IV. *On Repulsion resulting from Radiation.*—Part VI

By William Crookes, *F.R.S., &c.*

Contents.

DIRECTION OF THE LINES OF PRESSURE INSIDE THE RADIOMETER.

387. Although the general character of the reactions which cause repulsion under the influence of radiation is now understood, much light may be thrown on the subject by an experimental examination of the direction and strength of the lines of pressure inside the case of a radiometer on which light is allowed to fall. Radiation will pass almost unimpeded through a very thin, colourless and transparent substance such as mica, but molecular pressure or stress is arrested by such a body (232). By introducing fixed or movable screens in various parts of the case of a radiometer, the direction of pressure can be determined at will, and its force can be modified in many ways, whilst all the other conditions of the experiment remain unchanged.

In the present Part I propose to give the results of a long series of experiments on the action of thin mica screens in modifying the movements of the fly of a radiometer; I shall examine the action of the residual gas, the action of the sides of the glass case, and the applicability of the information so afforded to the construction of instruments of greatly increased sensitiveness for the purposes of research and illustration; and I shall also describe other experiments which have been tried from

time to time during the last few years—experiments which at the time were isolated in their bearings, but which now fit into their places.

388. My first experiments were directed to ascertain whether the lines of pressure could be deflected from their path by a thin plate of mica fixed on the fly of an ordinary radiometer. A two-disk radiometer was made, having flat roasted mica disks, lampblacked on one side (fig. 1, *a*). The lampblack surface is represented in
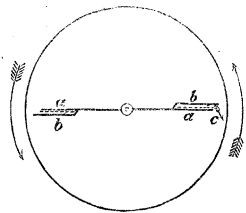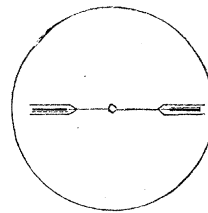
Fig. 1.

Fig. 2.

the figure by a row of dots close to the surface. In front of the black surface, and separated from it by a space of 1 millim., is fixed a thin disk of clear mica, *b*, about 1 millim. larger in diameter than the blacked disk. When properly exhausted and exposed to the radiation from a candle, the normal direction of movement would be opposite to that shown by the arrows, supposing no screen were present. The screen has, however, changed the direction; the pressure, instead of reacting between the black surfaces and the sides of the glass case opposed to them, is deflected back, as shown at *c*, and the result is rapid rotation in the direction shown by the arrows, the black side now approaching the light.

389. To test this action more completely, another thin mica disk was fixed on the plain side of the blacked disk, the latter being now guarded on each side, as in fig. 2. The effect of this is to cause an almost total loss of sensitiveness, the fly now only moving very slowly in full sunshine.

390. Two explanations of the action of the screen in fig. 1 suggest themselves. According to one, the radiation passes through the clear mica screen, and generates molecular disturbance on the black surface. The direction of greatest stress being prevented by the screen from exerting itself between the black surface and the glass bulb, is reflected back in the direction of the arrow, *c*, and produces negative rotation. Another view of the action is this. The radiation, falling on the compound fly, warms it in proportion to the amount absorbed. Molecular pressure is exerted on that side which is most easily warmed, and which most readily parts with its heat to the adjacent gaseous molecules. The roasted mica, *a*, coated on the inner side with lampblack, answers these conditions better than the clear mica; it warms up as a whole, and gives up its heat to the gaseous molecules on the outside, because there they are free to carry off the heat. This side, therefore, becomes the driving surface.

This view is rendered less probable on referring to the behaviour to a standard light

of silver-flake mica blacked on different sides.   I quote the following from par. 237 of Part V. of this series :—

Material of which the experimental disk in the torsion apparatus is composed.	Amount of repulsion under the influence of a standard light.
Lampblack (standard disk, pith)	100·
Mica, silver-flake, lampblacked on one side, black side exposed ..	151·
Mica, silver-flake	12·5
Mica, silver-flake, blacked on one side, black turned away from light..	— 9·8

391. It would throw much light on these two hypotheses, and probably enable the true law governing the movements to be disentangled from the individual results, if the screen were easily movable.   An instrument was accordingly constructed as shown in fig. 3.   *a a* are disks of silver-flake mica, lampblacked on one side.   They

Fig. 3.
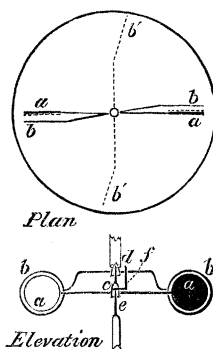
are mounted on aluminium arms, in the centre of which is a glass cap, *c*, balanced on the needle point, *e*, of the radiometer.   The cap, *c*, has a small needle point fused into the top, and this serves as the support of a second glass cap, *d*, to which arms are attached, carrying the clear mica disks, *b b*.   The upper cap, with the clear disks, is therefore pivoted on *c*, and will revolve freely round until arrested in one direction by striking against the blacked disks, and in the other direction by meeting the stop, *f*, which prevents the two pairs of arms from separating beyond a right angle, as shown by the dotted line, *b′ b′*.   The two pairs of disks will rotate together on the cap, *c*, and will not separate if no repulsive force is exerted between them; but if pressure is generated at the black surface, the disks will be pushed asunder.

