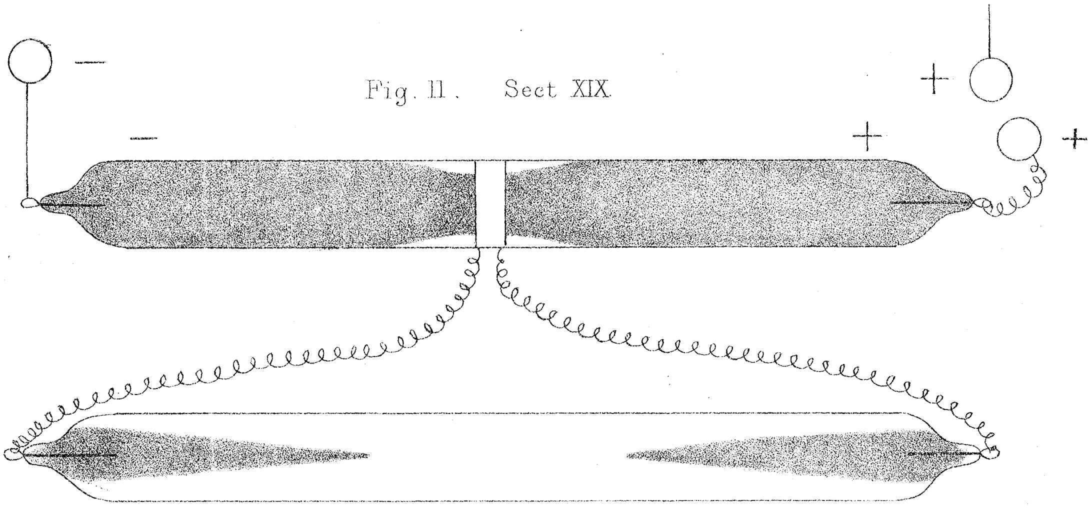

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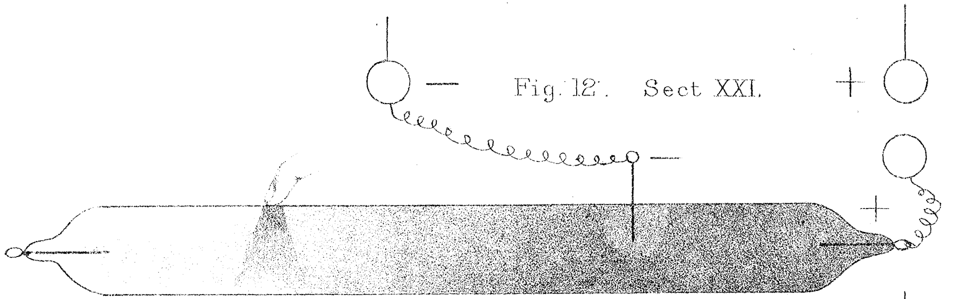

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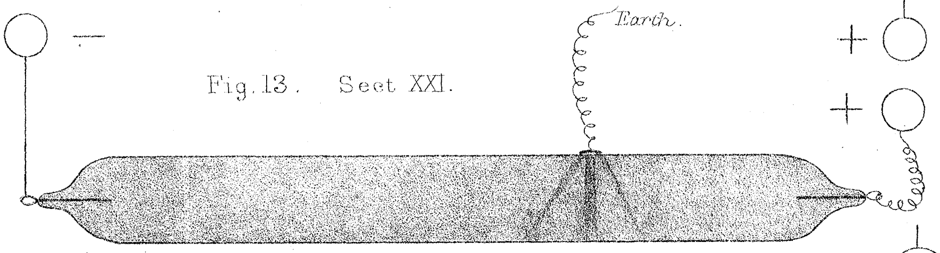

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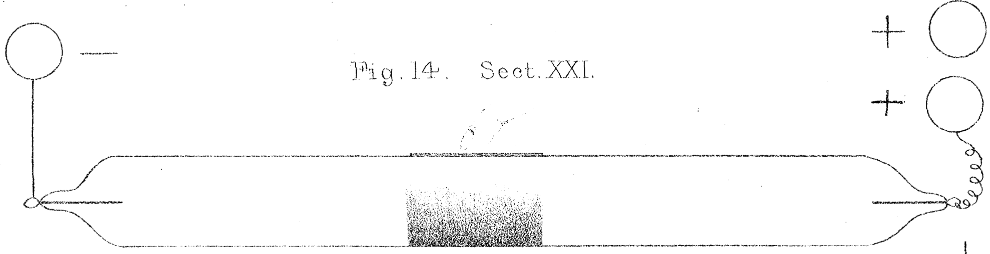

