V. THE BAKERIAN LECTURE.—*On the Illumination of Lines of Molecular Pressure, and the Trajectory of Molecules.*

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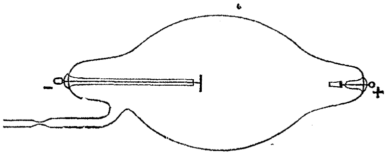
[PLATE 14.]

CONTENTS.

THE INDUCTION CURRENT THROUGH RAREFIED GASES. DARK SPACE ROUND THE NEGATIVE POLE.

486. When the spark from a good induction coil traverses a glass tube containing a rarefied gas, certain phenomena are observed which vary greatly with the kind of gas and the degree of exhaustion. There is one appearance, however, which is constant in all the gases which I have examined, and within very wide limits of pressure, viz.: the well-known dark space round the negative pole. I have long been impressed with the idea that this dark space coating the pole was in some way related to the layer of molecular pressure causing movement in the radiometer, and the following experiments were instituted with the object of testing this hypothesis.

Fig. 1.



A glass bulb (fig. 1) was furnished with platinum wire terminals sealed into the glass, ending outside in loops and inside in aluminium poles; the positive pole being a wire and the negative pole a disk about 10 millims. diameter, bare in front and covered with mica at the back. The bulb being full of dry air and connected with the SPRENGEL pump, was exhausted. An induction coil capable of giving sparks 68 millims. long in air when actuated by 3 GROVE'S cells, was connected with the terminals, the disk being always negative except when otherwise stated.

487. At a pressure of 20 millims. of mercury a soft velvety halo of violet light commenced to form on the edges of the disk; as the exhaustion proceeded, this glow flickered over different parts of the surface, till at a pressure of 15 millims. it remained steady all over the front of the disk.

Plate 14, fig. 2, shows the appearance at a pressure between 15 and 20 millims.: *a* shows the glow creeping over the disk as the exhaustion increases; *b* is the appearance on the mica side of the disk; and *c* shows the edge of the disk. By close examination edge-wise it can be seen that the glow and the metal are not in contact, but are separated by a very minute interval.

At a pressure of 7·5 millims. the glow is thicker, and the black space easily visible. At 1·6 millims. the appearance is as shown in Plate 14, fig. 3. The dark space is half a millim. in thickness, and the glow is very bright. As the exhaustion proceeds the appearance round the negative disk goes through the stages shown in Plate 14, figs. 4, 5, 6, and 7, the glow diminishing in intensity and the dark space widening out; the outline still being distinctly shown. Plate 14, fig. 7, shows the appearance at a pressure of ·078 millim., the thickness of the dark space being 8 millims.

488. At any particular pressure the dark space separating the glow from the metal disk can be slightly altered by varying the power of the contact breaker. When it is screwed so as to increase the intensity of the spark the dark space slightly contracts, and when the intensity of the spark is diminished the dark space slightly expands, the variation in size being about 1 millim. For the same intensity of spark and degree of exhaustion the dark space is always uniform in size.

489. Another bulb was now made of a different construction, to ascertain if the size of the dark space varied with the distance separating the poles. Each pole consisted of a flat metal disk, one being fixed and the other capable of sliding along a glass tube fitting loosely into a wider tube. By tapping the tube, the adjustible pole can be brought close to the fixed pole or removed some distance from it, contact between the disk and the outer loop being always preserved by wires in the sliding tubes.*

As the exhaustion proceeded the phenomena observed were similar to those already described. It was found that the dimensions and thickness of the dark space did not vary, whatever was the distance separating the fixed and sliding pole.

490. The battery power actuating the coil was also varied between 1, 2, 3, and 4

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* The device of making one of the poles of a vacuum tube extensible so as to alter the distance between the two poles has already been adopted by Mr. SPOTTISWOODE. Experiments with such a tube are described by Messrs. DE LA RUE and MÜLLER in the Phil. Trans. for 1878, p. 163.

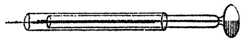
cells, but I could detect no alteration in the size of the dark space so long as the pressure remained constant. The only effect was to cause an increase or decrease in luminosity.

Air was let in and exhaustion recommenced several times. At the same exhaustion the dimensions of the dark space were always the same. It is indeed easy to tell the degree of exhaustion by measuring the thickness of the dark space. On afterwards taking the pressure in the usual way the agreement is seen to be close enough for ordinary observations.

When only one pole of the coil is connected with one pole of the tube the same sized dark space is seen round the pole as when the two poles are connected, but the light is faint, and the room requires to be darkened for accurate observations.

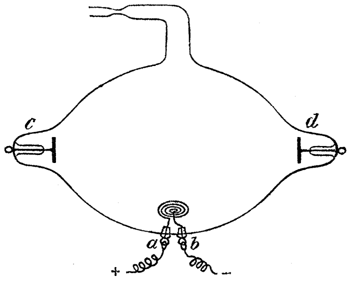
491. The sliding pole was now removed; one-half was coated with lampblack as shown in fig. 8, and it was replaced. Exhaustion was recommenced, and at a convenient pressure the coil was attached. The dark space round the pole was now seen to have lost its uniform thickness ; it was 1 millim. thick over the metallic half and 1·5 millims. thick over the lampblack half. On continuing to exhaust, the dark space became larger ; that over the lampblack keeping about the same proportion in excess of that over the bare metal. As the exhaustion increased the size of the dark space over the platinum gained a little more upon that over the bare metal.

Fig. 8.



492. A tube was made, as shown in fig. 9 ; *a b* are the two ends of a long platinum wire, coiled into a close spiral, and sealed in the bulb. The coils of the wire are not in contact, and the ends are sealed in separately, so that the spiral can be made red hot by connecting the wires *a* and *b* with a battery. *c* and *d* are two flat aluminium poles. An apparatus was connected with the pump whereby different gases could be introduced into the bulb and experimented with at different pressures.

Fig. 9.



493. The following experiments were tried with air :—At a pressure of 3·25 millims. the dark space round the negative pole was 1·75 millims. from the pole. The size and appearance were the same whether the negative pole was *c* or *d*, or whether the spiral *a b* was made negative. The induction spark was passed between *a b* (negative) and *c*

(positive); the dark space, as already mentioned, was 1·75 millims. from the platinum spiral pole; the wires *a b* were now connected with 3 GROVE's cells through a contact key, the induction spark passing at the same time. On pressing the key the spiral *a b* became ignited to bright redness, and the dark space immediately expanded from 1·75 to 2·5 millims. in thickness. On cutting off the igniting current the dark spheroid slowly contracted to its former dimensions.

494. At a pressure of 1·5 millims. the dark spheroid surrounded the platinum spiral to a distance of 4·5 millims. Igniting the spiral with the battery caused the dark space to expand considerably, but the amount of expansion could not be accurately seen, owing to its outline becoming very indistinct after it had expanded to about 7 millims. semi-diameter.

495. The poles *c* and *d* were connected with the induction coil, the spiral *a b* being still attached to the 3 GROVE's cells. The whole tube was filled with light, and I then made battery contact with the spiral, igniting it to redness. No space could be seen round the hot wire, and no alteration was observed in the illumination of the tube.

496. Hydrogen gas was now passed into the tube, and after several times exhausting and refilling with hydrogen the following experiments were tried: the spiral *a b* being always the negative pole of the induction coil, and also being connected with the 3-cell GROVE's battery.

At a pressure of 5 millims. the dark spheroid extended 1·75 millims. from the pole. On making the pole red hot the dark space expanded to 2·5 millims. in thickness.

At a pressure of 3·75 millims. the dark spheroid was 2·25 from the pole, expanding to 3·75 millims. when the pole was ignited.

At a pressure of 2·75 millims. the expansion of the dark space on heating the pole was from 4 millims. to 6·5 millims.

The phenomena in hydrogen are therefore similar to those in air, but the dark space round the negative pole is larger for the same degree of exhaustion.

497. Carbonic acid was then passed into the tube, and after several fillings and exhaustions the following experiments were tried:—

At a pressure considerably less than that at which the dark space would appear in air or hydrogen, there was no appearance of it in carbonic acid.

At a pressure of 4 millims. the dark space was ·75 millim. thick. At a pressure of ·62 millim. its thickness was 2·5 millims., and at a pressure of ·27 millim. its thickness was 4 millims. Igniting the negative pole caused expansion of the spheroid, but not to so great an extent as if the gas had been air or hydrogen.

ILLUMINATION OF LINES OF MOLECULAR PRESSURE.

498. These experiments appear to prove three things:—

a. Setting up an intense excitement in a disk of metal by electrical means produces a molecular disturbance which affects the surface of the disk and the surrounding gas.

When the gas is dense the disturbance extends a short distance only from the metal; but as rarefaction proceeds the layer of molecular disturbance increases in thickness. In air at a pressure of ·078 millim. this molecular disturbance extends for at least 8 millims. from the surface of the disk, forming an oblate spheroid around it. Had the pole been a point the spheroid would have become a sphere 16 millims. diameter.

b. The diameter of this dark space varies with the exhaustion; with the kind of gas in which it is produced; with the temperature of the negative pole; and, in a less degree, with the intensity of the spark. For equal degrees of exhaustion it is greatest in hydrogen and least in carbonic acid as compared with air.

c. The shape and size of this dark space do not vary with the distance separating the poles; nor, except very slightly, with alteration of battery power, or with intensity of spark. When the power is great the brilliancy of the unoccupied parts of the tube overpowers the dark space, rendering it difficult of observation; but on careful scrutiny it may still be seen unchanged in size, nor does it alter even when, with a very faint spark, it is scarcely visible. On still further reduction of the power it fades entirely away, but without change of form.

499. I consider, therefore, I am justified in assuming that if the molecular disturbance communicated to the surrounding gas by the metal were to be further reduced in intensity, the spheroid would still remain the same for the same pressure, although invisible. If instead of exciting the disturbance in the metal pole by electrical means, I effect the same by heating it to redness, the spheroid of molecular disturbance in the surrounding gas would probably be there; and if the disturbance is only produced by allowing light to shine on the metal plate, we may still imagine the molecular disturbance to extend around the plate, although vastly reduced in intensity.

500. The vibrations communicated by the induction spark to a metal plate are doubtless different in kind as well as in intensity from those caused by heating the plate, for the electrical excitement induces luminosity in the gas, although the metal pole is only slightly heated; while igniting the metal to bright redness in the absence of electrical excitement from the induction coil causes no luminosity in the surrounding gas.

501. Numerous experiments have been tried with the object of seeing if this *visible* layer of molecular disturbance was the same as the invisible layer of molecular pressure or stress, the investigation of which has formed the subject of many papers presented to the Royal Society*. Small exploring flies similar to the one described in a former paper (417)† were moved about in various parts of the bulb, both inside and outside the spheroid, but the results were most contradictory, and were difficult to obtain at all owing to the electrification of the fly.

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* Phil. Trans., Vol. 164, p. 501; Vol. 165, p. 519; Vol. 166, p. 325; Vol. 166, p. 355; Vol. 169, p. 243; Vol. 170, p. 87.

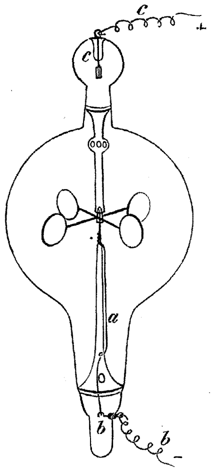
† Ibid., Vol. 170, p. 103.

ELECTRICAL RADIOMETERS.

502. Successful observations were ultimately obtained by making radiometers with metallic vanes, in the following manner :—

The needle point on which the fly rotates is connected with a copper wire, *a*, fig. 10, passing down the central tube and attached to the platinum terminal, *b*, sealed through the glass. The other terminal, *c*, passes through the top of the bulb, and is of aluminium wire inside. The vanes are of aluminium, lampblacked on one side, and connected by aluminium arms to a hard steel cup ; the whole fly is therefore in metallic connection with the lower terminal.

Fig. 10.