Experiment shows that, in whatever way the light is allowed to shine on the disks, there is an actual repulsive force produced between them, which causes them to separate to the furthest possible extent.   By gentle tapping in a faint light, the clear disks can be brought within 2 millims. of the lampblacked surfaces; a candle is now brought near, shaded by a screen; on removing the screen, so that the rays pass through one
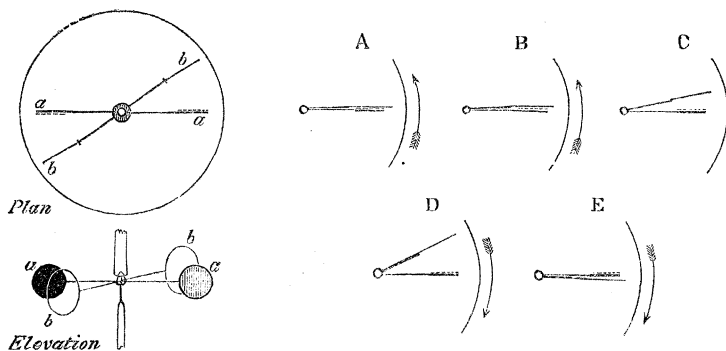
of the clear disks and fall on the black, the black disk immediately retreats, the clear disk remaining stationary for a moment, and then approaching the light. As soon as the disks have swung apart their full distance they keep there, and revolve like the fly of an ordinary four-vaned radiometer. The reason why the clear disk does not immediately move towards the light in proportion to the movement of the black disk away from the light, appears to be that the slight friction between the upper needle point and cup opposes, at first, such movement.

Another explanation has frequently occurred to me, which, however, I give with diffidence. This is, that when radiation first falls on a black surface the repulsion is produced, not by the chain of molecular impacts between the black surface and the solid body in face of it, but by the reaction between the black surface and the layer of normally-moving gaseous molecules near it, these forming a resisting cushion for the extra active molecules to react against and press back the black surface. This cushion of inactive molecules is, as it were, rapidly eaten into by the active molecules, until in a very short space of time the pressure spans across from one surface to the other.

If the candle is allowed to shine on the plain side of the black disk no movement takes place at first. Very soon the disks both move in the same direction away from the candle, the speed of the clear disk gradually increasing over that of the blacked disk.

392. In the instrument just described, the two pairs of disks were freely pivoted on separate points. Another radiometer was now made, in which the plain and blacked disks could be fixed beforehand in any relative positions. Fig. 4 shows the instru-

Fig. 4.

ment; the arms carrying the black disks, $a\,a$, are supported on a cup revolving on a needle point; the arms carrying the clear disks, $b\,b$, have a circular hole in the centre, which fits over the glass cap. The relative positions of the arms can easily be adjusted by inverting the radiometer and tapping it; when replaced in position they are held together by friction, and the fly moves as a whole.

Experiments with this radiometer fully confirm the results obtained with fixed screens. In position A, with the two plates touching, the black surface being inside,

the movement under the influence of radiation is similar to that observed when a mica screen was fixed on each side of the blacked disk, the rotation being slow, or altogether stopping if the candle is five or six inches off.

When, by tapping, the disks are removed to about 1 millim. apart, as in position B, the sensitiveness is about at the maximum, and the rotation is in the negative direction, the same as in the radiometer shown in fig. 1.

The speed of rotation in the positions between B and C gradually diminishes as the plates approach the latter position ; and in position C, the plates being about 7 millims. apart, the sensitiveness has vanished, no rotation taking place even in a strong light.

Between 7 millims. and 12 millims. apart there is an almost total absence of sensitiveness. Beyond 12 millims. apart the repulsion begins to act most on the black surface, causing positive rotation, as shown in position D. When the two arms are at right angles to each other, positive rotation is strong, and it increases in speed as the clear disk approaches the plain side of the blacked disk ; the speed being at its maximum in position E.

393. I am now able to decide between the two hypotheses advanced in par. 390. The result obtained when the screen is close to the black surface (fig. 4, A), in which the speed was considerably less than when they were 1 millim. apart, shows that the negative rotation obtained in these positions is not due to a molecular disturbance generated on the plain side of the blacked disk, and reacting directly between that and the glass case (the second hypothesis), but that it is caused by the warming up of the black surface by radiation falling direct on it through the clear screen, and the deflection backwards of the lines of molecular pressure thereby generated. At 1 millim. apart, sufficient of this pressure is deflected to produce good negative rotation ; at less distances much of the force is taken up in molecular beating to and fro between the disks ; while at greater distances the negative rotation due to the reflected force is more or less counterbalanced by the positive rotation due to the molecular impacts exerted directly between the black surface and the glass bulb.

