PHILOSOPHICAL TRANSACTIONS:

Contributions to Molecular Physics in High Vacua. Magnetic Deflection of Molecular Trajectory. Laws of Magnetic Rotation in High and Low Vacua. Phosphorogenic Properties of Molecular Discharge

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XVI. *Contributions to Molecular Physics in High Vacua.*

Magnetic Deflection of Molecular Trajectory.—Laws of Magnetic Rotation in High and Low Vacua.—Phosphorogenic Properties of Molecular Discharge.

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Contents.

586. The present paper is a continuation of the Bakerian Lecture "On the Illumination of Lines of Molecular Pressure and the Trajectory of Molecules," read before the Royal Society, December 5, 1878. Phenomena there briefly referred to have since been more fully examined; new facts have been observed, and their theoretical bearings discussed; and numerous experiments suggested by Professor Stokes and others have been tried, with the result of acquiring much information which cannot fail to be of value in assisting to evolve a theory capable of embracing all the phenomena under discussion.

587. In par. 514 I described a piece of apparatus by means of which the molecular rays electrically projected from the negative pole at a high exhaustion were converged to a focus, the pole itself being hemi-cylindrical in shape. On referring to the coloured drawing illustrating the experiments it will be observed that the green phosphorescence of the glass (by means of which the presence of the molecular rays is manifested) does not take place close to the negative pole. It has been since found that

there is absolutely no phosphorescence when the sensitive surface is fully within the narrow dark space surrounding the negative pole in imperfect vacua. As the rarefaction improves the dark space widens out, and phosphorescence begins to appear outside the luminous margin, but not inside it. On further exhausting, the luminous boundary of the dark space gets fainter and larger, till it disappears, and now the phosphorescence extends all over the sensitive surface. Several pieces of apparatus were constructed in order to test this fully. Negative poles of flat, convex, and concave shapes were experimented with, and various substances were used as the sensitive material for rendering apparent, by phosphorescence, the molecular rays. The result in all cases has been to confirm the first observation, viz. : that there is no phosphorescence within the dark space.

588. Experiments previously described have, I think, shown that the molecular stream hypothesis is the correct one. According to this, the molecules of the residual gas, coming in contact with the negative pole, acquire a negative charge, and immediately fly off by reason of the mutual repulsion exerted by similarly electrified bodies. Were the individual molecules solely acted on by the initial impulse from the negative pole, they would take a direction accurately normal to the surface repelling them, and would start with their full velocity. But the molecules, being all negatively electrified, exert mutual repulsion, and therefore diverge laterally. The negative pole, likewise, not only gives an initial impulse to the molecules, but it also continues to act on them by repulsion, the result being that the molecules move with an accelerating velocity the further they get from the pole. The lateral divergence of the molecules, owing to their negative electricity, will naturally increase with the amount of charge they carry; the greater the number of collisions the more the molecules lose negative charge, and the less divergent the stream becomes. This hypothesis is borne out by facts. When the vacuum is just good enough to allow the shadow to be seen, it is very faint (owing to few molecular rays), but is quite sharp (owing to the divergence of the molecules laterally). The variation in mutual repulsion is shown by the fact that the focus projected from a concave pole falls beyond the centre of curvature, and varies in position with the exhaustion, being longer at high than at low exhaustions.

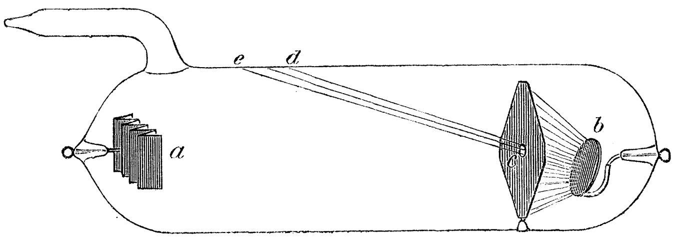
589. Assuming that the phosphorescence is due, either directly or indirectly, to the impact of the molecules on the phosphorescent surface, it is reasonable to suppose that a certain velocity is required to produce the effect. Within the dark space, at a moderate exhaustion, the velocity does not accumulate to a sufficient extent to produce phosphorescence; but at higher exhaustions the mean free path is long enough to allow the molecules to get up speed sufficient to cause phosphorescence. At a very high exhaustion the phosphorescence takes place nearer the negative pole than at lower exhaustions; this I consider results from the initial velocity of the molecules being sufficient to produce phosphorescence, their greater speed being due to the fewer collisions near the negative pole.

The luminous boundary to the dark space round the negative pole is probably due to the impact of molecule against molecule, producing phosphorescence of the gas in the same way as the impact of molecules against German glass produces phosphorescence of the glass.

590. The following experiments were commenced at the suggestion of Professor MAXWELL :—

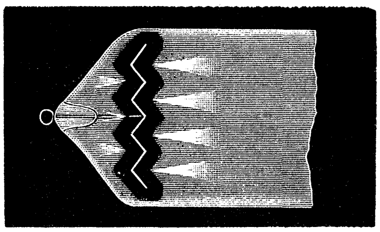
A tube was made as shown in fig. 1. The terminal *a* is a rectangular plate of aluminium, folded as shown in section fig. 2; the other terminal *b* is a flat disk of aluminium set obliquely to the axis of the tube. In front of the pole *b* is fixed a screen of mica, with a small hole in it, as shown at *c*; this hole is not in the axis of the tube, but a little to one side of it, so that rays starting normally from the centre of the pole *b* may pass through it and strike the glass at *d*, whilst at the same time rays passing direct between the poles *a* and *b* can also pass through the hole.

Fig. 1.



The questions which this apparatus was to answer are:—(1) Will there be molecular projections from the negative pole, *a*, in two series of plane strata normal to the sides of the individual furrows, or will the projection be perpendicular to the electrode as a whole, *i.e.*, along the axis of the tube? and (2), Will the molecular rays from the pole *b*, when it is made negative, issue through the aperture of the screen, along the axis of the tube, *i.e.*, direct to the positive pole, or will they leave the pole normal to its surface and strike the glass as shown at *d*?

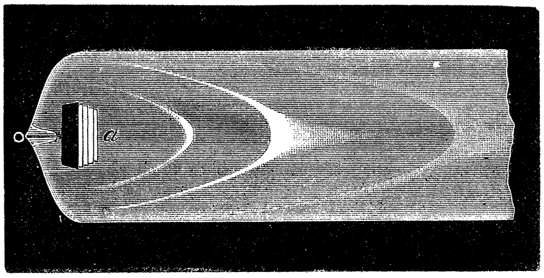
Fig. 2.