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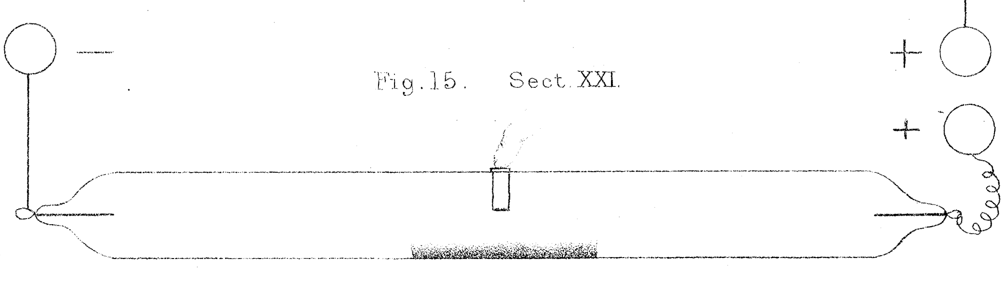

Fig. 15. Sect. XXI.

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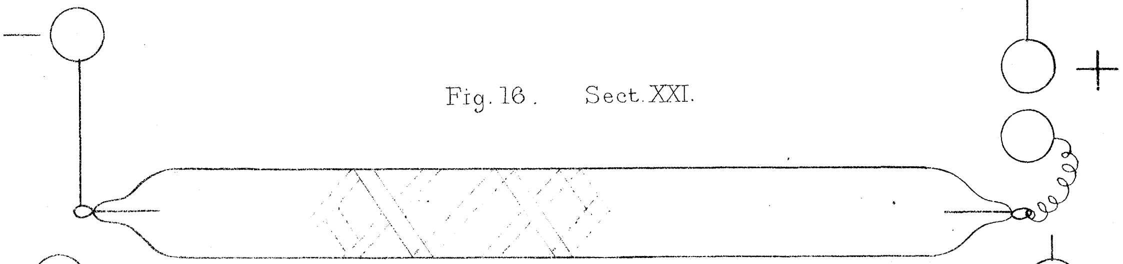

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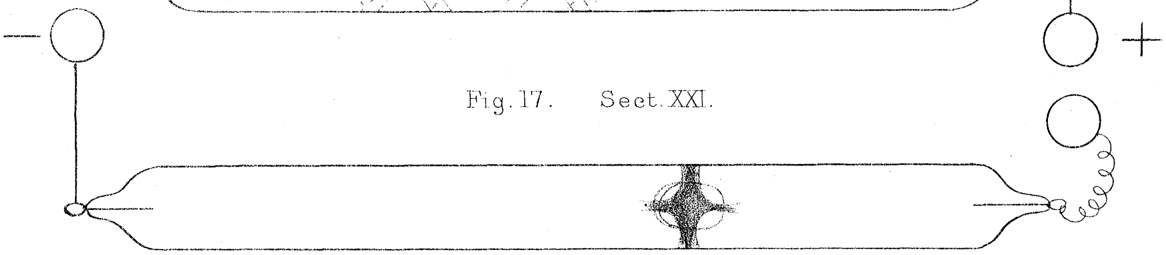

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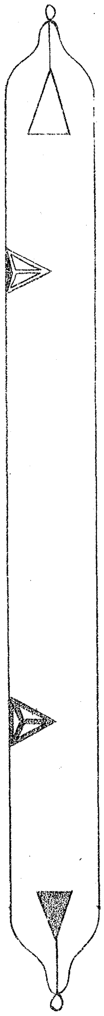