The cause of the maximum positive rotation taking place when the clear screen is close to the plain side of the blacked disk is, that in this position the difference of temperature between the outer sides of the compound disk is greatest.

394. The action of these radiometers is somewhat complicated, owing to the surfaces of the fixed disks being different in absorptive power. Another instrument was therefore made in which the vanes were of polished aluminium, perfectly flat and symmetrical to the bulb. The screens were of clear mica, and instead of being parallel to the vanes, as in the former instruments, they were at right angles to it, as in fig. 5. The aluminium plates are shown at a a ; the mica screens are at b c, they are fixed to their arms at a slight angle, so that in position A the screens touch the centre of the vanes at c, and project from them at right angles, whilst in position B the screens touch the vanes at b, near the outer edge, meeting them at an acute angle. The arms carrying the screens move easily on the centre cap, as in the previously-

described instruments (392), whilst they retain any position into which they are put by tapping.

Fig. 5.

Plan.

Elevation.
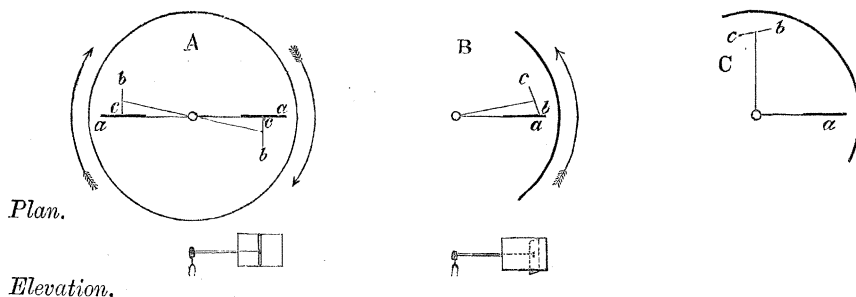
The candle in these experiments was 3 inches from the bulb. In position A the fly revolved in the direction of the arrows at a speed of 40 revolutions a minute. When the edge c of the screen was 3 millims. from the vane a, the revolutions were 30 a minute. When the distance was increased to 7 millims. the speed was reduced to 13 revolutions a minute, and at 15 millims. distance the speed was only 4 revolutions a minute. A little beyond this distance the rotation stopped.

The screens were now turned round till they touched the other sides of the vanes, as shown in position B. The speed was thereby greatly increased, being more than 60 revolutions a minute. When the edge b was separated 3 millims. from the vanes, the speed was 44 revolutions a minute; at 7 millims. apart the speed was 21 revolutions a minute; and at 15 millims. there were 10 revolutions a minute. At greater distances the speed rapidly diminished, and when the arms were at right angles to each other, as in position C, no rotation could be obtained.

395. The explanation of these movements is not difficult. At position C, when the vanes are not screened, the molecular pressure reacts equally on each side between the bright aluminium and the glass bulb, and no movement takes place. When the mica screen is put in position A, it offers obstruction to the lines of pressure between the inner half of one side of the aluminium plate and the side of the bulb, whilst the corresponding pressure is free to act on the other face. In position B the same occurs, but more of the aluminium plate is obscured by the mica screen. Hence, in each position the balance of pressure is exerted on the unscreened face of the plate, which retreats from the light, the available force being greater in position B than position A.

396. The screens were put into position A, and the whole bulb was heated with a spirit lamp. Strong negative rotation took place (screened side retreating); this kept on for 2·5 minutes; the fly now changed its direction and rotated positively, keeping on slowly for 12 minutes.

When the screens were in position B, the same phenomena occurred on heating the bulb and allowing it to cool, the first negative rotation being very rapid, and lasting 3 minutes, and the succeeding positive rotation being slower, and lasting 13 minutes. The negative rotation lasts whilst the glass bulb is giving heat to the fly; when the

bulb and fly are at the same temperature the movement stops; and as soon as the bulb and fly are cooling together, the fly being necessarily a little warmer than the bulb (306), the rotation is positive.

A hot iron ring applied equatorially to the bulb, the screens being in position B, gave strong negative rotation, changing to positive on cooling. A hot ring applied to the top of the bulb gave very slight negative rotation, also changing to positive on cooling (298 to 301).

397. The screens in the above-described radiometer were found to produce the greatest sensitiveness to radiation when in position B (fig. 5). Another instrument was therefore made, in which the indications thus given were followed out, the screens being placed in a different position, so as better to obstruct the molecular reaction between the vanes and the glass bulb. Fig. 6, A, shows the arrangement. The bright

Fig. 6.

Plan.