503. At a moderately low pressure, the coil being attached and the fly being made the negative pole, a faint halo appears on the bright side of the vanes, and there is a tendency to negative rotation. As the exhaustion proceeds, the dark space appears and gradually widens out. The space on the black side is nearly double the thickness of that on the bright side, but is fainter (491) ; on exhausting still more, the dark space widens out until it forms a large, irregular shaped, oval round each vane. Whilst the dimensions of this oval are small, the fly does not move definitely one way or the other, but when the dark space on the lampblacked side has grown till its luminous boundary touches the glass, positive rotation commences, and continues with increasing speed as the exhaustion increases. The difference in size between the dark spaces on each side of the vanes being but small, that from the bright side soon impinges against the glass, and prevents the positive rotation from acquiring much speed.

504. Another instrument was therefore made similar to the one last described, but having one side of each metallic vane covered with a thin piece of mica. It was connected with the coil, and experiments tried as exhaustion proceeded.

At a pressure of 4·5 millims. a halo of a velvety violet appearance forms on the metallic side of two of the vanes only, the others being dark. The movement is of a negative tendency.

At a pressure of 1·4 millims. the bright velvety light has spread over all four vanes on their metallic sides. With the screw of the coil arranged to give a faint spark the movement is negative. If a Leyden jar is inserted, or the contact screw turned to give strong sparks, the movement is positive. Inserting the jar makes the halo fainter. The best pressure for negative rotation is 1·14 millims.

When the pressure is ·51 millim., the dark space on the metallic side extends nearly to the glass, and the whole inside of the bulb is luminous; the rotation is now always positive with the coil. Introducing a piece of wet string into the circuit causes the vanes to go negatively.

As the exhaustion proceeds, the dark space widens out and flattens itself against the glass, the positive rotation getting faster until the maximum is reached. Exhaustion beyond that point causes the speed to diminish, but I cannot get negative rotation again by any amount of over exhaustion.

505. Two radiometers of this kind were made and sealed off, one at a pressure of ·19 millim., showing good positive rotation, and the other at a pressure of 1·14 millims, showing negative rotation. Connecting the two in series, that is to say, the vanes forming the negative pole of one with the positive of the other, and passing the induction current through, caused them both to rotate at the same time, one positively and the other negatively.

506. The vanes of the radiometer were now made of aluminium cups (334) slightly favourably presented to the side of the glass. They were almost hemispheres, bright on both sides. The other parts of the radiometer remained as before.

When the exhaustion is low and the induction coil is connected, the fly rotates negatively. This is caused by the electrified air flying off the edges of the cups, and driving them round like the well-known electrical fly. Luminosity appears on the cups at a pressure of 3·5 millims., and as the exhaustion proceeds it spreads over each side and is separated by a dark space. This widens out, retaining as much as possible the shape of the cup, passing successively through the appearances shown in Plate 14, fig. 11, *a, b, c, d,* and *e.* The luminous margin to the dark space is concentrated at the concave side of the cup, forming a luminous centre, and widens out at the convex side. As soon as the luminous boundary of the dark space reaches the side of the glass positive rotation commences. On continuing the exhaustion, the dark space becomes flattened against the glass, and the rotation becomes more rapid. At higher exhaustions, the dark spaces which surround each cup in the form of an irregular ellipsoid drawn in at the focus of the cup, touch one another. They now act as if they were solid elastic bodies, and become flattened out along the lines of contact (the distance between two cups not being large enough for complete ellipsoids) and form broad longitudinal lines of light down the bulb between each pair of cups, the rest of the bulb being comparatively dark. These lines are nearer the concave than the convex side, and turn with the fly.

507. The train of reasoning carried out in pars. 498, 499, and 500, is therefore seen

to be well supported by experiment, and justifies the theory that the induction spark actually illuminates the lines of molecular pressure caused by the electrical excitement of the negative pole. The thickness of the dark space is the measure of the length of the path between successive collisions of the molecules. The extra velocity with which the molecules rebound from the excited negative pole keeps back the more slowly-moving molecules which are advancing towards the pole. The conflict occurs at the boundary of the dark space, where the luminous margin bears witness to the energy of the discharge. When the exhaustion is sufficiently high for the length of path between successive collisions to be greater than the distance between the fly and the glass, the swiftly-moving rebounding molecules spend their energy, in part or in whole, on the sides of the vessel, and a production of light accompanies this sudden arrest of velocity.

CONVERGENCE OF MOLECULAR RAYS TO A FOCUS.

508. In the sixth part of my researches on "Repulsion resulting from Radiation," which was presented to the Royal Society in June last, I gave at par. 415 a theoretical explanation of the movement of radiometer flies with curved surfaces, on the supposition that the lines of molecular pressure acted in a direction normal to the surface. In the figures illustrating this theory (fig. 14, A and B, pars. 415 and 416) I drew the lines of pressure radiating outwards from the convex surface, and predicted their converging to a focus and thence diverging at the concave surface. These figures were drawn long before the experiments just described were commenced, and it is a corroboration almost amounting to absolute proof that the theory was correct, to see how well those old drawings represent the actual lines of pressure as illuminated by the induction spark.

509. The convergence of the lines of force to a focus, demanded closer investigation than was possible when the cup was in rapid rotation. A bulb was therefore made similar in general character to the electrical radiometers just described, but having the cup-shaped negative pole fixed instead of movable. Exhaustion was proceeded with, and the successive appearances noted were like those shown in fig. 11. On further continuing the exhaustion, the dark space spreads out still further, and the focus of light converging from the concave side falls on the luminous boundary. Inside this focus the rays can be seen converging, and are of a violet colour. Outside the line bounding the dark space the rays diverge from the focus, and are of a lighter colour than those inside; the whole appearance being strikingly similar to the rays of the sun reflected from a concave mirror through a foggy atmosphere.

GREEN PHOSPHORESCENT LIGHT OF MOLECULAR IMPACT.

510. When the exhaustion approaches 30 M,[*] a new phenomenon makes its appearance. The dark space has spread out so much that it nearly fills the bulb; the

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[*] M signifies the millionth of an atmosphere.

violet light by which the focus was rendered visible has become so faint as to be difficultly traced, but with care it can be seen converging to a focus beyond the focal point noticed at lower exhaustions. At the part of the bulb on which the rays impinge, a faint spot of greenish-yellow light is observed, sharp in outline. On exhausting to 14 M, and making the cup the negative pole of the coil, the projection from the cup is represented by a brilliant green spot of light about 7 millims. diameter, and the focus can scarcely be traced. The rest of the bulb is nearly dark, but at those parts furthest removed from the negative pole the faintly luminous boundary of the dark space can still be seen. A little blue light is seen round the positive pole extending somewhat into the bulb. On reversing the poles and making the cup positive, the bulb becomes beautifully illuminated with greenish-yellow light.

511. This phosphorescent light only appears in its full intensity when the dark space surrounding the negative pole extends to the surface of the bulb. At lower exhaustions, it can be detected when specially sought for outside the luminous boundary of the dark space, but it is faint and not easily noticeable. The colour depends on the kind of glass used. Most of my apparatus are made of soft German glass, and this gives a phosphorescent light of a greenish-yellow colour. English glass phosphoresces of a blue colour; uranium glass becomes green; a diamond became brilliantly blue.

512. The greenish-yellow phosphorescence of the soft German glass only takes place under the influence of the discharge from the negative pole.* As the exhaustion increases the light gets stronger. At 10 M the diffused violet light surrounding the positive pole is faint, and the green light on the glass is getting stronger. At 4 M

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* While this paper was passing through the press, my attention has been drawn to two Memoirs by H. EUGEN GOLDSTEIN, communicated to the Berlin Royal Academy of Sciences, May 4, 1876, and November 23, 1876, in which some of the results announced in this paper have been anticipated. Referring to the green phosphorescent light, H. E. GOLDSTEIN writes:—

"The author has specially examined the green light which appears in tubes of common glass at certain degrees of pressure and intensity of the discharge. The luminosity of the sides of the tube is not a phenomenon of fluorescence but of phosphorescence, and can change from green to orange.

"The negative light which produces this phosphorescence is, as was already assumed by HITTORF, a rectilinear radiation, which extends from the negative pole into surrounding space. Still there are essential differences between the diffusion of this remarkable motion and the likewise rectilinear movement of the light, some of which differences are here brought forward.

"HITTORF observed that a body placed between the side of the glass and a point-like cathode, throws a shadow in the phosphorescent light of the latter.

"Well defined, though not very sharp shadows of small objects may be obtained not merely from a point-like or linear negative pole, but also from extended negative surfaces placed at a small distance from the opaque object.

"A surface which merely radiates light, *e.g.*, an ignited body, under similar conditions throws a scarcely visible expanded penumbra.

"The negative light is therefore a rectilinear radiation, which is propagated preferably in a manner almost normal to the producing surface.

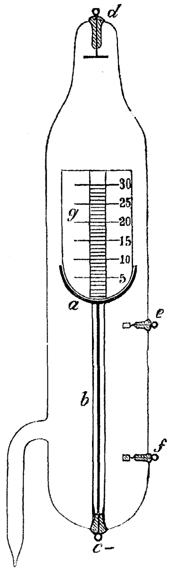
"If between the cathode and the green luminous side of the tube there is introduced a solid body, its the green light is still better, and there is no violet light on the positive pole. At ·9 M the green phosphorescence is about at its maximum. When the exhaustion reaches ·15 M the spark has a difficulty in passing, and the green light only appears in flashes occasionally, and then only in patches over the tube. At ·06 M the vacuum is almost non-conducting, and a spark can only be forced through by increasing the strength of the coil and well insulating the tube and wires leading to it. Beyond that exhaustion nothing can be observed.

513. It is difficult to experiment at these high vacua. After the induction spark has been forced through a few times, gas is liberated from the metallic poles or from the surface of the glass, conduction through the residual gas begins, and the appearance of light commences. Further exhaustion again impairs the conductivity. The greatest care must be taken to keep the conducting wires away from the tube except just where they touch the terminals; they should be well insulated and no metal should approach the tube. With all these precautions, however, it is difficult to prevent a spark passing through the side of the tube, when the vacuum is at once spoiled.

FOCUS OF MOLECULAR ENERGY.

514. To investigate still further the phenomena attending the concentration of force to a focus, another apparatus was made, as shown in fig. 12. *a* is a hemi-cylinder, 22 millims. diameter, accurately made of polished aluminium; it is supported in position by the glass tube *b*, through which passes a fine copper wire connecting

Fig. 12.



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shadow is thrown upon the side, since it excludes such rays of the cathode as impinge upon it from reaching the side. If the solid body after some time is removed, the shadow disappears, but an image of the body remains, distinguished from the surrounding luminous surface by its greater brightness, and exactly reproducing the shape of the former shadow."

the hemi-cylinder with the platinum terminal *c*. At the other end of the tube a flat aluminium disk forms the terminal. Other aluminium terminals are sealed in at *e* and *f*. In the axis of the tube, resting on the centre of the hemi-cylinder, and at right angles to its axis, is a flat glass plate *g*, on which is etched a millimetre scale.

515. On exhaustion, the hemi-cylinder *a* being made the negative pole through the wire *c*, the usual phenomena are observed. The dark space gradually increases in size, and as it spreads from the concave surface towards the centre it forms a denser and more luminous glow of light. As the exhaustion proceeds this glow becomes smaller and brighter, until it forms a narrow brilliant line along the axis of the hemi-cylinder. A bright spot forms on the scale at 11 millims. (the centre of curvature of the hemi-cylindrical pole), showing that the gaseous molecules from the negative pole are projected in a direction normal to the surface. The distance between the convex surface of the hemi-cylinder and the luminous boundary of the dark space is also about 11 millims. The pressure at this point is 106 M.

516. As the exhaustion becomes higher the rays projected from the concave surface of *a* are seen on the divided scale to cross each other, and the focus lengthens out and becomes ill-defined, as if the molecules from the centre of the pole were projected to a greater distance than those from the edges, giving an appearance of spherical aberration. It is difficult to fix the exact focal point, but it gradually creeps up from 11 millims. to about 19 millims.

517. When the focus of light has reached 20 millims. it is very faint. The green-yellow phosphorescent light has been visible for some time, and now, the pressure being 19·3 M, a faint concentration of green light is seen to occur at 11 millims. on the scale. This shows that the cause to which the green phosphorescence is due is not the same to which the luminosity previously noticed in the tube is due; for the two phenomena are now existing simultaneously.