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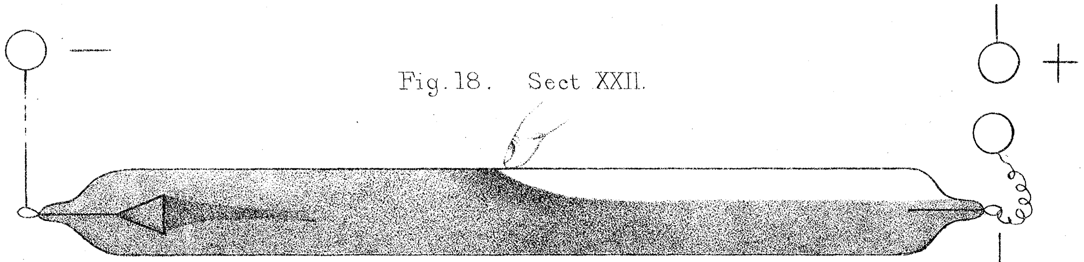

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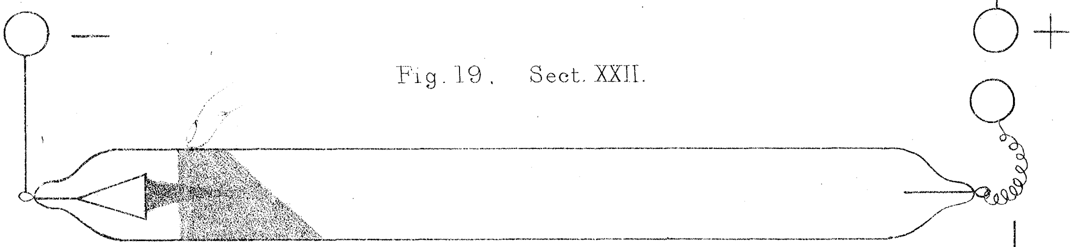

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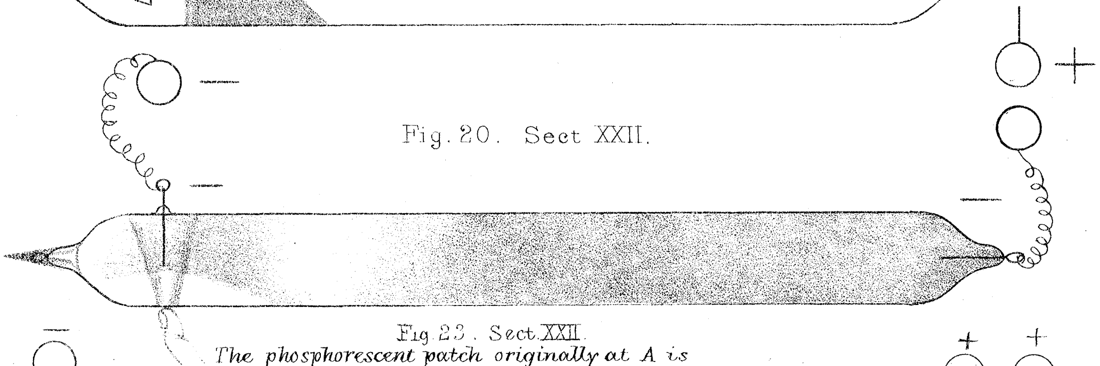
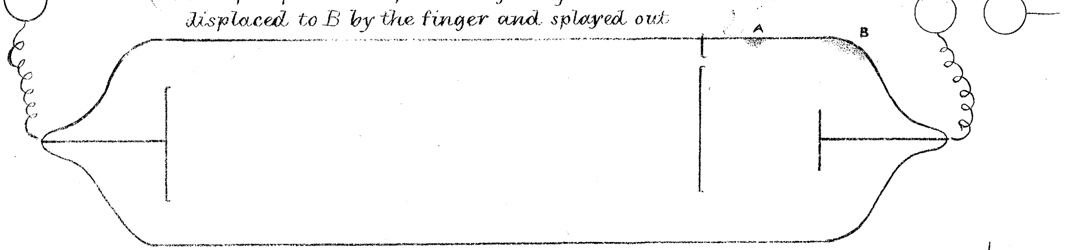