591. The tube was exhausted and connected with an induction coil; the following results were obtained :—At a moderate exhaustion, the corrugated pole being made negative, the dark space entirely surrounds it, slight indentations being visible opposite each hollow, where there also is a linear concentration of blue light. The appearance is in section as shown in fig. 2. At higher exhaustions the luminous margin disappears and the rays which previously formed the blue foci are now projected on the inner surface of the tube, where they make themselves evident in green phosphorescent light

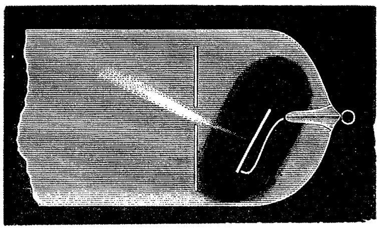
as portions of ellipses formed by the intersection of the several sheets of molecular rays with the cylindrical tube. Fig. 3 shows this appearance.

Fig. 3.



When the other pole was made negative, and the exhaustion was such that the dark space extended about 8 millims. from the pole, the first appearance noticed was that of a ray of dark blue light issuing through the hole in the mica screen, and shooting upwards towards the side of the tube, but not reaching it. Fig. 4 shows the dark space round the pole, and the ray of blue light. On increasing the exhaustion this blue line of light, and the luminous boundary to the dark space, disappeared, and presently a green oval spot appeared on the side of the tube, exactly on the place previously marked where the rays issuing normal from the surface of the pole should fall.

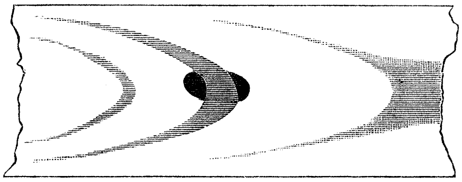
Fig. 4.



592. It happened that this oval spot fell on a portion of the tube where one of the elliptical projections from the opposite (corrugated) pole also fell when that was made negative. Thus by reversing the commutator I could get a narrow band of green phosphorescent light from one pole, or a wider oval of green light from the other pole, to fall alternately on the same portion of the glass. Fig. 5 shows these effects, which, however, did not occur together as represented in the figure, but alternately.

The narrow band shone very brightly with green phosphorescence, but on reversing the commutator and obtaining the oval spot, this was seen to be cut across the middle by a darker band where the phosphorescence was much less intense. The light of the band was always more intense than that from the spot; the impacts from the one being more concentrated than from the other, owing to the shape and position of the poles; moreover the experiments had been first tried with the corrugated pole negative. The glass along the band gradually becomes deadened by repeated impacts, and will not readily phosphoresce in reply to the weaker blows from the flat plate, although it still responds to the more energetic bombardment from the corrugated pole. This phenomenon almost disappears at very high exhaustions, or if the tube is allowed to rest for some time. The tired glass then recovers its phosphorescent power to some extent, but not completely.

Fig. 5.



593. To obtain this action in a more striking manner, a tube was made having a metal cross on a hinge opposite the negative pole. The sharp image of the cross was projected on the phosphorescent end of the bulb, where it appeared black on a green ground. After the coil had been playing for some time a sudden blow caused the cross to fall down, when immediately there appeared on the glass a bright green cross on a darker background. The part of the glass formerly occupied by the shadow, having been protected from bombardment, now shone out with full intensity, whilst the adjacent parts of the glass had lost some of their sensitiveness, owing to previous bombardment.

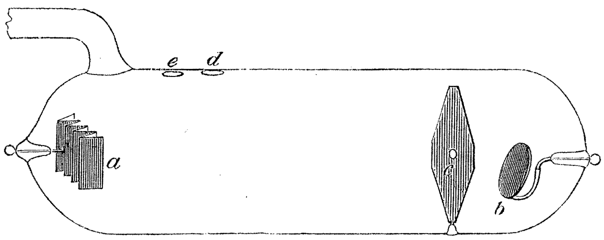
594. [This effect of deadening produced on glass by long-continued phosphorescence was shown in a very striking manner at a lecture delivered at the Royal Institution on April 4th, 1879, when the image of a cross was stencilled on the end of a large pear-shaped bulb.

I subsequently experimented further with this bulb, and found that the image of the cross remained firmly stencilled on the glass. The bulb was then opened and the wide end heated in the blowpipe flame till it was quite soft and melted out of shape. It was then blown out again into its original shape, and re-exhausted; on connecting it with the induction coil, the metal cross being down out of the line of discharge, the original ghost of the cross was seen to be still there, showing that the deadening of the phosphorescing powers the glass produced by the first experiment at the Royal Institution had survived the melting-up and re-blowing out of the bulb.—August 12, 1879.]

595. When experimenting with this apparatus a shifting of the line of molecular discharge was noticed when the current was first turned on. The flat pole *b* (fig. 6) being negative and the line *c d* being normal to its surface, the spot of light falls accurately on *d*, when the exhaustion is sufficiently good to give a sharp oval image of the hole *c*. But at higher exhaustions, when the outline of the image of *c* becomes irregular and continually changing, the patch of light at the moment of making contact is sometimes seen at *e*, and then almost instantly travels from *e* to *d*, where it remains as long as the current passes. The passage of the spot from *e* to *d* is very rapid, and requires close attention to observe it. If the coil is now stopped for a longer or shorter

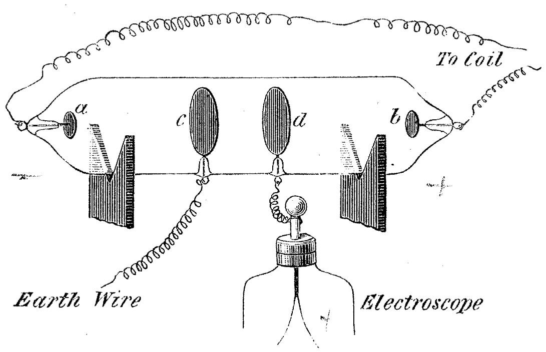
time, and contact is again made *the same way as before* (*b* being negative), the spot does not now start from position *e*, but falls on *d*, in the first instance. This can be repeated any number of times.

Fig. 6.



596. If now the pole *b* be made positive even for the shortest possible interval, and it then be made negative, the original phenomenon occurs, and the spot of light starts from *e* and rapidly travels to *d*. After this it again falls on *d*, *ab initio*, each time contact is made, so long as *b* is kept the negative pole. There seems no limit to the number of times these experiments can be repeated. The explanation of this result appears to depend on a temporary change in the condition of the wall of the glass tube when positively electrified molecules beat against it, a change which is undone by subsequent impact from negative molecules. This phenomenon is closely connected with some shadow and penumbra experiments described further on (601 to 605), and as the same explanation will apply to both I will defer any theoretical remarks for the present.

Fig. 7.