518. In another tube, similar to the one shown at fig. 12, but without the flat glass plate *g*, the appearance at an exhaustion of one millionth of an atmosphere when the induction current passes through, is shown in the coloured lithograph, Plate 14.

[Having received permission from Mr. De La Rue to test some of these high vacuum tubes with his large chloride of silver battery, I gladly availed myself of it, and tried some experiments, among others, with this tube. The exhaustion was the millionth of an atmosphere. Not knowing what the effect of so large a battery might be, cells were put on gradually. Up to 4800 cells scarcely any action was visible. At 6300 cells a current equal to 0·00048 weber passed through the tube, and the green phosphorescence commenced to be visible on the glass. With 7760 cells the current passing through was equal to 0·00095 weber, and the appearance of the tube was similar to that produced by an induction coil giving about a one-inch spark. When 9920 cells were used, the current through was =0·00143 weber, and the green phosphorescent curves on the tube were about as bright as when an 18-inch spark from an inductive coil was passed through. The chromo-lithograph (Plate 14) represents this very well. With 11,000 cells the current through was the same as with 9920 cells, and the phosphorescence was only a little brighter. The resistence of the tube was found to equal 7,642,600 ohms, and the tube potential was 10,600. I have to thank Mr. DE LA RUE for not only letting me use his battery, but for kindly taking these measurements for me.—W. C., August 12, 1879.]

NATURE OF THE GREEN PHOSPHORESCENT LIGHT.

519. Other differences are observed. The focus of the green phosphorescent light remains at the centre of curvature, appearing independent of the degree of exhaustion, provided this is good enough to render it visible; whilst the bluish focus of light lengthens out with the exhaustion. The green focus is not to be seen in the body of the tube, but only where the projection causing it strikes the glass; whilst the concentration of light first observed is only visible in the space of the tube, and produces no special effect when it touches the sides.

The bluish focus at low exhaustions, proceeding from the negative hemi-cylinder, is only seen when the pole *d* is positive, no light on the concave side being seen. When the exhaustion is high, and the green phosphorescent focus is bright, it makes little difference whether the positive pole is above the concave surface, at *d*, or below it, at *e* or *f*; in either case the projection from the concave surface of *a* is visibly focussed on the phosphorescent surface of the glass (526, 527, 549).

520. Spectrum observations show another difference equally decided. When the luminosity observed in the focus of the hemi-cylinder at a low exhaustion (say 100 M) is examined in the spectroscope, it shows the lines due to the residual gas, whether it be nitrogen, hydrogen, or carbonic acid; but when the exhaustion is at a very high point (say 1 M) the blue light has disappeared, and no lines are detected in the green phosphorescence whatever be the gas whose residue causes it. The spectrum of the greenish-yellow light, so beautifully illuminating the tube, is continuous, most of the red and the higher blue rays being absent.

521. The green phosphorescence commences at a lower exhaustion in hydrogen than it does in air, and the phenomena known to be due to hydrogen gas also disappear sooner than in the corresponding case with air. In all gases, however, when a high exhaustion is reached the subsequent phenomena are the same.

522. The viscosity of a gas is almost as persistent a characteristic of its individuality as its spectrum. For many years I have been carrying on a research on the variations of viscosity of different gases at high exhaustions. In the Proceedings of the Royal Society for November 16th, 1876,* I gave in a preliminary note a diagram of the variation of viscosity of air, hydrogen, and other gases, at exhaustions varying from 250 M to 0·1 M. A comparison of the indications on that diagram with the data given in the present paper will show that when the

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* Vol. xxv., p. 305.

exhaustion is such that the spectral and other luminous appearances in the tube are characteristic of the special gas under examination, the viscosity is little different from what it is at full atmospheric pressure. When, however, the spectral and other characteristics of the gas begin to disappear, the viscosity also commences to decline, and at an exhaustion at which the green phosphorescence is most brilliant, the viscosity has rapidly sunk to an insignificant amount.

523. Another special characteristic of a gas at exhaustions between 250 **M** and 35 to 40 **M**, is the molecular pressure generated, when light falls on a black surface immersed in it. In the diagram just referred to, the variation in the force of repulsion is also given. This is seen to decline rapidly and almost to die out along with the viscosity: the phosphorescent phenomena become more brilliant as these special characteristics of the gas disappear.

PROJECTION OF MOLECULAR SHADOWS.

524. In ordinary vacuum tubes, illuminated by the induction current, the luminous phenomena follow the tube through any amount of curves and angles; a hollow spiral becomes illuminated just as well as if the tube were in a straight line. Not so, however, the phenomena of green phosphorescence observed at these high exhaustions. The molecular ray which gives birth to green light absolutely refuses to turn a corner, and radiates from the negative pole in straight lines, casting strong and sharply-defined shadows* of anything which happens to be in its path. In a **U** tube with poles at each end, one leg will be bright green and the other almost dark, the light being cut off sharply by the bend of the glass, a shadow being projected on the curvature. I can detect no trace of polarisation in the green phosphorescent light on the surface of the glass, except, of course, when it emerges at an angle through the side of the glass tube.

525. The projection from the negative pole of a shadow rendered visible by a sharply-defined image on the side of the glass, seemed worthy of more close examination. A tube was accordingly made, as shown in fig. 13. In the centre, dividing the tube into nearly equal parts, is a screen of thin mica, *a a*, loosely fitting into a groove blown round the tube. A flat plate of uranium glass, *b*, about half a millimetre thick, is rivetted to the mica on one side. *c* is a star-shaped piece of aluminium foil attached to a platinum terminal, and *d* is a similar star made of mica. At each end of the tube are two terminals, *e* and *h*, being flat aluminium disks, and *f* and *g*, aluminium points.

With this apparatus experiments were carried on during exhaustion. When the exhaustion is moderate (say 1 or 2 millims.), so as to show stratifications and the ordinary phenomena of vacuum tubes, the luminosity extends from one pole to the other. Thus, if *e* and *g* are the two poles, the light extends the whole length of the

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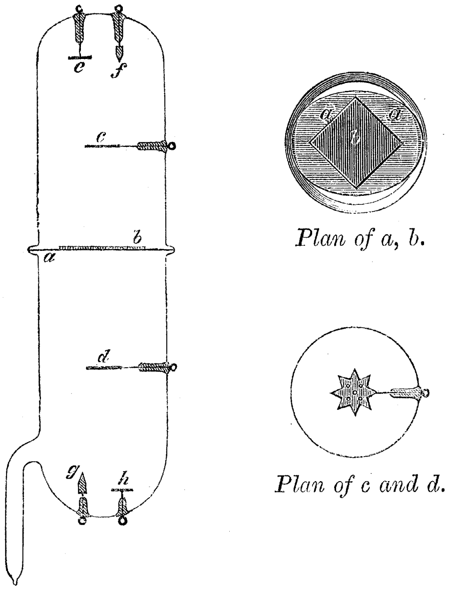
* See note, page 143.

tube; if, however, *e* or *f* is one pole and *c* the other, the luminosity only occupies the upper part of the tube, and if *e* and *f* are the two poles, the light keeps close to the top. The whole appearance shows that both poles are at work in producing the phenomena.

526. When, however, the vacuum is sufficiently high for the dark space round the negative pole to have swollen out to the dimensions of the tube, there is little difference in the phenomena of green phosphorescence and projection of the shadow of *c* on *b*, whichever is the positive pole, provided *e* be made the negative. The appearances are almost the same, and the shadows projected from the negative pole *e* are just as sharp and intense whether I make *f* or *h* the positive pole. The positive pole, in fact, seems to have little or nothing to do with the phenomena. (519, 527, 549.)

Fig. 13.



Plan of a, b.

Plan of c and d.

527. The best and sharpest shadows are cast by the flat disks *e* and *h*. The shadows thrown by the pointed poles *f* and *g* are faint and undecided in outline. An aluminium ring scarcely makes any shadow; a spherical pole, owing to the rays from it diverging more, gives faint and broad shadows; a square pole acts the same as a disk. Using the upper flat pole *e* as the negative, the shadow of the star *c* is thrown distinctly on the uranium plate *b*, where it is seen magnified about two diameters, but perfectly sharp in outline; either *f*, *g*, or *h*, and even the star itself may be made the positive pole without affecting the appearance of its shadow on *b*. (519, 526, 549.)

528. The whole upper part of the tube which is in the line of direct projection from the negative pole, glows with an intense yellowish-green fluorescent light. The uranium plate is still more brilliant, and of a greenish colour. Where the shadow of the star falls on it, no phosphorescence whatever is visible. The mica plate *a*, where uncovered at the side of the uranium plate, gives no phosphorescence, and no

shadow is therefore seen on it. When the lower pole, *h*, is made negative, so as to project the shadow of the mica star *d*, no shadow is seen on the mica plate, neither is any seen on the uranium plate above the mica. The thin film of mica entirely prevents the uranium glass from becoming fluorescent under the influence of the negative pole. Other experiments have, however, shown that the mica star gives just as sharp and intense a shadow as the aluminium star, provided a suitable screen is used to receive it on.

529. If the aluminium star is made the positive pole, any one of the others being the negative pole, it casts an enlarged and somewhat distorted image of itself all over the upper part of the tube. This image is not sharply defined.

The sharpness of the shadows cast by the negative pole is slightly affected by the intensity of the current; when the spark is very strong, the shadow widens out a little.

530. I have already advanced the theory that the thickness of the dark space surrounding the negative pole is the measure of the mean length of the path of the gaseous molecules between successive collisions (507). The electrified molecules are projected from the negative pole with enormous velocity, varying, however, with the degree of exhaustion and intensity of the induction current (498). In the dark space they are few in number in comparison to what they are at the luminous boundary. When the exhaustion is so high that the mean path of the molecules stretches right across the tube, their velocity is suddenly checked by the glass walls, and the production of light is the consequence of this sudden arrest of velocity. The light actually proceeds from the glass, and is caused by fluorescence or phosphorescence in or on its surface, and not by an evolution of light by the molecules themselves, crowding together and striking each other on the surface of the glass. Had this been the case—had the molecules themselves been the lamps—they would shine equally well whatever were the arresting surface, and their light would have shown the spectral characteristics of the gas whose residue they constituted. But no light is caused by a mica or quartz screen, however near it may be brought to the negative pole; and generally speaking the more fluorescent the material of the screen, the better the luminosity.

531. The theory best supported by experiment, and the one which although new is not at all improbable in the present state of our knowledge respecting molecules, is that the greenish-yellow phosphorescence of the glass is caused by the direct impact of the molecules on the surface of the glass. The shadows are not optical but *molecular* shadows, only they are revealed by an ordinary illuminating effect. The sharpness of the shadow, when projected from a wide pole, proves them to be molecular. Had the projection from the negative pole radiated in all directions, after the manner of light radiating from a luminous disk, the shadows would not be perfectly sharp, but would be surrounded by a penumbra. Being, however, projected material molecules in the same electrical state, they do not cross each other, but travel on in slightly divergent paths, giving perfectly sharp shadows with no penumbræ.

532. It was suggested by Professor STOKES, as an alternative to the above theory,

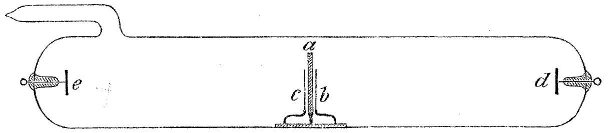
that the phosphorescence of the glass might possibly be excited, as we have hitherto known phosphorescence to be excited, by radiation, instead of being excited by the actual impact of the individual molecules on the molecules of the glass. The difficulty of this supposition was, where could the radiation come from? The sharpness of the shadows preclude the idea that it comes from the immediate neighbourhood of the negative electrode, which is far from being a mere point. It might, however, be supposed that the incandescent molecules were projected with such enormous velocity from the negative, that the space around it was kept comparatively clear; that there were comparatively few molecules within this space, but that, adjacent to the glass, there was a thin layer of them densely packed. Thus, if the molecules be thought of as lamps giving out, not the green light observed, but the invisible ultra-violet radiation which is capable of exciting the green phosphorescence, it is conceivable that the absence of phosphorescence within the sharply-bounded shadows might be accounted for by the absence of the thin overlying phosphorogenic stratum.