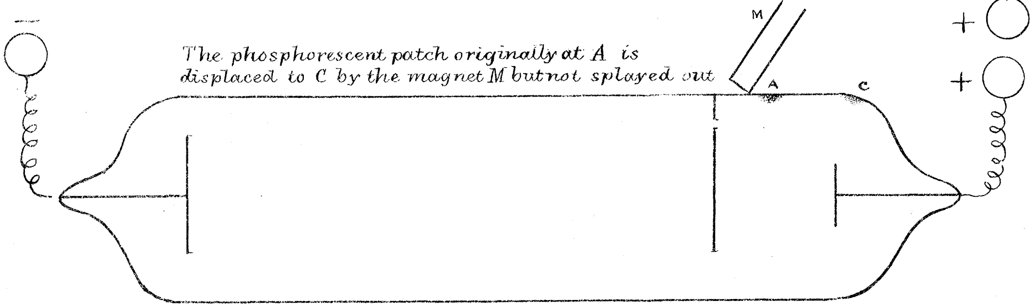
Fig. 20. Sect. XXII.

Fig. 23. Sect. XXII.

The phosphorescent patch originally at A is displaced to B by the finger and splayed out



The phosphorescent patch originally at A is displaced to C by the magnet M but not splayed out



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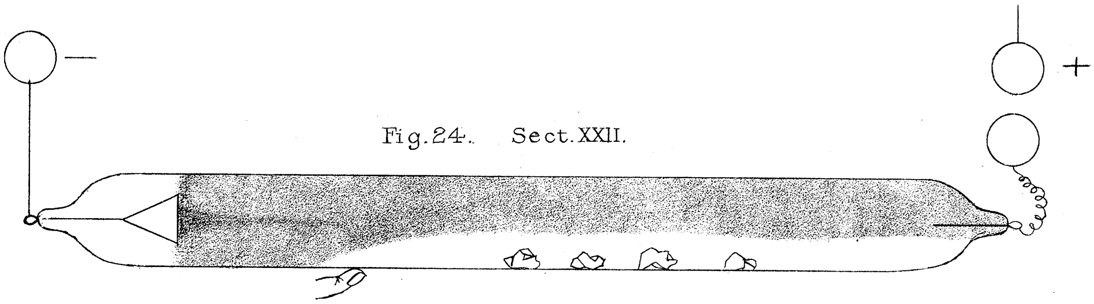

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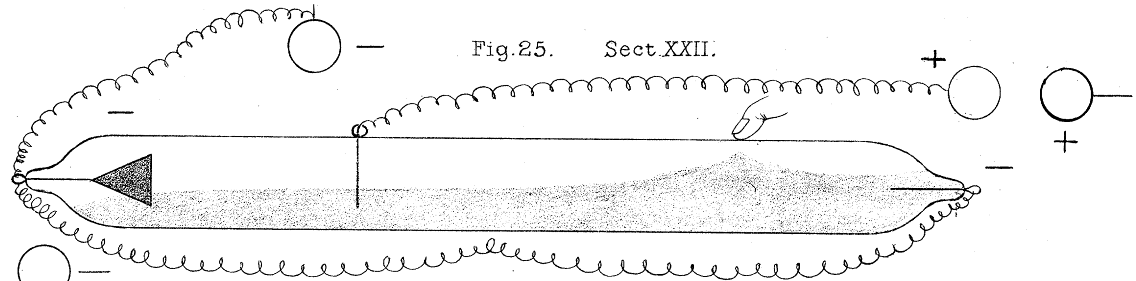

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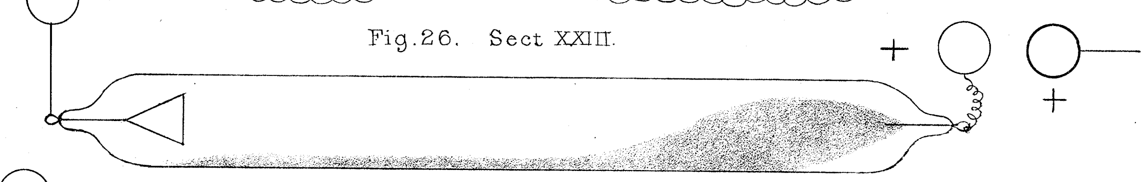