597. A suggestion was made by Professor MAXWELL that I should introduce a third, idle, electrode in a tube between the positive and negative electrodes so that the molecular stream might beat upon it, so as to see if the molecules gave up any electrical charge when impinging on an obstacle. A tube was therefore made as shown in fig. 7; *a* and *b* are the ordinary terminals; *c* and *d* are large aluminium disks nearly the diameter of the tube, connected with outer terminals. The poles *a* and *b* were connected with the induction coil, an earth wire was brought near the idle pole *c*, and a gold leaf electroscope was brought near *d*.

On passing the current at inferior exhaustions, when the dark space is about

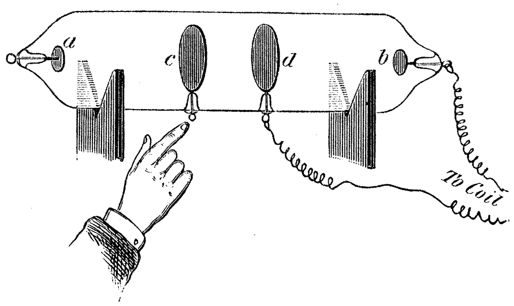
8 millims. from the negative pole, no movement of the gold leaves takes place whether *a* or *b* is negative, and whether *c* is connected with earth or is insulated.

At a good exhaustion, when the green phosphorescence of the glass is strong, the gold leaves are only slightly affected whichever way the current passes.

598. On increasing the exhaustion to a very high point, so that the green phosphorescence gets weaker and the spark has a difficulty in passing, the gold leaves are violently affected. When the pole *a* is negative and *b* positive, the leaves diverge to their fullest extent. On examining their potential it is found to be positive. The coil was stopped and the gold leaves remained open. A touch with the finger caused them to collapse. They then gradually opened again, but not to the original extent. The finger again discharged them, when they reopened slightly a third time. Experiment showed that the electrical excitement took many minutes to recover equilibrium. A Leyden jar put to the idle pole *d* was charged positively.

599. The earth wire and electroscope remaining as shown in the figure, the direction of current was reversed, so as to make *a* positive and *b* negative. The gold leaves were now less strongly affected; they opened a little, and remained quivering, as if under the influence of rapidly-alternating currents.

Fig. 8.



600. The wires were rearranged as shown in fig. 8, *b* and *d* being connected with the coil. When *d* was made negative faint sparks about 1 millim. long could be drawn by the finger from *c*; but when *d* was made positive the sparks from *c* were 10 millims. long. The same results are obtained when the finger is brought near *a*, so long as *c* remains insulated. If, however, *c* be connected with earth by a wire, no sparks can be got from *a*, whichever way the current passes between *b* and *d*. Connecting *a* with earth diminishes the length of the sparks which can be drawn from *c* by about one-half.

The poles *a* and *b* being connected with the coil, and the idle poles *c* and *d* having loose wires hanging from them, the wires were strongly repelled from each other.

601. The above experiments show that an idle pole in the direct line between the positive and the negative poles, and consequently receiving the full impact of the molecules driven from the negative pole, has a strong positive charge.

602. It now became of interest to ascertain whether the trajectory of the molecules

suffered any deflection in passing an idle pole when it was suddenly uninsulated by an earth contact. For this purpose I used the tube described in a former paper,* where the shadow of an aluminium star was projected on a plate of phosphorescent glass. So long as the aluminium star is insulated the shadow is sharp, as already described; but on touching the star to earth, the shadow widens out forming a tolerably well-defined penumbra outside the original shadow, which can still be seen unchanged in size and intensity. On removing the earth connexion, the penumbra disappears, the umbra remaining as before. The same penumbra is produced by connecting the idle pole with the negative pole through a very high resistance, such as a piece of wet string, instead of connecting it with earth. On bringing a magnet near the negative pole, the shadow of the (insulated) star is much increased in definition, the adjacent luminous parts of the screen becoming more luminous. Touching the star now brings a large, somewhat blurred, penumbra round the original image. The penumbra obeys the magnet the same as the umbra.

603. The aluminium star was now made the positive pole, the other pole remaining unchanged. The shadow of the star was projected on the phosphorescent plate of the same sharpness and almost the same intensity of light and shade as if the positive pole had been the one ordinarily used as such. The image obeyed the magnet as usual. With this arrangement the penumbral action could not be tested.

604. This, therefore, confirms the above-described results—that the idle pole, the shadow of which is cast by the negative pole, has strong positive charge. Now the stream of molecules must be assumed to carry negative electricity; when they actually strike the idle pole they are arrested, but those which graze the edge are attracted inwards by the positive electricity, and form the shadow. When the idle pole is connected with earth, its potential would become zero were the discharge to cease; but, inasmuch as a constant positive charge is kept up from the passage of the current through the tube, we must assume that the potential of the uninsulated idle pole is still sufficiently positive to neutralise the negative charge which the impinging molecules would give it, and leave some surplus of positive. The effect of alternately uninsulating and insulating the idle pole is therefore to vary its positive electricity between considerable limits, and consequently its attractive action on the molecules which graze its edge.†

Let a (fig. 9) be the negative pole, b the idle pole, whose shadow falls at c; and let b be at first supposed to be insulated. Molecular rays impelled from a in a slightly divergent direction,‡ on passing the positively electrified idle pole b, are rendered much less divergent, and bending inwards take the directions of the lines $a\ d\ d'$,

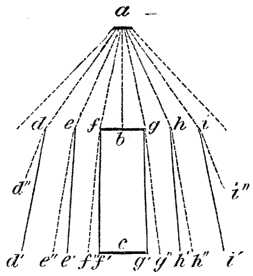
* Phil. Trans., 1879, Vol. 170, p. 147.

† I am aware that the theory which makes these effects of deflection depend on electrostatic attractions and repulsions is open to some grave objections; still it was that which in a great measure guided me in my experiments, and it could not well be omitted without reducing the description of them to a dry record of apparently unconnected facts.

‡ The divergence in the figure is purposely exaggerated in order to better illustrate the argument.

$a\,e\,e'$, $a\,f\!f'$, &c., the rays $a\,f\!f'$ and $a\,g\,g'$ forming the shadow $f'\,g'$. Now let us suppose the idle pole b to be joined to earth: its positive charge is now very small, and its attraction on the negatively electrified molecular streams correspondingly less; they are, therefore, scarcely at all converged from the direction originally impressed on them by the pole a, and they follow the directions $a\,f\!f''$, $a\,g\,g''$, &c., the shadow-forming rays $a\,f$ and $a\,g$ now proceeding to f'' and g'', forming a wider shadow. The effect of the umbra and penumbra is caused by the idle pole not being permanently at the very low positive potential, but being rapidly charged and discharged, the wide and narrow shadows following each other so quickly that they appear to be simultaneous.