Elevation.
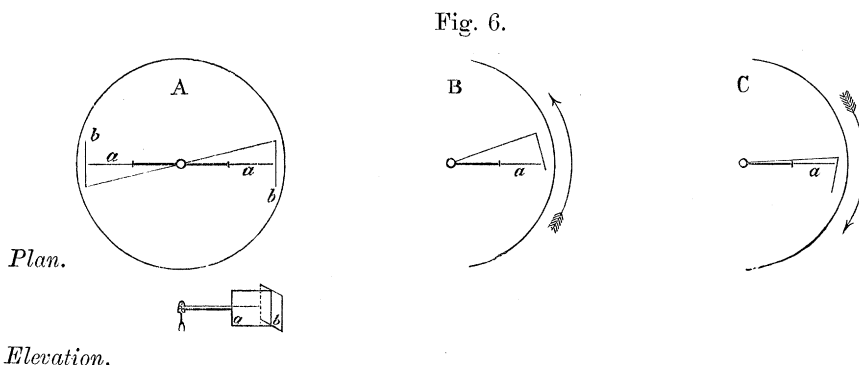
aluminium vanes, $a\,a$, are connected by thin arms, and are pivoted on a glass cap and needle point in the usual way. The mica screens, $b\,b$, are supported on independent arms, so that by tapping they can be put in any relative position in respect to the vanes $a\,a$. The screens are so fixed to the arms that they will pass between the vanes and the glass bulb, and be at right angles to them, as shown in the elevation. In position A, when exposed to light, or when heated with a lamp, no movement was produced. In position B strong rotation was given in the direction of the arrow, and when the screen was adjusted to shade off the other side, as in position C, equally strong rotation was produced in the opposite direction.

On heating the bulb with the screens in position B or C, strong negative rotation was caused, reversing to positive on cooling.

398. In a preliminary notice* sent to the Royal Society, November 16, 1876, when discussing the action of light upon the cup-shaped vanes of a radiometer, I advanced the hypothesis that some of the phenomena might be explained on the assumption that the molecular pressure acted chiefly in a direction normal to the surface of the vanes; and concluded that " it would not be difficult to test this view experimentally, by placing a small mica screen in the focus of a concave cup, where the molecular force should be concentrated."

* Proc. Roy. Soc., No. 175, 1876, vol. xxv. p. 304.

Following out this idea, a series of eight radiometers were made, having flies as shown in plan in fig. 7, A, B, C, D, E, F, G, H.   The cups were of thin aluminium, and clear mica disks were attached in the positions shown in the drawings.   In the pairs A and B the aluminium cups were bright on each side, and the mica screens were, in A, facing

Fig. 7.
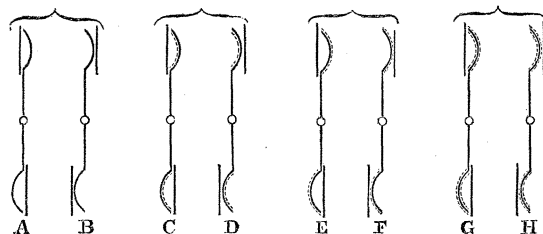
the concave side, and in B facing the convex side.   In the pairs C and D the aluminium cups were blacked on the concave side ; in E and F they were blacked on the convex side ; and in G and H on both sides.   The screens in each pair followed the arrange-ment in A and B.   The whole series compares with the similar series without screens given in Part V., par. 322.

Experiments were tried with each of these in succession ; the radiometers being exposed—1, to the direct rays of a candle, 3 inches from the bulb ; 2, to the same candle, after having cut off the light from the concave side by an opaque screen ; and 3, after screening the light from the convex side.

I will not describe each experiment in detail, but will briefly record that in each case, when the eight radiometers were exposed to the candle shining on both sides of the fly, the movement was one of rotation, being very strong with G ; less so with B, C, F, and H ; moderate with E ; and only slight with D.

When the opaque screen was placed so as to shade the candle light from the concave side of the fly, there was strong rotation in the case of E, F, G, and H ; moderate rota-tion with A, B, and C ; but no rotation with D.

When the light was cut off from the convex side of the fly, there was strong rotation with B, C, G, and H ; moderate with D and F ; and no rotation with E.

In every case where rotation was produced the direction of movement was the same, the mica screen approaching the light and the aluminium cups being repelled, irre-spective of the side turned to the light or of the position of the black coating.

399. On reference to the previously-quoted experiments on similar radiometers without mica screens in front (322), it will be seen that in two instances only was there no rotation, viz., 1, when the cups were blacked on the concave side, and the light was only allowed to shine on the convex side ; and 2, when the cups were blacked on the convex side, and the light was allowed to shine only on the concave side.   It will be seen in the present experiments that rotation is produced in all but the two analogous forms, viz., D and E, the former when the concave side is screened

from the light, and the latter when the convex side is screened from the light. The screen in these cases, being interposed between the cups and the light, could not assist rotation. In other cases the mica screen appears to intensify the action of repulsion.

400. It was now necessary to ascertain what effect would be produced by varying the distance of the screens from the metallic cup-shaped vanes. The simplest form of cups, with no lampblack on them, was chosen, and to avoid the difficulty which was sometimes found in starting the rotation and keeping it uniform, four vanes were used instead of two. The instrument had the form shown in elevation in fig. 8, the aluminium cups are affixed to rigid arms pivoted on a glass cap and needle point, and the four clear mica disks, acting as screens, are also pivoted on a quadruple arm capable of adjustment in any relative position in respect to the arms carrying the cups.