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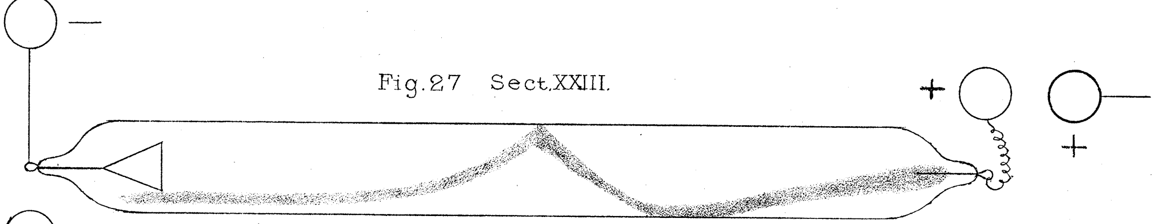

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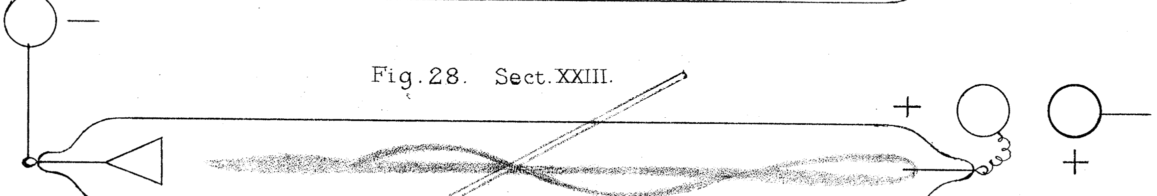

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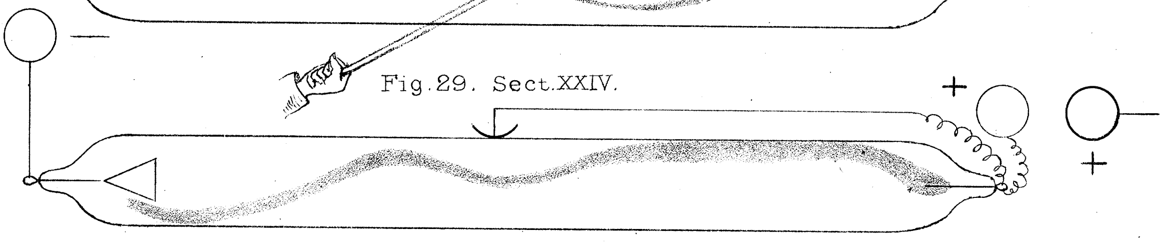

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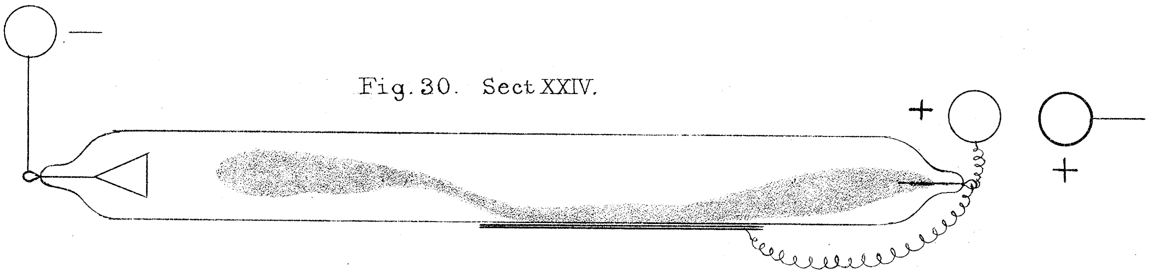

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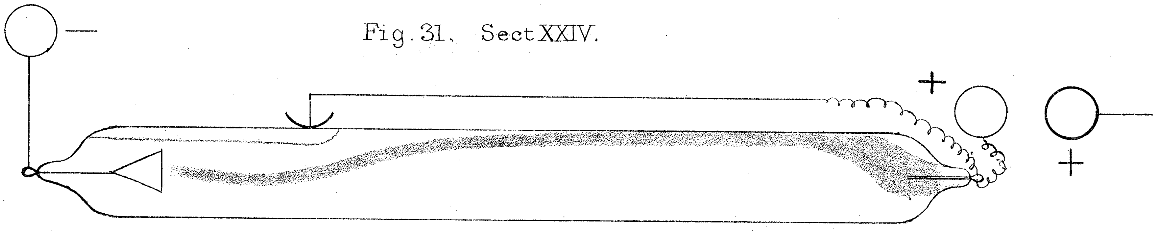

Fig. 31. Sect. XXIV.

West, Newman & Co lith.