Fig. 9.



605. Experiments were tried with an idle pole and shadow tube whilst the exhaustion was going on. At such a rarefaction that the shadow can just be made out, it is quite sharp; touching the idle pole causes a small penumbra to appear round its shadow. When the exhaustion is at the best point for obtaining the green phosphorescence on the glass, the shadow is very sharp and well defined; and connecting the idle pole with earth gives a much wider penumbra, the width of the penumbra increasing with the degree of rarefaction. When the vacuum is so high that the spark has difficulty in passing, the penumbra (which becomes visible on uninsulating the idle pole) is much wider than before, and apparently eight or ten times as wide as it was at the lowest exhaustion at which observations were taken.

If the object whose shadow is cast on the screen is a non-conductor (such as a piece of glass rod), its shadow remains constant at all exhaustions, no penumbra being visible, as it cannot be uninsulated.

606. [Professor STOKES, whose suggestions throughout the course of this research have been most valuable, considered that much information might be gained by experimenting with an apparatus constructed in the following manner: The two poles of the tube (fig. 10) are at a and b. At c is a fluorescent screen; d is a fixed bar of aluminium, and e is another aluminium bar hanging from a platinum pole f, by a metal chain. The bar and pendulum are on opposite sides of the horizontal axis of the tube, as shown in the plan, so that when properly exhausted and the pole a made negative, the shadows of bar and pendulum shall fall side by side on the screen, as shown in fig. 10A. On swinging the pendulum, the shadow alternately overlaps and recedes from the shadow of the bar (figs. 10B and 10C).

This apparatus was tried many times with an induction coil, and also with a Holtz machine; but the results were not sufficiently definite to render it safe to draw any inference from them. By the kindness of Mr. De La Rue, I have lately had the opportunity of experimenting with his large chloride of silver battery, and the results now come out with great sharpness and with none of the flickering and indecision met with when working with an induction coil.

Fig. 10.

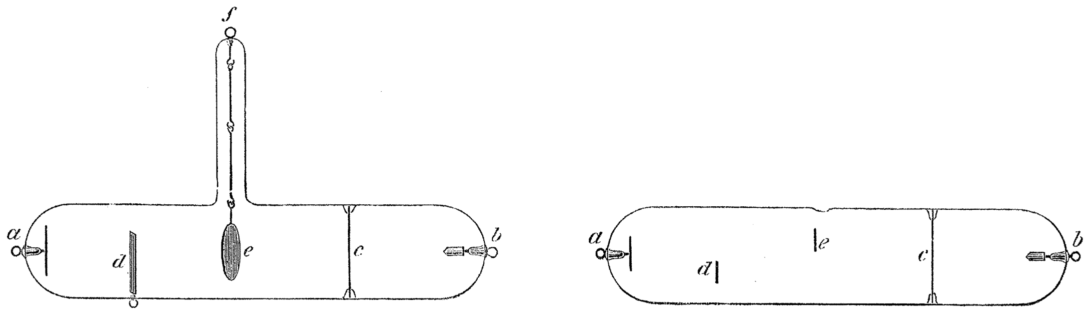
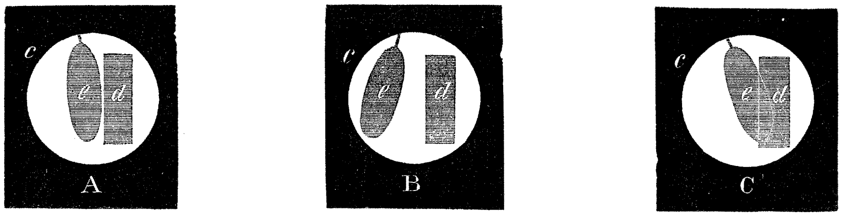


Fig. 10A. Fig. 10B. Fig. 10C.

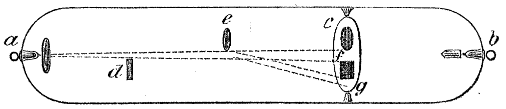


The tube was so adjusted that the pendulum hung free, and a narrow line of molecular discharge passed between the edges of the bar and the pendulum, forming a line of light between the two shadows on the screen (fig. 10A). When the pendulum was set swinging, and the idle pole *f* connected with it was kept insulated, the regular appearance of the moving and fixed shadows was very slightly interfered with. That is to say, the shadows followed the successive positions between those shown in figs. 10B and 10C almost as if they had been cast by a luminous point in place of the negative pole. As the shadow of the swinging pendulum came very near that of the bar, the latter shadow seemed to shrink away, showing that the pendulum itself exerted slight repulsion on the molecules which passed close to its edge.

The pendulum was again set stationary, as shown on the plan (fig. 11), the line of light separating the two being at *f*, so that the appearance on the screen was as shown at fig. 10A. The pendulum pole was then connected with earth, and instantly the line of light which separated the poles moved from *f* to *g* through an angle, measured from *e*, of about 30°, the shadow widening out and getting indistinct at the same time.

When the pole *a* was negative and *b* positive, the bar *d* and pendulum *e* were each found to be positively electrified. The outside of the glass tube, both near the negative pole and near the positive pole, was also positively electrified.

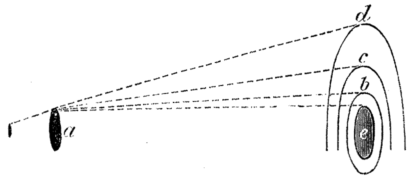
Fig. 11.



The above experiments were tried with 6300 cells, a resistance equal to 800,000 ohms being interposed. The current through the tube was 0·00383 weber. These measurements were taken by Mr. De La Rue, to whom I am greatly indebted for permission to experiment with his magnificent battery, and who himself kindly assisted me in making the arrangements.—August 12, 1879.]

607. These phenomena agree with the explanation above given (604). Experiments recorded in a previous paper (556 to 571) have proved that the velocity of the molecules is greater as the vacuum gets higher, and that in consequence the trajectory of the molecules under the deflecting action of a magnet is flatter at high than at low vacua. The space covered by the penumbra may be taken as representing the size of the shadow when the positive charge of the idle pole is so small as to have little deflecting action on the molecular rays. The deflecting action being constant (like

Fig. 12.