Fig. 8.

Elevation.   6 per min.   3 per min.   0.   6·5 per min.   12 per min.   30 per min.   50 per min.
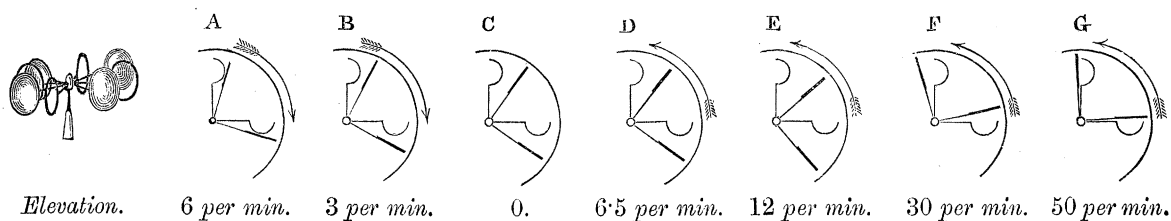
The candle was kept at a distance of 4 inches from the bulb. The first experiment was tried with the disks as close as possible to the convex side of the cup, but not touching, as in position A. Rotation took place in the direction of the arrow, at the rate of 6 revolutions a minute.

In position B the screens were adjusted 2 millims. from the convex surface. The direction of rotation was as before, but the speed was reduced to 3 revolutions a minute.

The space between the convex side and the screens was now increased to 3 millims., as in position C. No rotation took place.

The vanes were still further separated from the cups, being now 6 millims. from the convex sides, as in position D. The direction of movement changed, rotation being produced, in the direction of the arrows, at the rate of 6·5 revolutions a minute.

When the screens were midway between the cups, i.e., 10 millims. from the convex side and 10 millims. from the plane of the concave side, as in position E, the revolutions in the direction of the arrow were 12 a minute.

In position F, with the screens 5 millims. from the convex sides of the vanes, the speed in the direction of the arrows was 30 a minute.

When the disks were brought as close as possible to the concave sides of the cups, as in position G, the speed was 50 a minute.

401. These experiments, taken in conjunction with those immediately preceding, prove that, under the influence of radiation, a pressure is exerted between each side of the metal cup and the side of the glass case facing it, the pressure from the convex side

being greater than that from the concave side. The proportion is roughly 50 to 6, for when the molecular pressure is as completely as possible cut off between the convex side of the cup and the glass bulb, as in position A, fig. 8, the rotation due to the repulsion generated by the concave side is at the rate of 6 revolutions a minute; but when the screen is in position G, fig. 8, cutting off the pressure between the concave side and the bulb, and allowing that from the convex side fully to act, the revolutions become 50 a minute. In position C, the screen is at such a point that the active pressure is nearly equal from each side of the cups, and the result is neutrality. In the other positions a balance of pressure, represented by the stated revolutions per minute, is allowed by the screens to escape and react against the glass bulb.

402. I now endeavoured to ascertain if there was a difference between clear mica and blacked mica screens in front of metal cups. A radiometer was made similar to the one last experimented with (fig. 8), but the mica screens were lampblacked on the sides facing the concave surfaces of the cups. This altered the action considerably. At an exhaustion of 47 **M**, and with the candle 3 inches off, there was no movement when the screen was close to the concave surface, as at fig. 9. When the

Fig. 9.
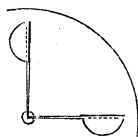
distance was increased to 2 millims., there was very slow positive rotation at the rate of 1 in $1\frac{1}{2}$ minute. With the screen midway between the disks, the speed was scarcely increased, and when it was 2 millims. from the convex surface the rotation was only at the rate of 1 per minute.

The exhaustion of 47 **M** was chosen, as that is near the point of maximum sensitiveness for ordinary radiometers (334, 382). I next tried the effect of exhausting the instrument to a higher point, at which an ordinary radiometer would begin to lose sensitiveness. At an exhaustion of 26 **M**, the speed was found to be 5 revolutions per minute in the negative direction, when the screens were in the position of fig. 9. With the screens 2 millims. from the concave side there was no motion, and beyond this point the more the screens approached the convex sides of the cups the more decided was the positive rotation.

403. The mica screens were now arranged in a horizontal plane, the metal cups remaining vertical (fig. 10). The exhaustion was 8 **M**, the candle remaining as before. In the position shown by the black lines the speed in the positive direction was 15 revolutions per minute. When the screens were moved to the positions shown by the dotted lines, the speed was reduced to 6 a minute; and at any intermediate distance between these two positions, the velocity of rotation likewise varied in proportion.

I was unable to produce negative rotation, or a position of rest, with this form of instrument.

Fig. 10.
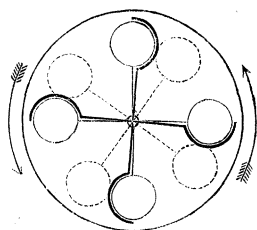
Plan.