PHOSPHORESCENCE OF THIN FILMS.

533. An experiment was suggested by Professor STOKES which seemed calculated to be decisive, or almost decisive, between these different views. If the phosphorescence were really produced by impact, it must be confined to a stratum of almost infinitesimal thinness, but if it were produced by radiation from a thin layer of densely-packed gaseous molecules, glowing with phosphorogenic light, the fluorescence should extend a measurable distance into the glass; and if an excessively thin film of the glass were taken (thin enough to show the colours of thin plates), and placed in front of a thicker plate of phosphorescent glass, the full amount of fluorescence should not be excited on it, but some of the phosphorogenic rays would be likely to pass through, and the thin film should not cast a black shadow. By taking very thin films of different glasses, and also thin plates of quartz, the result would be more conclusively shown, for it is not likely that thin layers of all these media possess a metallic opacity to the phosphorogenic rays.

534. To experiment on these points, an apparatus was made in the following

Fig. 14.



manner:—In the centre of a tube, furnished with flat aluminium terminals, *d*, *e*, is supported a plate of uranium glass, *a*. About half a millimetre on one side is a film of uranium glass, *b*, and on the other side a similar film of German glass, *c*. The two films are thin enough to show brilliant colours of thin plates when viewed by reflected light, and are only large enough to partially cover the uranium plate. The plate and the two films are supported on a light aluminium frame.

535. When the tube is exhausted to within a few millionths of an atmosphere, and the pole *d* is made negative, the uranium film *b* casts a strong shadow on the uranium plate *a*. No phosphorescence can be detected on the part of the plate which is beneath the films, but where the plate is uncovered it shines with its characteristic greenish light.

536. On making contact with the coil, the film *b* flashes out suddenly, all over its surface, with a yellowish-green phosphorescence, which instantly disappears except at the part where it is stuck to the aluminium support at its back. The plate does not seem to become phosphorescent quite suddenly, but the phosphorescence remains permanent as long as the coil is kept at work.

537. When the contact hammer of the coil is screwed so as to make the spark excessively faint, the thin film remains more luminous than the plate; but if the screw is turned so as to get an intense spark, the luminosity of the film sinks, and that of the uncovered part of the plate increases; the plate now being three or four times brighter than the film.

538. If an intense spark be used and the contact made and broken suddenly, so as to send one spark at a time through the tube, only the film becomes visible, flashing out with a brilliant yellowish-green light, the plate, even in its uncovered part, remaining dark.

539. Exactly similar phenomena take place if the pole *e* be made negative, so as to experiment with the film of German glass, *c*. The only difference is in the colour of the phosphorescent light, which is much yellower with German than with uranium glass. In other tubes, English glass, which phosphoresces with a bluish light, has been found to behave in the same way. A very thin film of quartz casts a perfectly opaque shadow, but it does not become phosphorescent. The same thing occurs with mica.

540. These experiments are conclusive against the phosphorescence being caused by the radiation of phosphorogenic ultra-violet light from a thin layer of arrested molecules at the surface of the glass, for were this the cause the film could under no circumstances be superior to the plate.

The momentary phosphorescence of the film, and its rapid fading out, prove more than this. The molecular bombardment is too much for the thin film. It responds to it at first, but immediately gets heated by the impacts and then ceases to be luminous, except where it is attached to the aluminium support, which conducts the heat away. The plate, however, stands the heating without getting hot enough to lose its power of phosphorescing. The experiment demonstrates for the first time the transference to a finite distance, from molecule to molecule, of even that short period vibration on which phosphorescence depends, and it further exhibits experimentally the decadence of phosphorescence by transformation into a disturbance of longer period, which is quickly propagated from molecule to molecule, and carried away as heat.

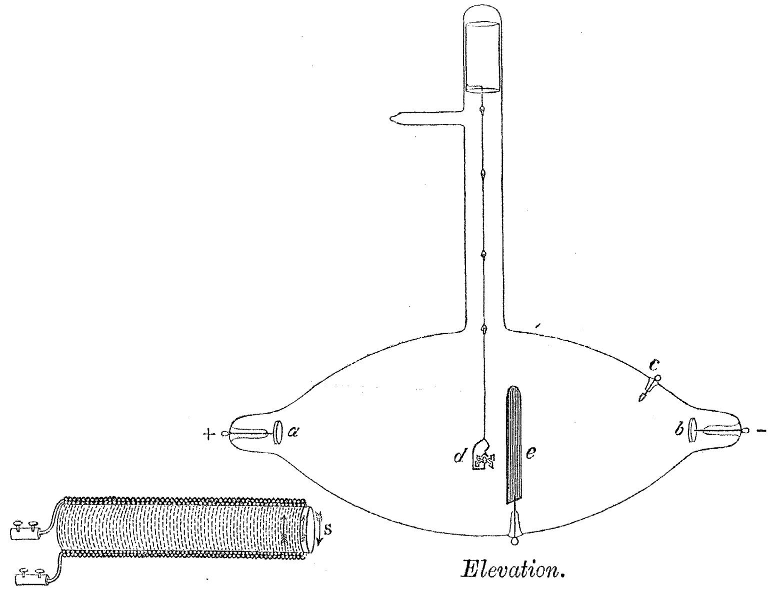
The cessation of phosphorescence by the heating of the phosphorescent body was observed by Professor STOKES. In his paper on the "Change of the Refrangibility of Light," in the Phil. Trans. for 1852, at page 532, it is mentioned that glasses and certain sulphides, which were phosphorescent when cold, lost their sensitiveness on heating, but recovered it again on cooling.

MECHANICAL ACTION OF PROJECTED MOLECULES.

541. It was noticed that when the coil was first turned on, the thin glass film was driven back at the moment of becoming phosphorescent. This seemed to point to an actual material blow being given by the molecular impact, and the following experiment was devised to render this mechanical action more evident.

A large somewhat egg-shaped bulb (fig. 15, elevation) is furnished at each end with flat aluminium poles, *a* and *b*; a pointed aluminium pole is inserted at *c*. At *d*, a little indicator is suspended from jointed glass fibres, so as to admit of being brought into any position near the middle of the bulb, by tilting the apparatus. The indicator consists of a small radiometer fly 8 millims. in diameter, furnished with clear mica vanes 2 millims. across, and delicately supported on a glass cup and needle point. A screen, cut out of a flat aluminium plate 12 millims. wide and 30 millims. high, is supported upright in the bulb at *e*, a little on one side of its axis, being attached to the bulb by a platinum wire passing through the glass, so that if needed the screen *e* can be used as a pole.

Fig. 15.



Elevation.

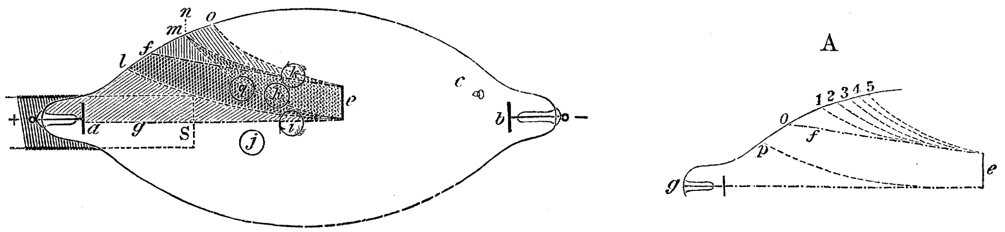
542. This apparatus was designed with a double object. The indicator fly is not blacked on one side or favourably presented, therefore if immersed in a full stream of projected molecules, there will be no tendency for it to turn one way rather than the

other. If, however, I tilt the bulb so as to bring the indicator half in and half out of the molecular shadow cast by the screen, I should expect to see the fly driven round to the right or to the left by the molecules striking one side only, thus confirming the observation on the movement of the thin glass film under the molecular impact (541).

543. The other subject which I had in view was the following. It is well known that a movable conductor carrying a current of electricity is deflected under the influence of magnetic force, and experiments tried very early in this research, and repeated with the apparatus already described, showed that the stream of molecules projected from the negative pole obeyed in a very marked manner the power of a magnet. It was hoped that the form of apparatus now under experiment would throw some light on this action of magnetism on molecules.

544. The bulb being exhausted to the necessary high degree, the pole *b* is made negative, so as to cast the shadow of the screen *e* across the tube, where it can be traced as a broad band along the lower part of the glass. Fig. 16, plan, shows the appearance, the shadow of *e* projected by the pole *b* being enclosed within the lines *f e*, *g e*, shaded diagonally.

Fig. 16.



Plan.

The indicator fly is first brought into position *h*, where it is entirely screened from the molecular stream; no movement takes place. The apparatus is slightly tilted, till the fly comes into position *i*, half in and half out of the shadow; very rapid rotation takes place in the direction of the arrow, showing that impacts occur in the direction anticipated. The apparatus being further tilted, so as to bring the indicator quite outside the shadow into position *j*, no movement takes place. When the indicator is brought to the other side of the shadow into position *k*, the rotation is very rapid in the direction of the arrow, opposite to what it is when at *i*.

MAGNETIC DEFLECTION OF LINES OF MOLECULAR FORCE.

545. An electro-magnet is placed beneath the bulb, shown at S in fig. 15, elevation, and by dotted lines at S in fig. 16, plan. A battery of from 1 to 5 GROVE'S cells is connected with the magnet. The current is made to pass in such a direction that the pole under the bulb (marked S) is the one which would point towards the south were the magnet freely suspended.

546. The induction current being turned on, the shadow of *e* is projected straight along the tube in the position *f e*, *g e*; the edge of the shadow *f* is called the zero position, marked 0 on fig. 16, A. The electro-magnet is now excited by 1 cell. The shadow is deflected sideways to the position shown by 1, *p*, the edge *f e* now moving to 1, and the edge *g e* moving to *p e*. The lines *f e* and *g e*, when under no magnetic influence, are marked along the bottom of the bulb by perfectly straight lines, but when deflected by the magnet they are curved as at 1 *e*, *p e*.

On increasing the number of cells actuating the electro-magnet, the deflection of the shadow likewise increases. Thus, the following is the deflection of the edge *f e* under varying magnetic force :—

No. of cells.	Position on drawing. (Fig. 16, A.)	Distance deflected, measured from zero, or *f*.
		millims.
0	*f e*	0
1	1	6
2	2	10
3	3	13
4	4	16
5	5	17·7

547. The width of the deflected shadow varies in like manner with the magnetic force, as seen by the following table :—

No. of cells.	Width of shadow, measured along the side of the bulb.
	millims.
0	39
1	24
2	17
3	13
4	10
5	7·5

With 3 cells the position of the shadow is shown at *l m* in fig. 16, plan, shaded from left to right by diagonal lines, and with five cells the shadow is in position *n o*, indicated in the figure by horizontal lines. The position of the shadow when not under magnetic influence is represented by diagonal lines running from right to left.

On reversing the battery current passing round the magnet, the above-named deflections are obtained in the opposite direction.

548. The indicator fly is brought into position *h* (fig. 15, plan), and the induction spark passed, the pole *b* being negative. The shadow entirely envelopes the indicator, and no movement is produced. The current from 3 cells is then sent round the electro-magnet. This twists the shadow round to position *l e*, *m e*, and thereby brings half the indicator into the stream of molecules. Instantly the fly rotates with great speed in the normal direction, the same as it did at *i*. The indicator is now brought into position *q*, where it is entirely immersed in the shadow whilst deflected by the magnet. No movement occurs until battery contact is broken with the electro-magnet, when the shadow instantly returns to its normal position, and the further half of the fly being thereby left uncovered it rotates rapidly in the same direction as it did at *k*.

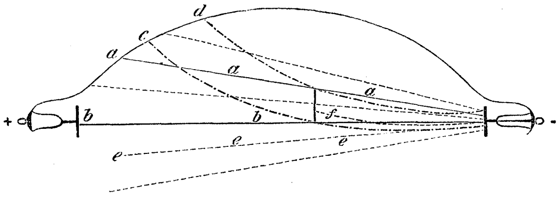
549. The pole *b* being negative, no difference in any of the phenomena here recorded could be detected, whether the positive wire was connected with the pole *a* or the pole *c*, or even when the screen itself, *e*, was made the positive pole. (519, 526, 527.)