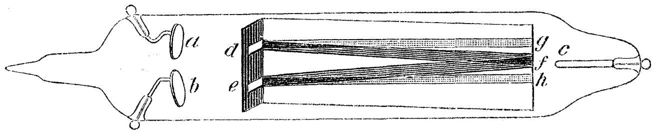
that of the permanent magnet in the experiments just quoted), a different trajectory corresponds to different velocities; therefore at a low vacuum, where the penumbra is not much larger than the original shadow, the molecules pass the object or idle pole *a*, slowly, and are deflected to *b*. At a higher exhaustion the molecular velocity is greater, and the deflecting force having less time to act they go to *c*; whilst at the highest vacuum, when the velocity of the molecules is very great, they are scarcely deflected at all, and proceed to *d*. On allowing the idle pole *a* to remain insulated, its positive charge increases during rarefaction in the same degree as does the negative charge of the molecular stream; the velocity and the deflecting force, therefore, keep about equal, and the result is that the shadow *e* remains now nearly constant at all exhaustions.

It is not unlikely that, at the highest exhaustions, when the penumbra is very large, the negative electricity of the molecular stream overcomes the slight positive charge of the uninsulated idle pole (604) and gives it a negative charge, which causes the stream to be repelled outwards instead of attracted inwards.

608. The coil being connected with an exhausted tube showing any of the phenomena I have already described, the negative terminal was thoroughly well connected with earth. This made no difference whatever in the phenomena observed in the tubes, which took place just as well as if the negative pole had not been connected with earth.

609. It has been shown that the stream of molecules are shot off from the negative pole in a negatively charged condition, and their velocity is owing to the mutual repulsion between the similarly electrified pole and molecules. It became of interest to ascertain whether lateral repulsion was exerted between the molecules themselves. If the stream of molecules coming from the negative pole carried an electric current, two parallel rays should exert mutual attraction; but if nothing of the nature of an electric current was carried by the stream, it was likely that the two parallel rays would act simply as negatively electrified bodies and exert lateral repulsion. This was not difficult to put to the test of experiment.

Fig. 13.



610. A tube was made with two flat aluminium terminals, *a b*, close together at one end, and one terminal, *c*, at the other, as shown in fig. 11. Along the centre of the tube, cutting the axis obliquely, is a screen of mica, painted over with a phosphorescent powder, and between the screen and the double poles, *a b*, is a disc of mica crossing the axis of the tube, and therefore nearly at right angles to the phosphorescent screen. In this mica disc are two slits—one opposite each pole *a* and *b*—running in such a direction that the molecular streams emanating from *a* and *b* when made negative shall pass through the slits, forming two horizontal sheets. These sheets striking against the oblique screen will be made evident as two horizontal lines of light. The poles *a* and *b* were somewhat bent, so that the lines of light were not quite parallel, but slightly converged. The tube being properly exhausted, the pole *a* was made negative, and *c* positive, the lower pole *b* being left idle. A sharp ray of phosphorescent light shot across the screen along the line *d f*. The negative wire was now transferred from *a* to *b*, when a ray of light shot along the screen from *e* to *f*. The two poles *a* and *b* were now connected by a wire, and the two together were made the negative pole. Two lines of light now shone on the screen, but their positions, instead of being, as before, *d f* and *e f*, were now *d g* and *e h*, as shown by the dotted lines. The wire joining the poles *a b* was removed, and the pole *a* made negative; the ray from it followed the line *d f* as before. While the coil was working, another wire hanging loose from the pole *b* was brought up to *a*, so as to make them both negative. Instantly the ray *e h* shot across the screen, and simultaneously the ray *d f*

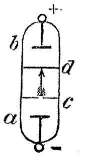
shifted its position up to *d g*. The same phenomena were observed when the pole *b* was connected with the coil, and contact was alternately made and broken with *a*; as the ray *d g* shot across, the ray *e f* dipped to *e h*.

These experiments show that two parallel rays of molecules issuing from the negative pole exert lateral *repulsion*, acting like adjacent streams of similarly-electrified bodies. Had they carried an electric current they should have attracted each other, unless, indeed, the attraction in this case was not strong enough to overcome the repulsion.

611. Many experiments have been made to ascertain the law of the action of magnets and of wires carrying currents, on the stream of molecules.

As an indicator, a small tube, as shown in fig. 14, was employed. The two poles are at *a* and *b*, *a* being the negative. At *c* is a plate of mica with a hole in its centre, and at *d* is a phosphorescent screen. A sharp image of the hole in the mica is projected on the centre of *d*, and the approach of a magnet causes this bright spot to move to different parts of the phosphorescent screen.

Fig. 14.



A large electro-magnet was used, actuated by two GROVE's cells, and the indicator tube was carried round the magnet in different positions and the results noted. The molecular stream when under no magnetic influence passes along the axis of the tube, as shown by the small arrow (fig. 14). It will be seen that the indicator can occupy three different directions in respect to the magnet. The magnet being held horizontally, the direction of the molecular stream may be parallel to the axis, tangential to it, or at right angles to it. In either of these positions, also, the stream may be directed one way or the other (by turning the tube round endwise). In these different positions various results are obtained which are easily illustrated with a solid model, but are somewhat complicated to explain by means of flat drawings. In figs. 15, 16, and 17 I have separated the effects one from the other, and I hope with the accompanying description that they will be intelligible.

612. Fig. 15 shows the electro-magnet lying horizontally, the current passing in such a direction that the S pole is on the left. The indicator tube is supposed to be held in front of the magnet and at right angles to its axis, the stream of molecules moving, when not under magnetic influence, vertically up or down according as the negative electrode is at the bottom or the top. The black arrows represent the different positions in which the indicator tube was held, and the direction of the arrow shows the direction of the molecular stream. The point of the arrow would fall on the phosphorescent screen, and the feather end represents the hole in the mica plate.

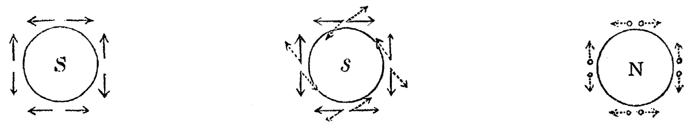
The dotted arrows represent the directions taken by the molecular stream when the current circulated round the magnet. The blunt end is stationary, as the starting point of the molecules—the hole in the mica plate—did not move; the point shows the direction in which the spot of light moved across the phosphorescent screen, and the slope of the dotted arrow shows the deflection given to the molecular stream. The feathered arrows have nothing to do with the molecular stream, but indicate the direction of the electric current round the magnet.

613. When the molecular ray was at the S end, the movement was to the right when the stream was upwards, and to the left when the stream was downwards. A section at this point (along the line *a b*) shows no movement when looking in the direction of the axis, as the rays only move to and fro along the line of sight.

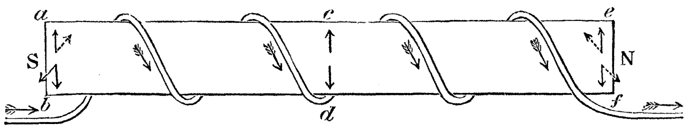
In the centre of the magnet the rays are moved inwards or outwards according to their direction, the upward stream going from, and the downward stream to the observer. This cannot be seen on the horizontal magnet but is shown in the section across *c d*. Although this section is supposed to be across the centre of the magnet, I have marked it S, as the observer is supposed to be looking at it from the S end.