404. My next endeavour was to ascertain what difference in action was caused by an alteration in the size and shape of the screens. A radiometer was constructed like the one shown in fig. 8 (400), except that the mica disks which acted as screens were 2 millims. smaller in diameter than the metal cups. The screens were adjustable. This instrument was found to be less sensitive than the one described in par. 400, where the screens and cups were of the same diameter, and under the influence of the candle it behaved differently. When the screens were close to the concave side of the cup, as shown at G, fig. 8, the revolutions were 20 per minute. When they were midway between the cups, as at E, fig. 8, the revolutions were 10 per minute. With the screens close to the convex sides, as at A, fig. 8, there was no movement at all. When rotation occurred it was in each case positive. The rotation when the screens were 2 millims. from the convex sides of the cups, as at B, fig. 8, was positive at the rate of 3 revolutions a minute. With the larger screens, as described and figured in par. 400, the rotation in this position was *negative*, at the rate of 3 per minute.

The exhaustion in these experiments was 12 **M.**

405. Other radiometers were made of the forms shown in fig. 11. In A, the mica

Fig. 11.
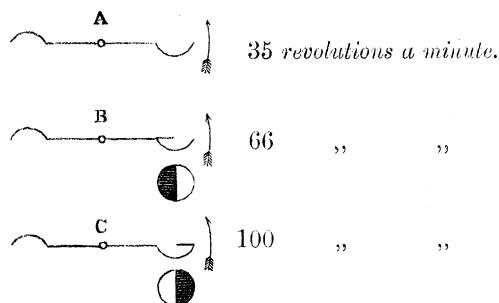
screen was absent; in B it was in the form of a half disk covering the inner half of the cup, and in C a similar screen covered the outer half of the cup. The form A was the least sensitive, and the form C most so; the speed in forms A, B, and C being 35, 66, and 100 revolutions a minute.

These experiments show that the inner half of the concavity of the cups sends a considerable amount of molecular disturbance to react on the glass case, although it is not so effective in this respect as the outer half of the concavity.

406. The metal cups used in these experiments were now lampblacked on the inside, and their speed compared with what it had been when they were bright, as at fig. 11, A. It was increased from 35 to 75 revolutions per minute. A mica disk, lampblacked on the inside, was now fixed close to the concave side of the cup, when the speed rose from 75 to 150 revolutions per minute. Had the blacked mica screens been some little distance from the cups, this doubling of the speed would have been easily understood, as the screens would have acted as additional driving vanes to the radiometer; but being close to the cup they can only act by absorbing and radiating back the heat given out from the bright concave surface of the cups, and thereby increasing the difference between the temperature of the black convex and bright mica surfaces.

407. The experiments hitherto described have been with mica screens. Mica being a bad conductor and radiator of heat, I next tried replacing it by aluminium, to see if the employment of a good conductor as a screen made any radical change in the phenomena. A radiometer was constructed like the one shown at fig. 8, with the exception that the screens as well as the cups were of aluminium, and the outsides of the cups were coated with lampblack, as at fig. 7, E. The diameters of the cups and the disks were the same.

The experiments were tried with the screens in the same positions as are shown in fig. 8, so I will refer to that figure in illustrating the results. The screens could not be got closer than 4 millims. to the black convex surfaces (intermediate in position between C and D, fig. 8), so I could not ascertain if there was a point of neutrality; in this position the speed was at the rate of 6 per minute in the positive direction. In position G, the screens being as close as possible to the concave surfaces of the cups, the positive rotation was at the rate of 120 revolutions a minute; and at any intermediate point between these two extreme positions the speed, in the positive direction, was proportionally intermediate between 6 and 120.

Making allowance for the increased sensitiveness communicated to the cups by blacking their convex surfaces, these results agree fairly well with those illustrated in fig. 8, and prove that the action of the screens is almost entirely one of mechanical obstruction, and does not depend on their special power of conducting, absorbing, or radiating heat.

408. In most of the instruments hitherto experimented with, the screens have been in such a position in respect to the glass bulb that the secondary action which the candle may set up by reason of its shining on the bulb has tended somewhat to complicate the results. The cup-shape of the vanes is also not the simplest form with which to investigate these reactions. A careful examination of the results obtained in the foregoing experiments with screens, throws much light on the physics of the

attenuated gas in the radiometer, and on consideration it seemed likely that by a slight modification in the shape of the vanes and screens, much that was obscure and contradictory might be rendered clear and harmonious.

Instead of cups I employed hemi-cylinders for the vanes, and the screens were square plates of mica held at right angles to the supporting arm, so that they should always be in a plane parallel to a tangent to the curvature of the bulb which they faced. Thus any reaction which might take place between the bulb and the surface of the screen could have no tendency to cause rotation in either direction.