550. The position of the magnet was now moved from under the positive pole *a*, to under the negative pole *b*, its axis still remaining parallel to that of the axis of the bulb. The shadow was now deflected when the magnet was excited with two cells, to a greater extent than it was with five cells in the former position.

THE TRAJECTORY OF MOLECULES.

551. The indicator in the apparatus just described (541) is supported by a thin fibre of German glass, which becomes highly fluorescent in the molecular stream. By moving it about in different parts of the bulb the shape of the shadow can be determined as it passes through space. Fig. 17 shows the trajectory of the molecules forming the shadow when under the influence of the electro-magnet actuated by 3 cells. The normal position being represented by *a a*, *b b*, the deflected shadow is shown by *c c*, *d d*. On tracing *c d* back past the screen to the negative pole the trajectory of the molecules forming it is found to be a curved line. The lines *b b* and *a a* are straight, but the corresponding lines, *c c* and *d d*, are curved. Moreover, the line *c c* starts from the negative pole in a contrary direction to that which it ultimately takes. This shows that the line of molecules whose straight path forms the boundary line of shadow *b b* is

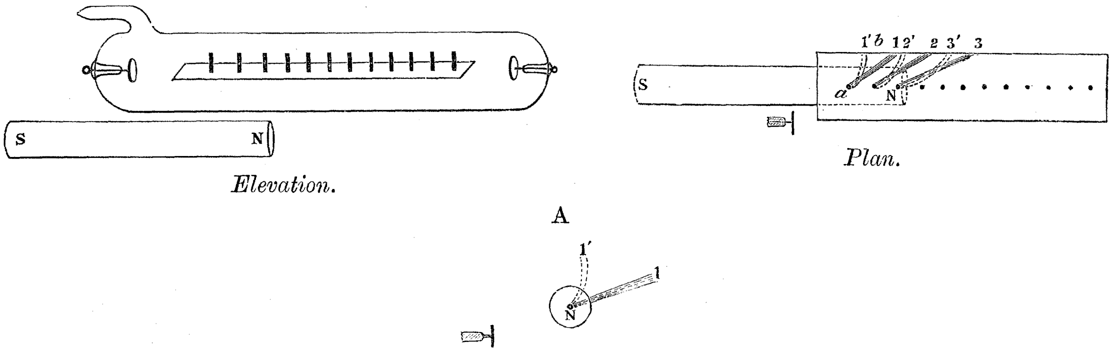
Fig. 17.



not the same line of molecules which forms the curved line *c c*. The action of the magnetic force is to twist the whole of the trajectories of the molecules round in a direction at an angle to their normal path, and to a greater extent as they are nearer the magnet, the direction of twist being that of the electric current passing round the electro-magnet. The line *c c* is therefore not the line *b b* twisted out of its place, but is another line, *e e*, which is bent round from *e* to *c* by the magnet, the line *b b* passing away somewhat in the direction *f f*.

552. A long glass tube, fig. 18, was made with a flat fluorescent screen running along its whole length; this screen had 12 vertical glass pegs fixed into it at intervals of 25 millims. apart. The negative pole of the coil was not quite in the axis of the tube, but a little on one side, so as to cast sloping shadows of the pegs across the fluorescent plate. When the magnet was placed in the position S N, but not excited, the shadows fell as at 1, 2, 3; but when the current was turned on the shadows twisted round to 1′ 2′ 3′, shadow No. 1 bending in at *a* as well as out at *b*, and the others acting in a similar way to a less extent.

Fig. 18.



Elevation.

Plan.

553. When the north pole of the magnet is placed vertically under one of the pegs, as at fig. 18, A, the shadow is twisted from position 1 to 1′.

554. These phenomena of magnetic deflection are obtained with permanent magnets as well as with electro-magnets. A copper wire helix without the iron core acts like an electro-magnet, but fainter, when an electric current is passed through it. The shadows experimented with in the tubes and bulbs already described are easily deflected by bringing a magnet near.

ALTERATION OF MOLECULAR VELOCITY.—LAW OF MAGNETIC DEFLECTION.

555. It has been shown (546) that the position of the edge of the shadow is affected by varying the magnetic power used to deflect it. It became of interest to see if by keeping the magnetic power constant, the position of the edge of the shadow could be altered by any circumstance affecting the intensity of the spark, such as intercalating a Leyden jar in the circuit, or screwing the contact breaker one way or

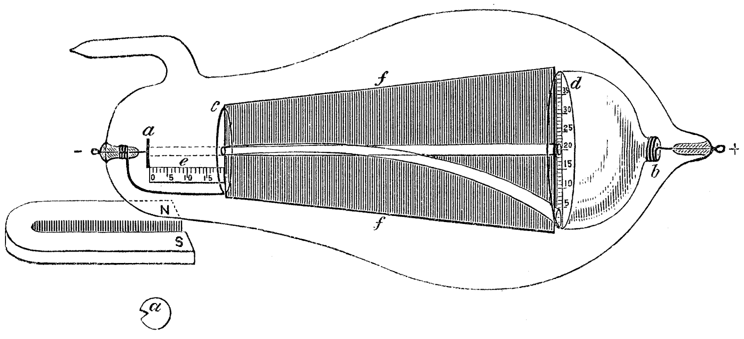
the other. If the molecules are projected from the negative pole with different velocities we might expect that under a constant magnetic deflection the higher velocities would show the flatter trajectories. With the apparatus shown at figs. 15 and 16, these variations in the trajectory of the molecules were not obtained in a decided manner, although indications of an alteration of curve by intensifying the spark were apparent.

556. Another apparatus was accordingly made in order to test this point, and also to obtain a more definite relation between the dimensions of the dark space round the negative pole, the commencement of the green phosphorescence, and the magnetic deflection under varying conditions of pressure in different gases.

I have spoken of shadows being deflected by the magnet as a convenient way of describing the phenomena observed; but it will be understood that what is really deflected is the path of the molecules driven from the negative pole and whose impact on the phosphorescent surface causes light. The shadows are the effect of a material obstacle in the way of the molecules.

In the apparatus now about to be described, a ray of light was used instead of a shadow. Fig. 19 shows the arrangement.

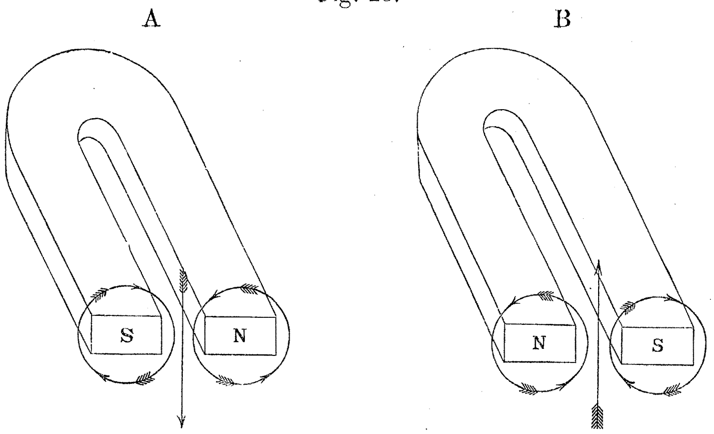
Fig. 19.



The poles are at *a* and *b*. The negative pole *a* is a flat aluminium disk with a notch cut in it. The pole *b* is a ring of aluminium; *c* is a mica screen with a small hole in the middle about 1 millim. in diameter; *d* is a flat plate of German glass with a millimetre scale engraved on it vertically; *e* is a mica scale of millimetres. The scale *e* is to measure the thickness of the dark space as the exhaustion proceeds; the hole in *c* is to enable a spot of light to be thrown on the scale *d* from the pole *a*; the notch in the pole is to enable me to see if the spot of light projected on *d* is an image of the pole *a*, or of the hole in *c*; the scale on *d* is to enable me to measure the deflection of the ray proceeding from *a*, through *c*, to *d*, when bent by the magnet; *ff* is a vertical screen of mica in the plane of the movement of the ray, covered with a phosphorescent powder. On this the path of the ray traces itself in a straight line when the magnet is absent, and curved when the magnet is present.

557. The magnet used is a compound horseshoe magnet capable of supporting about 5 lbs. It is placed underneath the negative pole, as shown in fig. 18 at N S. The experiments already tried with the straight electro-magnet show that the molecular ray is deflected in a spiral to the right or to the left according to the pole presented to it. When two opposite poles, as in a horseshoe magnet, are placed in a line with the normal direction of movement of the molecules, one tends to twist it spirally to the right, and the other to the left (fig. 20, A, B). The resultant direction is that the ray is bent in a curve, up or down, along a plane at right angles to the plane of the magnet, and the line joining the poles, according to whether the N pole is to the right or to the left. The magnet is so arranged that it can be put in position or moved away as often as necessary, with the certainty of always being replaced in exactly the same position.

Fig. 20.



The first observations were taken with air at different pressures. Exhaustion = 411·7 millionths of an atmosphere. The thickness of the dark space in front of the negative pole, measured along the scale *e*, is 6·5 millims. The bulb is filled with blue and violet light; no green phosphorescence is visible.

558. Exhaustion = 161·8 M. Thickness of dark space = 8·5 millims. Some green phosphorescence is seen near the negative pole, but no projection of an image is yet seen on the screen *d*.

559. Exhaustion = 102·6 M. Thickness of dark space = 12 millims. A spot of green light is now seen projected on the scale *d*, bright in the centre and shading off at the edges. The spot is about 5·5 millims. diameter. The centre of the spot, the magnet being away, is at 18·3 millims. on the scale. On placing the magnet in position, the spot of light is bent vertically down to 5 millims. on the scale, or a distance of 13·3 millims.

The magnet would easily bend the light much more if brought nearer, but it was not thought advisable to get a greater deflection for fear of the light coming off the scale in other gases.

560. Exhaustion = 55·2 M. Thickness of dark space = 15 millims. The green phosphorescence is increasing in the bulb. The spot of light on the screen is better defined, but no image of the notch can be seen in it. The magnet brings the spot down to about the same position as in the last experiment.

561. Exhaustion = 30·5 M. Thickness of dark space = 16 millims., but it is getting very faint. The spot of light on the screen is much more brilliant and is also sharply defined. The magnet brings the spot down to 6·8 on the scale, showing a deflection of 11·5 millims. The effect of greater exhaustion is therefore to flatten the trajectory of the molecules.

562. Exhaustion = 26·3 M. Thickness of dark space about 25 millims., but it is too ill-defined to measure accurately. The bulb is very green, and only a little blue light is visible near the positive pole. The spot of light keeps steady at 18·3 on the scale; it is very brilliant, but somewhat ill-defined in outline. When the magnet is put into position the spot sinks to 8·5, showing a deflection of 9·8 millims.

When the spot of light is bent down to division 8·5 on the scale, its position can be varied about 1 millim. by altering the intensity of the induction spark.

563. Exhaustion = 9·7 M. The dark space has now disappeared, and the whole tube, except the parts in shadow, glows with a bright greenish-yellow light. The spot of light is now no longer of any particular shape, but may be likened to a *splash* of green light on the scale. It is also unsteady in position, the centre varying between 18° and 20° on the scale. The magnet makes it more steady and brings it down to 16°, giving a deflection of about 3 millims.

Exhaustion = 8·9 M. The spot of light is too unsteady to enable its position to be determined with accuracy. The magnet brings it down between 2° and 3°.

564. It being found difficult to get a higher vacuum than this in so large a bulb, carbonic acid was let in, and after exhausting and refilling several times with pure carbonic acid, the following experiments were tried.

Exhaustion = 456·5 M. Thickness of dark space = 4·5 millims. No spot of light is to be seen on the scale, and no green phosphorescence in the bulb.

565. Exhaustion = 264·4 M. Thickness of dark space = 6·5 millims. Traces of green phosphorescence are visible, but there is no spot of light on the scale.