At the N end of the magnet the action is the same in degree, but opposite in direction to that at the S end. It is shown by the section across *e f*.

Fig. 15.



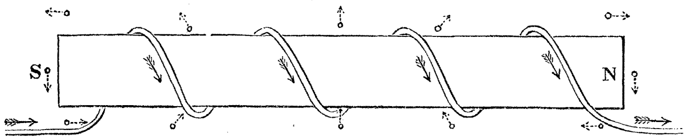
Section across a b. *Section across c d.* *Section across e f.*



Molecules moving up and down.

614. The magnet being in the same position as before, the indicator tube was turned so that the stream of molecules should move in a direct line to or from the observer,

Fig. 16.



Molecules moving to the observer.

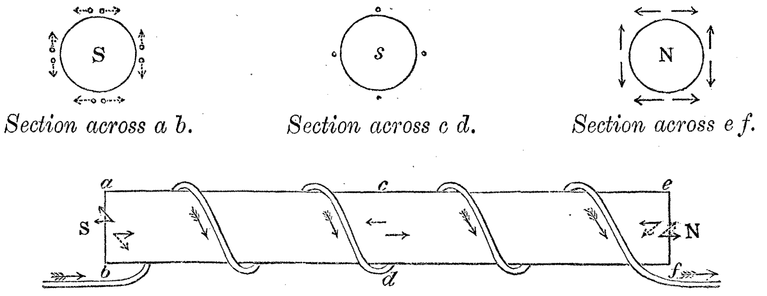
and it was carried round in a vertical plane passing through the axis of the magnet. The dotted arrows in fig. 16, show the deflection suffered by the stream of molecules in the different positions. The line of molecules when not under magnetic influence is supposed to be coming towards the observer. It can only be seen in section as a dot at the base of each arrow.

615. When the indicator tube is in front of the magnet, so that the molecular stream goes to the right or to the left, as shown by the black arrows in fig. 17, the deflection at the S end is upwards for left-handed rays, and downwards for right-handed rays. The section across *a b* shows the direction taken by the molecules when the magnetism is acting. When not under magnetic influence the stream can only be represented in this section by dots at the base of each arrow.

In the central position *c d*, no movement is noticed, whatever way the ray is viewed.

At the N end of the magnet the action is exactly opposite to that at the S end.

Fig. 17.



Molecules moving right and left.

616. When the indicator tube is held so that the molecular rays travel along the prolongation of the axis of the magnet, no movement to one side or the other is given to them, but the whole bundle twist round the axis to a greater or less extent as they are near to or far from the magnetic pole. This twist is well seen in some tubes where the green phosphorescence of the glass is strongly excited by rays driven from a pole some distance off. The rays appear to be drawn in, vortex-fashion, and the green lines on the glass strikingly resemble some of the spiral nebulæ. All the results above described can be obtained when a wire helix carrying a current is used instead of an electro-magnet; they are however much fainter.

617. A long tube was made similar to the small indicator shown in fig. 14, but having a molecular trajectory six inches long. It was only exhausted to the point at which the image of the spot was just seen sharply defined on the screen, as at higher exhaustions the action of magnetism is less. The phosphorescent screen was divided into squares for convenience of noting the deflection of the spot of light. So sensitive was this to magnetic influence, that when the tube was placed parallel to the earth's equator, the earth's magnetism was sufficient to cause the spot to move 5 millims. away from the position it occupied when parallel to the dipping needle (in which position the earth's magnetism did not appear to act). When held equatorially and rotated on its axis, the spot of light being always driven in one direction independent of the rotation of the tube, appeared to travel round its normal position in a circle 10 millims. diameter.

618. I have long tried to obtain continuous rotation of the molecular rays under magnetic influence, analogous to the well known rotation obtained at lower exhaustions. Many circumstances had led me to think that such rotation could be effected. After many failures an apparatus was constructed as follows, which gave the desired results.

Fig. 18.

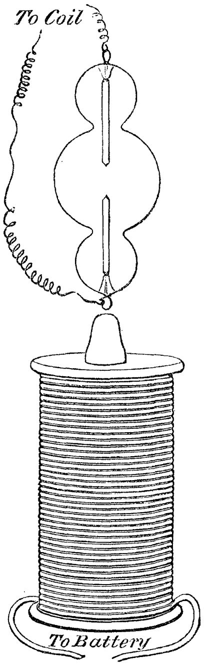
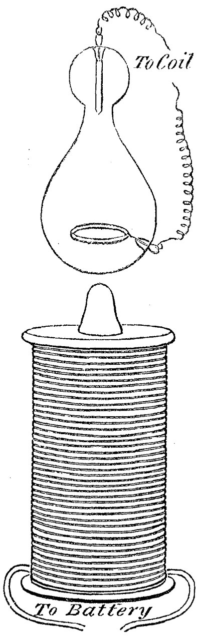


Fig. 19.



A bulb (fig. 18) was blown of German glass, and a smaller bulb was connected to each end of the larger bulb by an open, very short neck. At each extremity was a long aluminium pole projecting partly into the large bulb and turned conical at the end. After good exhaustion the passage of an induction current through this apparatus fills the centre bulb with a very fine green light, whilst the neck surrounding the pole which happens to be negative is covered with two or three dark and bright patches in constant motion, following each other round first one way and then the other, constantly changing direction and velocity, sometimes dividing into other patches, and at others fusing together into one. After a little time, probably owing to the magnetism of the earth, or that of the core of the induction coil not far off, the movements sometimes become more regular, and slow rotation takes place. The patches of light concentrate into two or three, and the green light in the bulb gets more intense along two opposite lines joining the poles forming two faintly outlined patches, which slowly move round the bulb equatorially, following each other a semi-circumference apart.

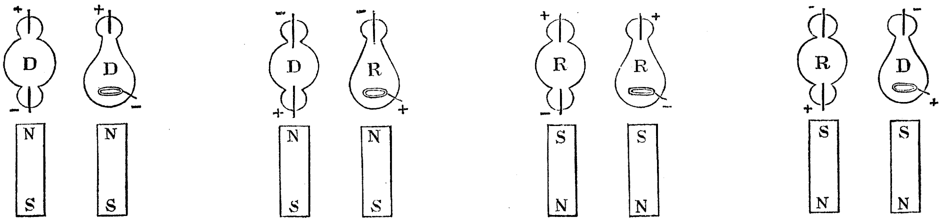
An electro-magnet placed beneath in a line with the terminals (fig. 18), converts these undecided movements into one of orderly rotation, which keeps up as long as the coil and magnet are at work.