Fig. 12.
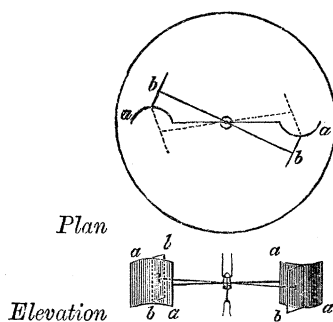
Plan

Elevation

Fig. 12 shows the radiometer in plan and elevation. $a\,a$ are half cylinders of bright aluminium; $b\,b$ are the mica screens on an adjustible arm, so that by tapping they can be shifted into any relative position in respect to the hemi-cylinders, from touching the convex surfaces, as shown by the black lines, to touching the concave surfaces, as shown by the dotted lines. The radiometer was kept attached to the pump during the experiments, so that the degree of exhaustion could be varied, whilst the distance between the screens and vanes was at the same time altered.

409. The vanes and mica screens were set as shown in fig. 13 a, A, the screens

Fig. 13 a.
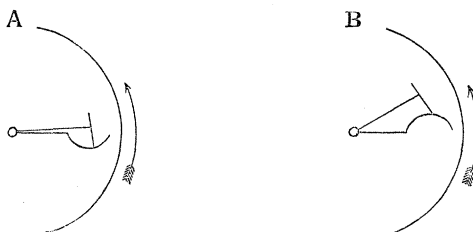
Exhaustion 117 M.

touching the concave surfaces. A candle was placed 3 inches from the bulb, and the pump was set to work. At a pressure of 540 **M**, positive rotation commenced in the direction of the arrow. A tendency to positive rotation was observed at a lower exhaustion, but it is best to take the first point of permanent rotation. When the screen was moved away from the vane, rotation stopped.

The vanes were now set touching the convex side as at fig. 13 a, B. The exhaustion continued, and when it had reached 117 M, permanent negative rotation commenced in the direction of the arrow. As the position of the screen was gradually shifted from B to A, the exhaustion remaining 117 M, the rotation got quicker and quicker, showing that for this exhaustion, position A is most sensitive, and position B least sensitive.

410. The screen was put into position 13 a, B, touching the convex side of the vane, and the pumping was continued. The positive rotation got a little quicker, until at 82 M the speed was 5 revolutions a minute. The screen was moved over to position A, the pressure remaining the same, when the speed in the positive direction was 13 a minute. As the screen was moved round from touching the convex side to touching the concave side, the speed of positive rotation of the fly increased.

411. The screens were now replaced in position B, touching the convex side of the vanes, and pumping was continued. As the exhaustion increased the rotation got slower and slower, until at a pressure of 87 M, the vanes stopped. Before the movement ceased the vanes acted as if, in revolving, they came successively under the influence of a strong attractive force. Each vane went quickly up to the spot of warm glass opposite the candle, then hesitated, and got past with difficulty. This hesitation became more and more decided, till at last a vane refused to pass the dead centre, when it swung back and the fly set equidistant from the candle.

On continuing the exhaustion a tendency to negative movement was soon observed, and at an exhaustion of 12 M, permanent negative rotation commenced, the screens all this time remaining in position B. At this pressure of 12 M, the speed in position A was 46 times a minute, positive. As the screen was moved from the concave side the speed got less. When it was 6 millims. from the convex surface (position C, fig. 13 b), the speed was 3 revolutions a minute, positive ; when they were 3 millims. apart (position D), the rotation stopped ; and when the screens and convex surfaces touched (position B) there was negative rotation, at the rate of about 1 turn a minute.

Fig. 13 b.
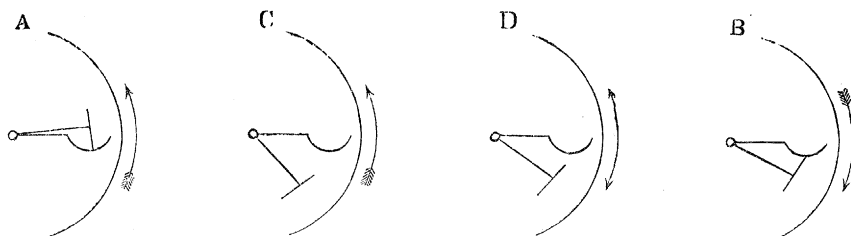
Exhaustion 12 M.

412. When in position 13 b, A, no change in direction of rotation takes place, whatever the exhaustion. There is an increase of speed up to a rarefaction of about 15 M, after which further exhaustion has little or no effect on the speed.

413. The exhaustion was now carried to ·18 **M**, and the following observations were taken :—

Fig. 13 c.
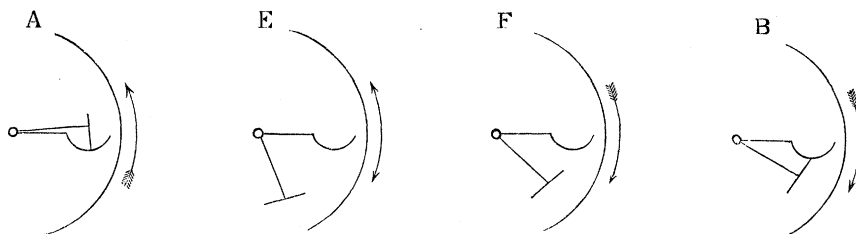
Exhaustion ·18 **M**.