566. Exhaustion = 206·6 M. Thickness of dark space = 8·5 millims. The projected spot of light can just be detected with difficulty on the screen, at about 18° on the scale.

567. Exhaustion = 59·2 M. Thickness of dark space = 12·5 millims. Green light is appearing in the tube and the spot of light on the screen is brighter. The magnet causes it to sink 14°.

568. Exhaustion = 28·4 M. Thickness of dark space = 13·5 millims. The spot of light on the screen is brighter, and a well defined circle, no notch being seen on its edge. The magnet brings it down 11°.

569. Exhaustion = 10·2M. Thickness of dark space is about 21 millims., but it is

very ill-defined and appears broken in the centre, leaving two curves of light at the sides. The spot of light is unsteady and ill-defined. The magnet brings it down 9·5°. By increasing the intensity of the spark as much as possible, the deflection caused by the magnet is diminished, the spot only sinking 6·5 millims. instead of 9·5 millims.

570. The apparatus was now filled with electrolytic hydrogen, and after exhausting and refilling with the gas several times, the following experiments were tried :—

Exhaustion = 427 M. Thickness of dark space = 7 millims. There is on the screen an exceedingly faint spot of green light, which is deflected by a magnet, but it is not bright enough to allow observations to be taken.

571. Exhaustion = 147 M. Thickness of dark space = 12 millims. The spot of light on the screen is now brighter and better defined. The magnet being brought into position lowers the spot 13 millims. The light in the tube shows hydrogen, both by the colour and to the spectroscope ; the green phosphorescence is spreading.

572. Exhaustion = 27 M. Thickness of dark space = 15·5 millims. The spot of green light is much brighter and very well defined. The magnet lowers it 11·5 millims.

573. Exhaustion = 14·8 M. Thickness of dark space = 17 millims. The spot of light is bright and round. The magnet brings it down 10·5 millims. The tube is of a brighter green than usual, and there is less hydrogen light about the poles.

574. Exhaustion = 10·25 M. No dark space is to be seen. The light on the screen is no longer well defined, but is a mere splash of very bright green light. The rest of tube is of a brilliant green colour. The magnet lowers the spot of light about 3 millims.

575. Exhaustion = 7·25 M. The exhaustion is getting rather too high for the green light, which is not quite so bright. The sparks will not always pass through. The magnet has very little action on the spot of light.

576. These experiments prove several important points. In par. 559, when working with an air vacuum, it is recorded that the spot of green light is visible on the screen at a pressure of 102·6 M when the thickness of the dark space is only 12 millims. from the pole. Assuming, as I do, that this is a measure of the free path of the molecules before collision, it follows that some of the molecules sufficient to cause green phosphorescence on the screen, are projected the whole distance from the pole to the screen, or 102 millims., without being stopped by collisions. It is probable that this would have occurred at a still lower exhaustion, for on reference to par. 566, it is seen that the green spot was detected on the screen when the mean path in carbonic acid was 8·5 millims., and it was seen with hydrogen (570) when the mean path was only 7 millims.

577. If we suppose the magnet permanently in position, and thus exerting a uniform downward pull on the molecules, it is seen that their trajectory is much curved at low exhaustions, and gets flatter as the exhaustion increases. A flatter trajectory corresponding to a higher velocity of the molecules, it follows that the molecules move quicker the better the exhaustion. This may arise from one of two causes : either the

initial impulse given by the negative pole is stronger, or the collisions are less frequent. I consider the latter to be the true cause. The molecules which produce the green phosphorescence must be looked upon as in a different state from those which are arrested by frequent collisions. These impede the velocity of the free molecules and allow longer time for the magnetism to act on them; and although the deflecting force of magnetism might be expected to increase with the velocity of the molecules, Professor STOKES has pointed out that it would have to increase as the square of the velocity in order that the deflection should be as great at high as at low velocities.

Comparing the free molecules to cannon balls, the magnetic pull to the earth's gravitation, and the electrical excitation of the negative pole to the explosion of the powder in the gun, the trajectory will be quite flat when no gravitation acts, and gets curved under the influence of gravitation ; it is also much curved when the ball passes through a dense resisting medium ; it is less curved when the resisting medium gets rarer, and, from par. 562, it is seen that intensifying the induction spark, equivalent to increasing the charge of powder, gives greater initial velocity, and therefore flattens the trajectory. The parallelism is still closer if we compare the evolution of light seen when the shot strikes the target, with the phosphorescence produced in the glass screen by molecular impacts.

578. In carbonic acid the mean free path of the molecules is shorter for the same degree of exhaustion than in air, and the velocity of the molecules measured by the flatness of the trajectory under magnetic influence is also lower than what it is in air at similar pressures.

579. Although in many cases, especially at a moderate exhaustion and using a feeble spark, the image on the screen was a perfectly well-defined circle, I could detect no image of the notch cut in the negative pole. The hole in the mica was quite small enough to have given a good image of the negative pole inverted on the screen had it been shining by ordinary light, but the rays being corpuscular and the particles not crossing, no image of the pole is formed, but only the image of the hole in the mica.*

580. Attempts to obtain continuous rotation of the ray of molecular light by means of a magnet have hitherto failed. The stream of molecules does not obey AMPÈRE'S Law as it would were it a perfectly flexible conductor joining the negative and positive pole. The molecules are projected from the negative pole, but the position of the positive pole, whether in front, at the side, or even behind the negative pole, has no influence on their subsequent behaviour, either in causing phosphorescence, producing mechanical effects, or in their magnetic deflection (519, 526, 527, 549). The magnet seems to give them a spiral twist, greater or less, according to its power, but diminishing as the molecules get further off, and independent of their direction.

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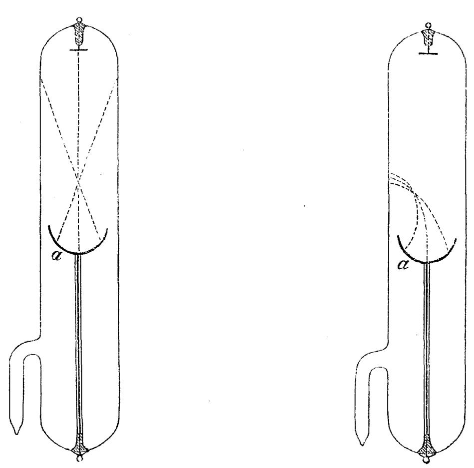
* With another apparatus, in which the pole and screen are nearer together and the mica with the hole in it capable of being moved to and fro, I have succeeded in seeing an ill-defined image of the negative pole. This only occurs at low exhaustions and soon disappears, giving way to a sharp image of the hole.

FOCUS OF MOLECULAR HEAT OF IMPACT.

581. In the experiment described at pars. 536 to 540, the heating effect of the molecular bombardment is assumed to be the cause of certain phenomena. It was thought that by concentrating the molecular impacts to one point the heat produced might be rendered apparent. The experiments tried in the apparatus shown in fig. 21 prove that this supposition is correct. A polished aluminium cup *a* is made the negative pole in a properly exhausted tube. The focus is seen very sharp and distinct, as at A, and of a dark blue colour. The light, although blue in the centre of the tube, when it spreads out and strikes the tube at the end, illuminates it beautifully with the yellowish-green light. By means of a magnet the focus was deflected to the side of the tube, as shown at B, the path of the rays being beautifully curved. On the tube the appearance was that of a sharply-defined oval of a yellowish-green colour with a dark spot in the centre. To ascertain if heat were developed here I touched it with my finger and immediately raised a blister. The spot where the focus fell was nearly red hot.

Fig. 21.



582. Another apparatus was now made, as shown in fig. 22. A nearly hemispherical cup of polished aluminium *a* is made one pole in a bulb, and a small disk of aluminium *b* is made the other pole. At *c* a strip of platinum is held by a wire passing through the glass, and forming another pole at *d*. The tip of the platinum strip is brought to the centre of curvature, and the whole is exhausted to a very high point. On first turning on the induction current, the cup being made the negative pole, the platinum strip entered into very rapid vibration. This soon stopped, and the platinum quickly rose to a white heat, and would have melted had I not stopped the action of the coil.

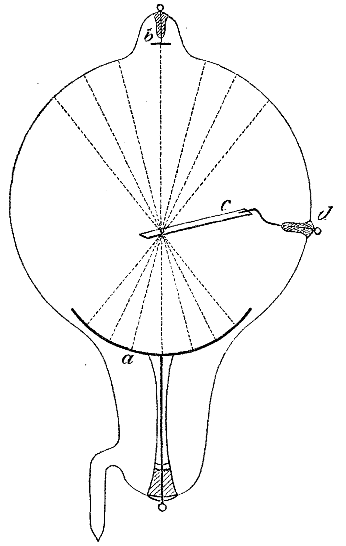
The same phenomena of ignition take place if the platinum strip itself is made the positive pole.

583. Experiments in a similar tube in which a piece of charcoal is the body to

be ignited, show that the ignition takes place at a less high exhaustion in hydrogen gas than it does in air.

I have great pleasure in expressing my continued obligation to the great skill in glass-blowing and manipulation possessed by my friend and assistant, Mr. C. H. GIMINGHAM, whose dexterity in executing complicated forms of apparatus has rendered easy a research which otherwise would have been full of difficulties.

Fig. 22.



584. I hope I may be allowed to record some theoretical speculations which have gradually formed in my mind during the progress of these experiments. I put them forward only as working hypotheses, useful, perhaps necessary, in the first dawn of new knowledge, but only to be retained as long as they are of assistance; for experimental research is necessarily and slowly progressive, and one's early provisional hypotheses have to be modified, adjusted, perhaps altogether abandoned in deference to later observations.

AN ULTRA-GASEOUS STATE OF MATTER.

585. The modern idea of the gaseous state of matter is based upon the supposition that a given space of the capacity of, say, a cubic centimetre, contains millions of millions of molecules in rapid motion in all directions, each having millions of encounters in a second. In such a case the length of the mean free path of the molecules is excessively small as compared with the dimensions of the vessel, and properties are observed which constitute the ordinary gaseous state of matter, and which depend upon constant collisions. But by great rarefaction the free path may be made so long that the hits in a given time are negligible in comparison to the misses,

in which case the average molecule is allowed to obey its own motions or laws without interference; and if the mean free path is comparable to the dimensions of the vessel, the properties which constitute gaseity are reduced to a minimum, and the matter becomes exalted to an ultra-gaseous or molecular state, in which the very decided but hitherto masked properties now under investigation come into play.

The phenomena in these exhausted tubes reveal to physical science a new world—a world where matter may exist in a fourth state, where the corpuscular theory of light may be true, and where light does not always move in straight lines, but where we can never enter, and with which we must be content to observe and experiment from the outside.

Fig.2

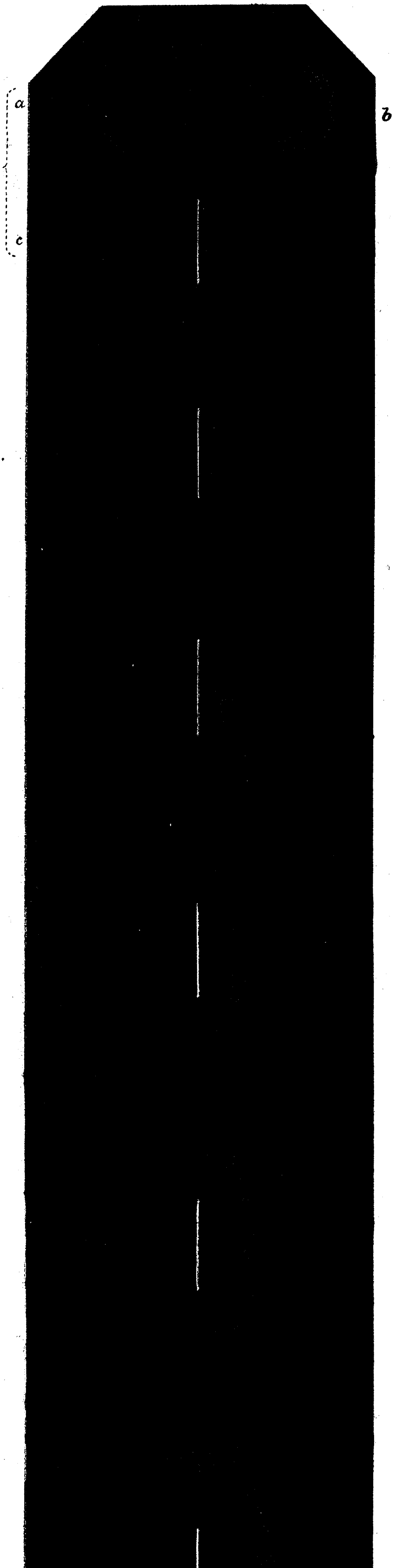
Fig.3.