619. In order to compare accurately the behaviour of the molecular streams at high exhaustions with that of the ordinary discharge through a moderately rarefied gas,

another tube was taken having the upper pole an aluminium wire, and the lower one a ring, fig 19. It was only exhausted to such a point that the induction spark should pass freely from one pole to the other in the form of a luminous band of light, this being the form of discharge usually considered most sensitive to magnetic influence. This tube was also mounted over an electro-magnet, and the two sets of apparatus being actuated successively with the same coil and battery the following observations were made.

620. The tubes will be distinguished by the terms "high vacuum" (fig. 18) and "low vacuum" (fig. 19). The rotation produced in each tube will be recorded in the direction in which it would be seen by an observer above, looking vertically down on the tube, his eye being in a line with the terminals and with the axis of the magnet. When the rotation thus viewed is in the direction of the hands of a watch, it is called *direct;* the opposite movement being called *reverse.* To facilitate a clear appreciation of the actions, an outline sketch accompanies each experiment. The shape of the tube shows whether it is the high or low vacuum tube, and the letter D or R shows the direction of rotation.

Fig. 20.



Case a. *Case b.* *Case c.* *Case d.*

621. *a.* Upper pole of electro-magnets *north.*
Induction current passing through tubes so as to make the top electrode *positive.*
Rotation in the high vacuum *direct.*
Rotation in the low vacuum *direct.*

b. Upper pole of magnets *north.*
Top electrode of tubes *negative.*
Rotation in high vacuum *direct.*
Rotation in low vacuum *reverse.*

c. Upper pole of magnets *south.*
Top electrode of tubes *positive.*
Rotation in high vacuum *reverse.*
Rotation in low vacuum *reverse.*

d. Upper pole of magnet *south.*
Top electrode of tubes *negative.*
Rotation in high vacuum *reverse.*
Rotation in low vacuum *direct.*

622. These experiments show that the law is not the same at high as at low exhaustions. At high exhaustions the magnet acts the same on the molecules whether they are coming to the magnet or going from it, the direction of rotation being entirely governed by the magnetic pole presented to them, as shown in cases *a* and *b* where the north pole rotates the molecular stream in a *direct* sense, although in one case the top electrode is positive and in the other negative. Cases *c* and *d* are similar; here the magnetic pole being changed, the direction of rotation changes also. The direction of rotation impressed on the molecules by a magnetic pole is opposite to the direction of the electric current circulating round the magnet.

623. The magnetic rotations in low vacua are not only fainter than in high vacua, but they depend as much on the direction in which the induction spark passes through the rarefied atmosphere, as upon the pole of the magnet presented to it. The luminous discharge connecting the positive and negative electrode carries a current, and the rotation is governed by the mutual action of the magnet on the perfectly flexible conductor formed by the discharge.

In high vacua, however, the law is not the same, for in cases *b* and *d* similar arrangements produce opposite rotations in high and in low vacua. The deflection exerted by a magnet on the molecular stream in a high vacuum may be compared to the action of a strong wind blowing across the line of fire from a mitrailleuse. The deflection is independent of the to-and-fro direction of the bullets, and depends entirely upon the direction of the wind.

624. I have already mentioned that platinum will fuse in the focus of converging molecular rays projected from a concave pole (582). If a brush of very fine iridio-platinum wire, which has a much higher fusing point than platinum, be used to receive the molecular bombardment, a brilliant light is produced, which might perhaps be utilised. By drawing the focus to the side of a glass tube by means of a magnet, a series of phenomena take place. The brilliant green phosphorescence first developed by the impact of the focus rapidly fades out owing to the heat. The centre of the focus becomes dark brown, and if the coil is now stopped this brown spot remains permanent as a superficial stain on the glass, and the glass has lost its power of phosphorescing at this place. If, however, the focus is kept steadily on one spot a sparkling appearance is noticed, and a superficial disintegration takes place as if the glass were fusing. Thick tubes now crack at this stage, but thin bulbs soften by the heat, when the pressure of the atmosphere forces the glass in and bursts through a fine hole which comes in the centre of the indentation.

625. The dark brown spot which forms in the focus is only a concentration of a stain which gradually forms on anything which is long submitted to molecular bombardment when aluminium and probably other poles are used. It has nothing to do with a reduction of the constituents of the glass, for it forms equally well on the polished surface of a diamond. It is not aluminium, for it is not dissolved by boiling in strong potash solution or in chlorhydric acid; and is only slowly attacked by *aqua-*

regia. Under the highest microscopical power it shows only as a stain, with no signs of granulation.

626. A piece of glass from a tube which had cracked at incipient fusion was examined under the microscope. The surface appeared curiously crumpled up and filled with minute bubbles, as if the glass had been boiling.

Another piece of apparatus was constructed, in which a plate of German glass was held in the focus of the molecular bombardment. The vacuum was so good that no hydrogen or other lines could be seen in the spectrum of the emitted light. The focus was now allowed to play on the glass, when the glass soon became red hot. Gas appeared in the tube, and hydrogen lines now were visible in the spectrum. The gas was pumped out until hydrogen disappeared from the spectrum. It was now possible to heat the glass to dull redness without hydrogen coming in the tube; but as soon as the heat approached the fusing point, the characteristic lines appeared. It was found that however highly I heated the glass, and then pumped the tube free from hydrogen, I had only to heat the glass to a still higher temperature to get a hydrogen spectrum in the tube. I consider the hydrogen comes from vapour of water, which is obstinately held in the superficial pores, and which is not entirely driven off by anything short of actual fusion of the glass. The bubbles noticed when the disintegrated and fused surface of the tube was examined under the microscope are probably caused by escaping vapour of water.

627. When the negative discharge has been playing for some time on German glass, so as to render it strongly phosphorescent, the intensity of glow gradually diminishes (592). Some of this decline is due to the heating of the glass or to some other temporary action, for the glass partially recovers its property after rest; some is due to a superficial change of the surface of the glass; but part of the diminished sensitiveness is due to the surface of the glass becoming coated with this brown stain.

628. The luminous image of a hole in a plate of mica was projected from a *platinum* plate used as a negative pole, to the side of a glass bulb. The coil was kept playing for some time until the inside of the bulb was thoroughly darkened by projected platinum. Although a bundle of molecular rays could be seen all the time passing from the platinum, through the hole in the mica, to the glass, where it shone with a bright green light, I could detect no trace of extra darkening when the part of the glass formerly occupied by the green spot was carefully examined. Platinum is a metal which flies off in a remarkable manner when it forms the negative pole. It therefore appears from this experiment that the molecular stream does not consist of particles of the negative pole shot off from it.

629. One of the most striking of the phenomena attending this research has been the remarkable power which the molecular rays in a high vacuum possess of causing phosphorescence in bodies on which they fall. Substances known to be phosphorescent under ordinary circumstances shine with great splendour when subjected to the negative discharge in a high vacuum. Thus, a preparation of sulphide of calcium, much

used now in Paris for coating clock faces, which remain luminous after dark, is invaluable in these researches for the preparation of phosphorescent screens whereon to trace the paths and trajectories of the molecules. It shines with a bright blue-violet light, and, when on a surface of several square inches, is sufficient to light up a room. Modifications of these phosphorescent sulphides shine with a yellow, orange, and green light.

630. The only body I have yet met with which surpasses the luminous sulphides both in brilliancy and variety of colour is the diamond. Most of these gems, whether cut or in the rough, when coming from the South African fields, phosphoresce of a brilliant light blue colour. Diamonds from other localities shine with different colours, such as bright blue, pale blue, apricot, red, yellowish-green, orange, and bright green. One beautiful green diamond in my collection when phosphorescing in a good vacuum gives almost as much light as a candle: the light is pale green—almost white. A beautiful collection of diamond crystals kindly lent me by Professor MASKELYNE phosphoresce with nearly all the colours of the rainbow, the different faces glowing with different shades of colour.

631. Next to the diamond, alumina in the form of ruby is perhaps the most strikingly phosphorescent stone I have examined. It glows with a rich, full red; and a remarkable feature is that it is of little consequence what degree of colour the earth or stone possesses naturally, the colour of the phosphorescence is nearly the same in all cases; chemically precipitated amorphous alumina, rubies of a pale reddish-yellow, and gems of the prized "pigeon's blood" colour, glowing alike in the vacuum, thus corroborating E. BECQUEREL'S results on the action of light on alumina and its compounds in the phosphoroscope ('Annales de Chimie et de Physique,' ser. 3, vol. lvii.). Nothing can be more beautiful than the effect presented by a mass of rough rubies when the molecular discharge plays on them in a high vacuum. They glow as if they were red hot, and the illuminating effect is almost equal to that of the diamond under similar circumstances.

632. By the kindness of M. CH. FEIL, who has placed large masses of his artificial ruby crystals at my service, I have been enabled to compare the behaviour of the artificially formed crystals with that of the natural ruby. In the vacuum there is no difference whatever; the colour of the phosphorescence emitted by M. FEIL'S crystals is of just as intense a colour, and quite as pure in character, as that given by the natural stone. This affords another proof, if one were needed, that Messrs. FREMY and FEIL have actually succeeded in the artificial formation of the veritable ruby, and have not simply obtained crystals which imitate it in hardness and colour.

633. The appearance of the alumina glow in the spectroscope is remarkable. There is a faint continuous spectrum ending in the red somewhere near the line B; then a black space, and next an intensely brilliant and sharp red line to which nearly the whole of the intensity of the coloured glow is due. The wave-length of this red line, which appears characteristic of this form of alumina, is 689·5 m.m.m., as near as I can measure in my spectroscope; the maximum probable error being about $\pm$·3.

This line coincides with the one described by E. BECQUEREL as being the most brilliant of the lines in the spectrum of the light of alumina, in its various forms, when glowing in the phosphoroscope.

This coincidence affords a good proof of the identity of the phosphorescent light, whether the phosphorescence be produced by radiation, as in BECQUEREL'S experiments, or by molecular impact in a high vacuum.

634. I have been favoured by my friend Professor MASKELYNE with the following notes of results obtained on submitting to the molecular discharge various crystals which he lent me for the purpose of these experiments :—

"Diamond crystals. A very small crystal, exhibiting large cube faces with the edges and angles truncated, was of a rich apricot colour, the dodecahedral faces of a clear yellow, and the octahedral of another yellow tint. No polarisation of the light was detected. Some were opaque ; some gave a bluish hazy light.

"Emerald. A small hexagonal prism gave out a fine crimson-red colour. The light was polarised, apparently completely, in a plane perpendicular to the axis ; this would correspond therefore to extraordinary rays which in emerald, as a negative crystal, represent the quicker rays vibrating presumably parallel to the optic axis of the crystal.

"Other emeralds behaved in the same way, though the illumination in two others experimented with appeared confined more particularly to one end—the end opposite to that at which the crystals presented some (in one instance fine) terminal faces.

"Beryls exhibited no corresponding phenomena.

"Sapphires gave out a bluish-grey light, distinctly polarised in a plane perpendicular to the axis. In this case, again, the ray developed corresponds to the extraordinary or quicker ray.

"Ruby gives out a transcendently fine crimson colour, exhibiting no marked distinction in the plane of its polarisation, though in one part of a stone the colour was extinguished by a NICOL prism with its long diagonal parallel to the axis of the crystal, Here, therefore, also the light was that of the extraordinary ray.

"It seemed desirable to determine the nature of the phenomena in the case of positive crystals, and accordingly crystals of quartz, phenakite, tinstone, and hyacinth, (zircon) were placed in a tube and experimented on.

"The only crystals that gave definite results were tinstone and hyacinth. A small crystal of the former mineral glowed with a fine yellow light, which was extinguished almost entirely when the long diagonal of the NICOL was perpendicular to the axis of the crystal.

"Here, therefore, the plane of polarisation of the emitted light was parallel to the axis of the crystal, and here it is again the quicker, though in this case (of an optically positive crystal) it is the ordinary ray which corresponds to the light evoked by the electric stream.

"So far, then, the experiments accord with the quicker vibrations being called into play, and therefore in a negative crystal the extraordinary and in a positive crystal the ordinary is the ray evoked.

"A crystal of hyacinth, however, introduced a new phenomenon. In this optically positive crystal the ordinary ray was of a pale pink hue, the extraordinary of a very beautiful lavender-blue colour. In another crystal, like the former from Expailly, the ordinary ray was of a pale blue, the extraordinary of a deep violet. A large crystal from Ceylon gave the ordinary ray of a yellow colour, the extraordinary ray of a deep violet-blue.

"Several other substances were experimented on, including some that are remarkable for optical properties, among which were tourmaline, andalusite, enstatite, minerals of the augite class, apatite, topaz, chrysoberyl, peridot, garnets of various kinds, and parisite. So far, however, these minerals have given no result, and it will be seen that the crystals which have thus far given out light in any remarkable degree are, besides diamond, uniaxal crystals (an anomaly not likely to be sustained by further experiment); and the only conclusion arrived at is, that the rays whose direction of vibration corresponds to the direction of maximum optical elasticity in the crystal are always originated where any light is given out. As yet, however, the induction on which so remarkable a principle is suggested cannot be considered sufficiently extended to justify that principle being accepted as other than probable."