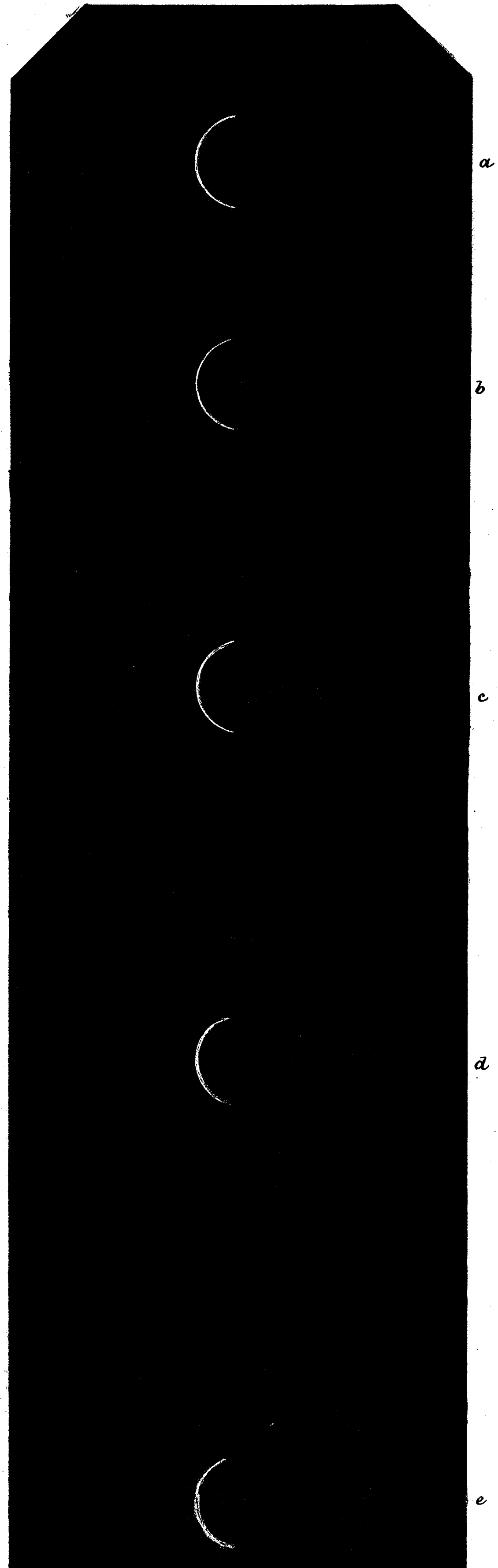
Fig.4

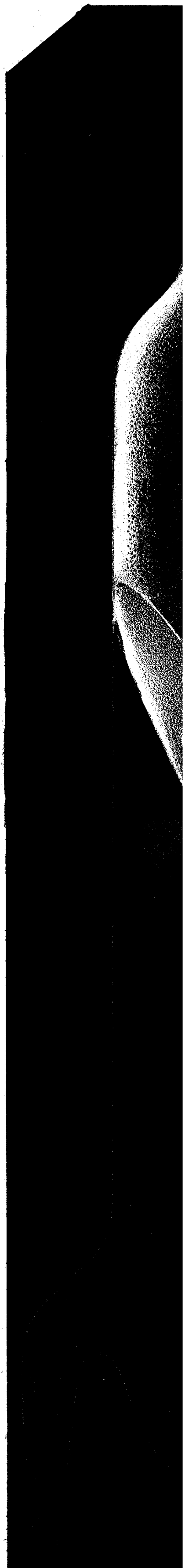
Fig.5

Fig.6

Fig.7







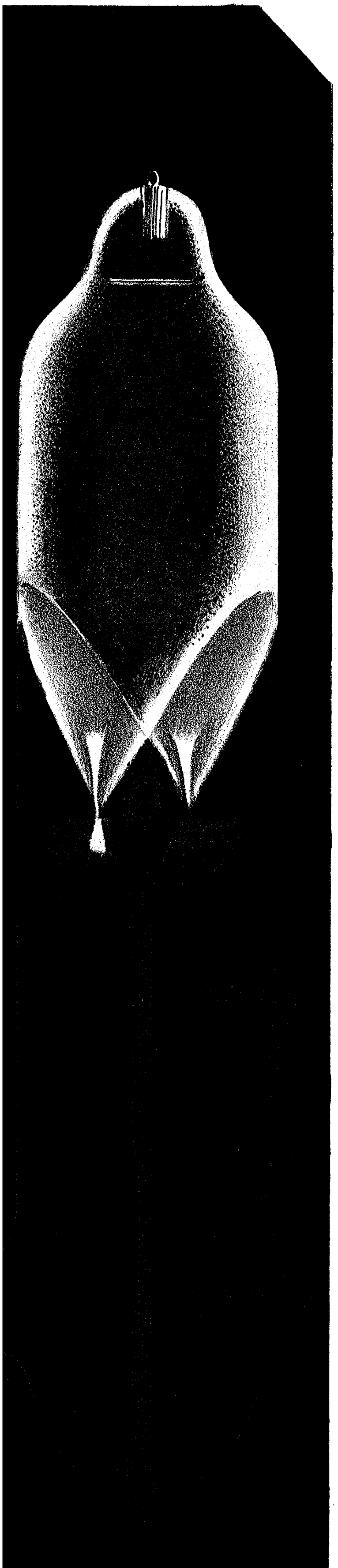
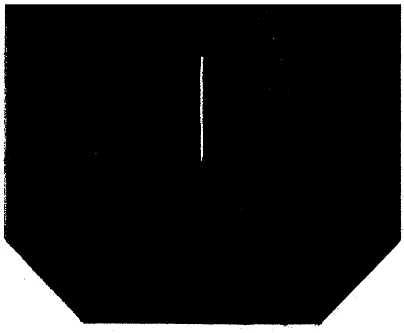


Fig.7



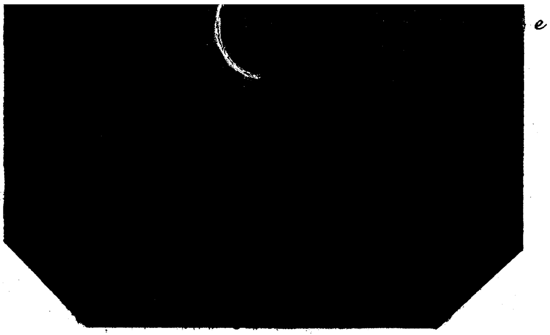


Fig.11.

[redacted]

Fig. 2

Fig. 3.

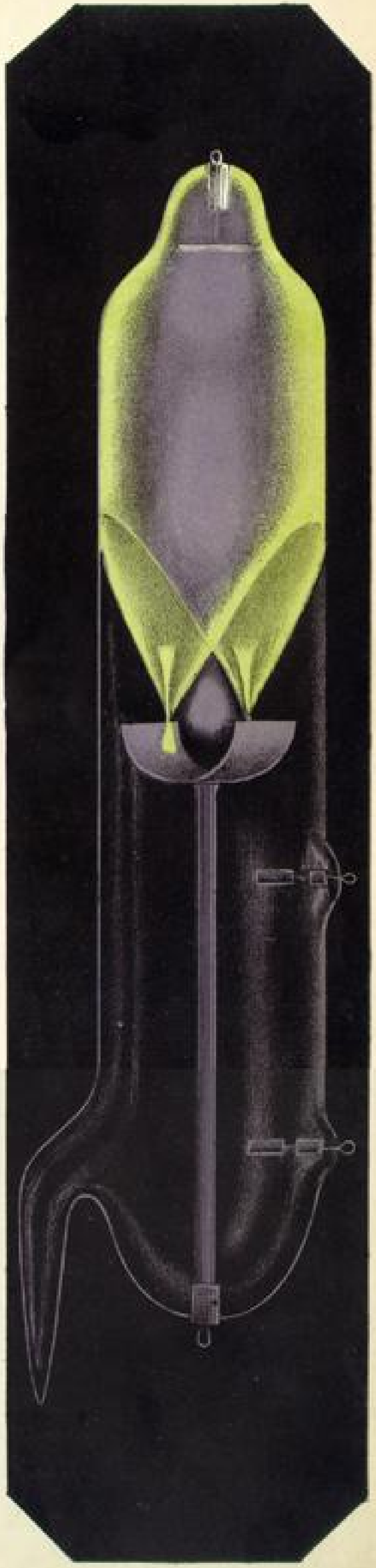
Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 11.



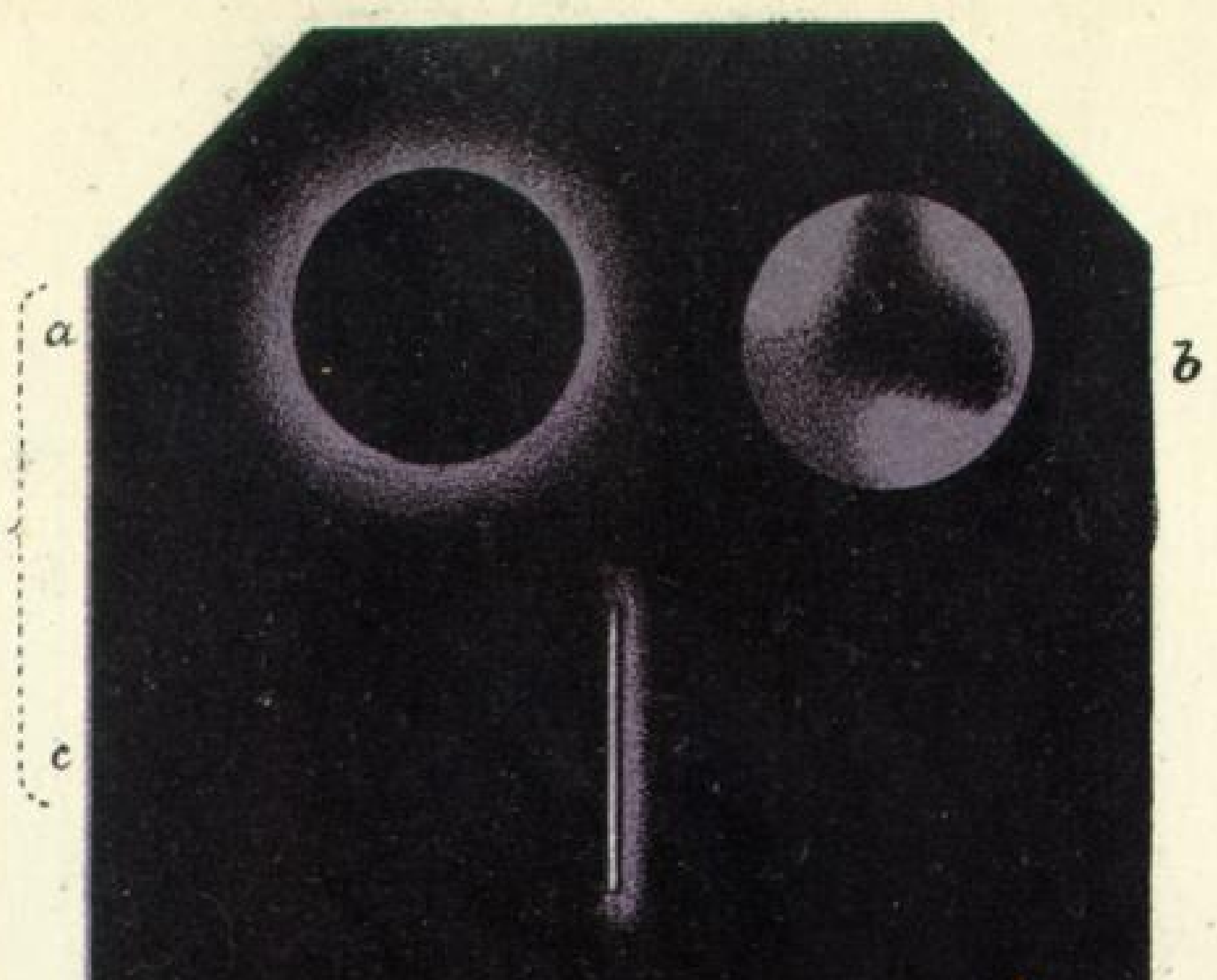


Fig.2

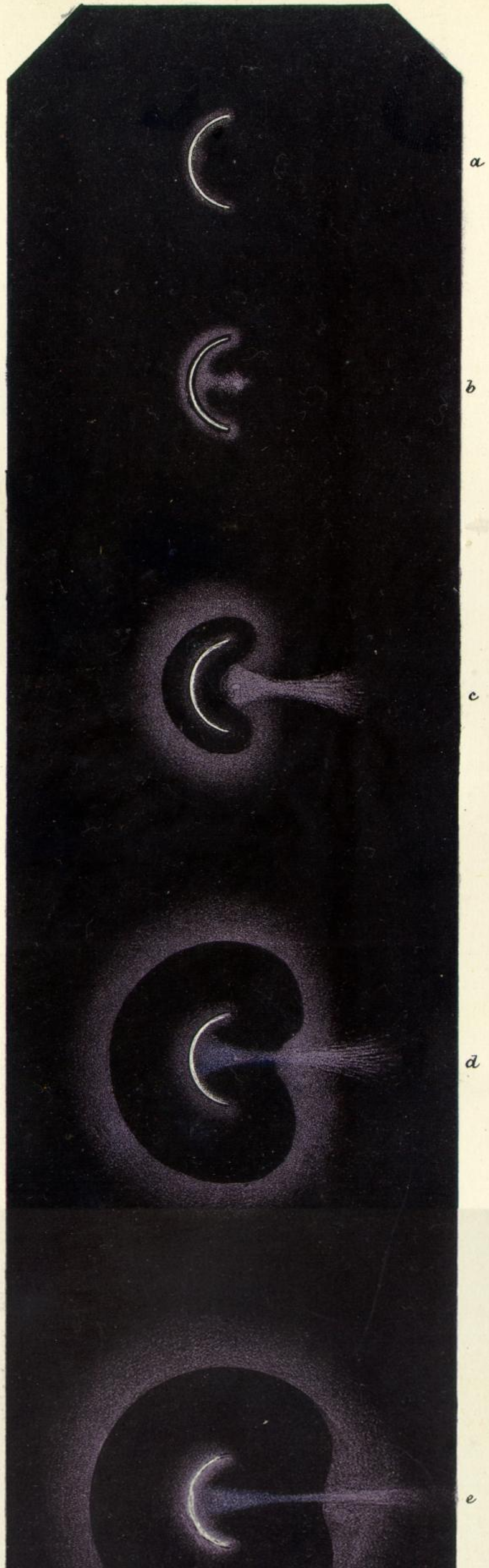

Fig.3.


Fig.4


Fig.5.


Fig.6


Fig.7



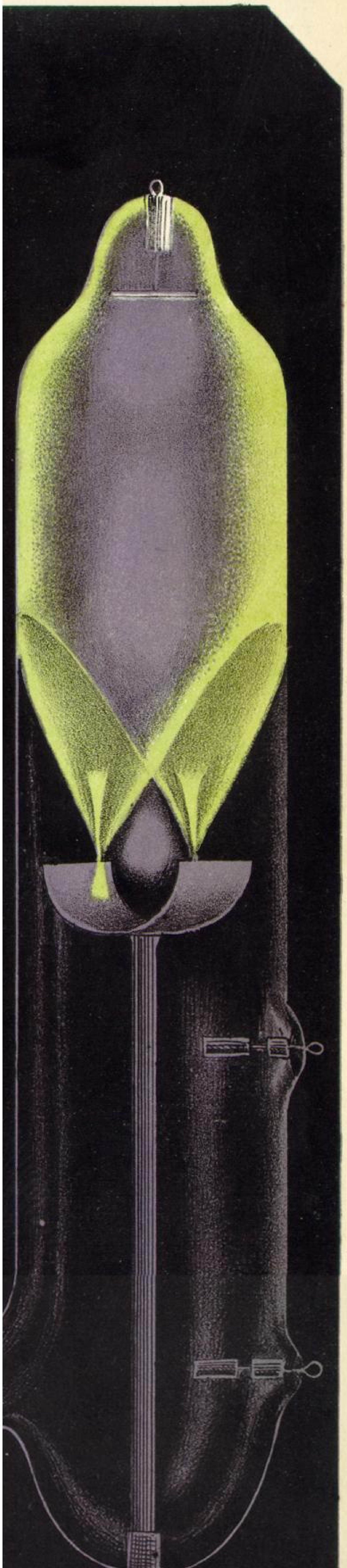
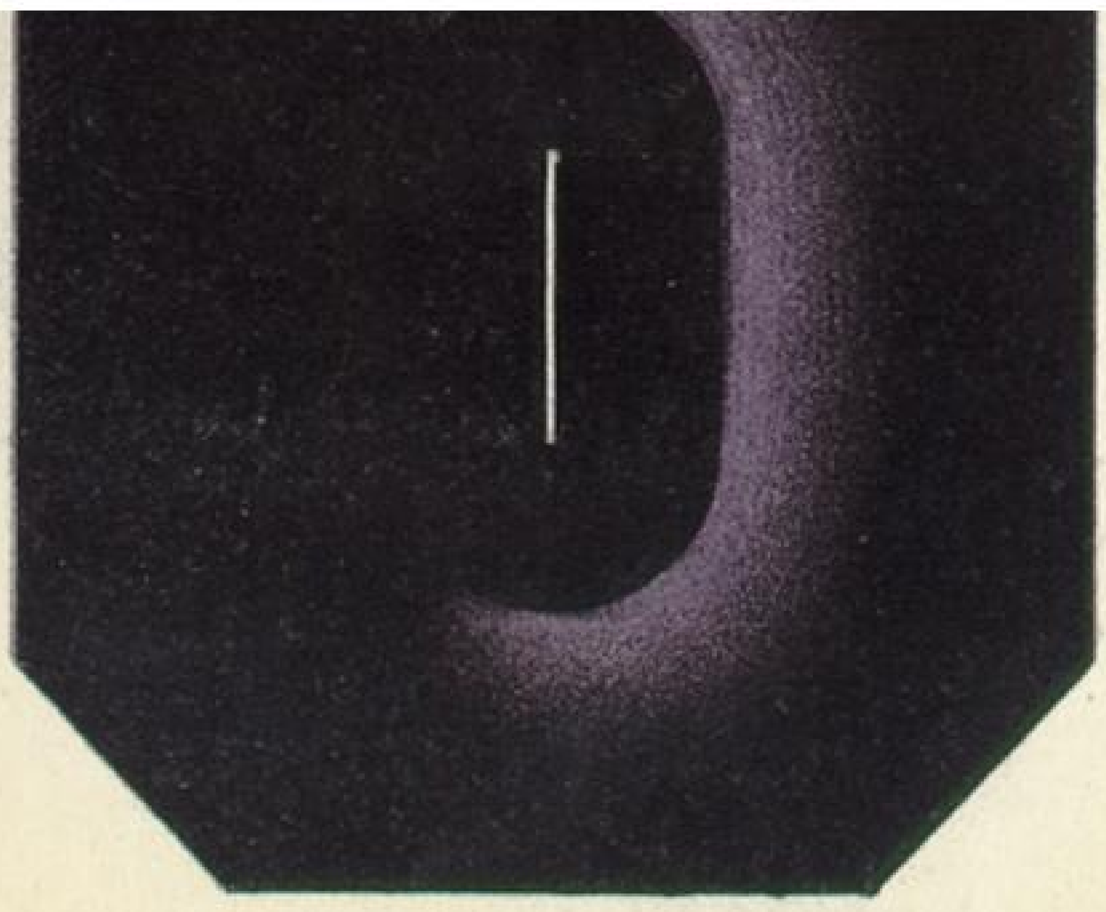


Fig. 7



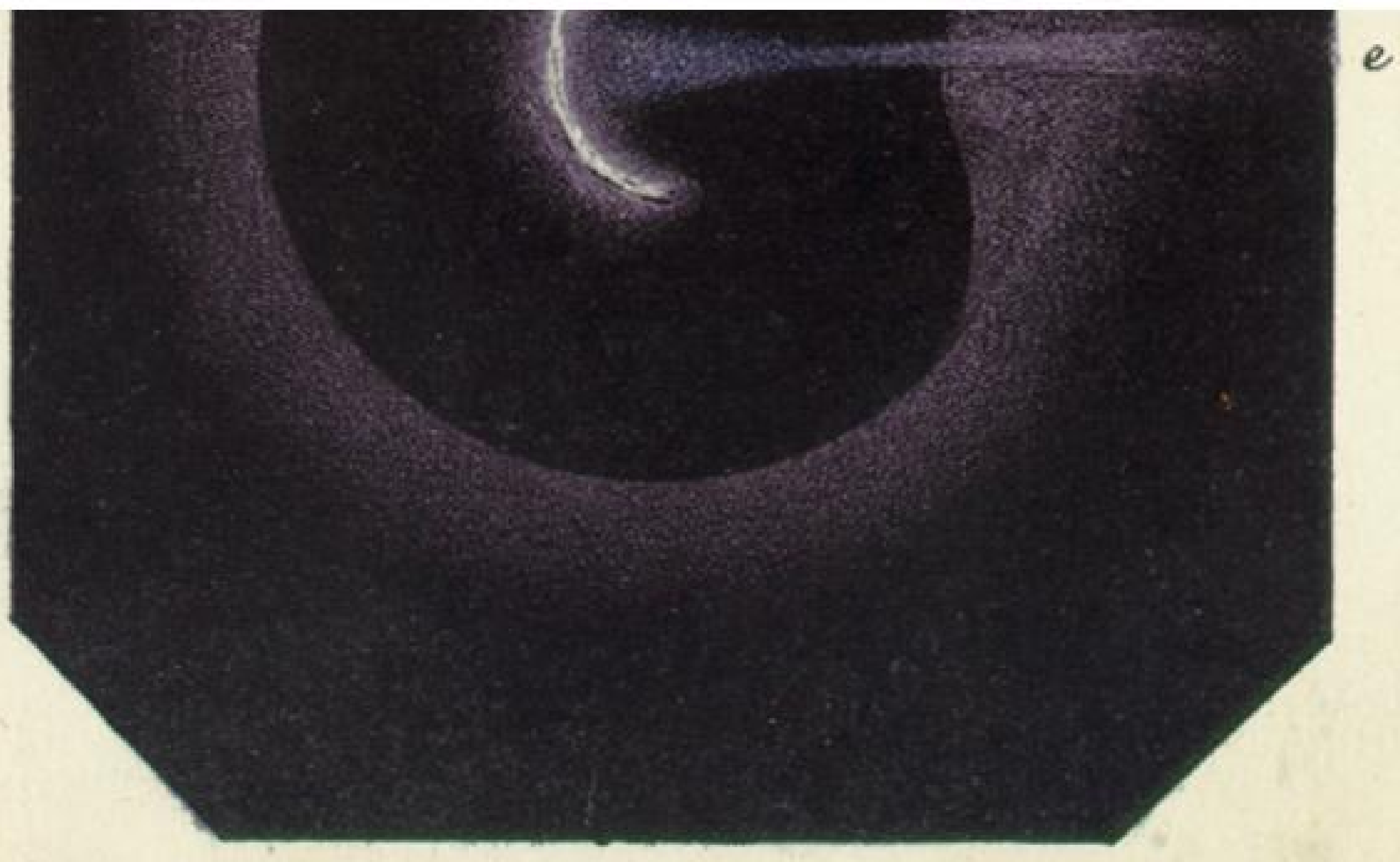


Fig. 11.