In position A (Fig. 13 c), the speed was 53 revolutions a minute positive.

In position E, the screen being 13 millims. from the convex side of the vanes, there was no rotation.

In position F, the screen and vanes being 5 millims. apart, there was negative rotation of 4 revolutions a minute.

In position B, the vanes and screens touching on the convex side, there was negative rotation at the rate 12·5 turns a minute.

414. From these observations, which are in conformity with several hundreds of experiments tried at different distances and pressures, the following laws can be traced.

a. When the screen touches the concave surface of the vanes, the rotation is always positive. It commences at a low exhaustion, increases in speed till the rarefaction is so high that an ordinary radiometer would begin to lose sensitiveness, and afterwards remains at about the same speed up to the highest rarefaction yet obtained.

b. At any rarefaction after 87 **M**, there is a neutral position for the screen. When it is on the concave side of this neutral position the direction of rotation is positive, and when on the convex side of the neutral position the direction of rotation is negative. The speed of rotation is greater as the vanes are further removed from this neutral position on either side.

c. The position of this neutral point varies with the degree of exhaustion. Thus, at 12 **M** the screens must be 3 millims. from the convex side ; at ·18 **M** they must be 13 millims. from the convex side. The higher the exhaustion the greater the distance which must separate the convex side of the hemi-cylinders and the screens.

415. The various behaviours of these screened flies can be explained in the following manner. Fig. 14, A and B, represents the instrument in full sized plan, when the screen touches the convex surface of the hemi-cylinder. The radial black and dotted lines are supposed to represent the direction and extent of lines of pressure in a manner sufficient to enable the mind to follow the train of reasoning, but without implying that they indicate more than a very limited part of the whole action. It will be remembered that in this position, when the exhaustion is 117 **M**, the fly rotates positively (409), and that at an exhaustion of ·18 **M**, the fly rotates negatively (414).

Fig. 14.

Exhaustion 117 M.   *Exhaustion* ·18 M.
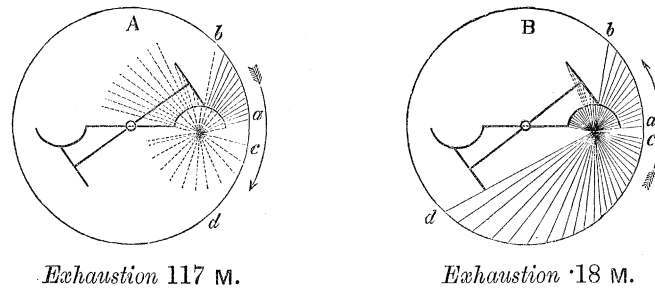
I have already shown (312) that when thin aluminium vanes are exposed to candle light the metal becomes equally warm throughout, and a layer of molecular pressure is generated at its surface. The thickness of this layer of pressure, or the length of the lines of force of repulsion, varies with the degree of exhaustion, being longer as the exhaustion increases. The lines of force radiate from every part of the warm metal, and being strongest in a direction normal to the surface it will be convenient only to recognise these in a discussion of their action. The force of repulsion is also greater the closer the repelled body is to the generating or driving surface, and the force diminishes rapidly as the distance increases, according to a law which has not yet been accurately determined,* but which does not appear to be the law of "inverse squares." It will also simplify matters if the interfering action caused by the pressure generated by the warm glass bulb is neglected.

In fig. 14, A, the exhaustion is low (117 M), and the thickness of the layer of pressure I assume to extend to a distance of 10 millims. from the surface of the aluminium vane. The lines in the diagram are represented as extending for that length from the hemi-cylinder in directions normal to the surface. Where the lines of force extend from the fly to the glass case, as at a to b and c to d, pressure is exerted along the line, and repulsion ensues ; these are represented by black radial lines. But where the lines of force do not reach to the glass, as shown by dotted lines, no pressure is exerted. In the position and under the conditions shown in fig. 14, A, the rotation must be in the direction of the arrow or positive, as the pressure in the positive direction exerted by the lines of force between a and b more than counterbalances that in the negative direction exerted by the lines between c and d. Inasmuch as some active lines of force are cut off by the screen, increase of the distance between the screen and the convex surface of the vane will allow more rays of force to become active, and will increase the speed in the positive direction.

416. In fig. 14, B, I have represented the action when the screens and vanes are in the same position as in 14, A, but at an exhaustion of ·18 M. Here the thickness of the layer of molecular pressure is supposed to extend to a distance limited by the

* See the Author's "Experimental Contributions to the Theory of the Radiometer." Proc. Roy. Soc., November 16, 1876, No. 175, vol. xxv. p. 310.

size of the bulb. The positive pressure between a and b is now overweighted by the negative pressure between c and d, and rotation is therefore produced in the direction of the arrow, or negatively. If we imagine the arm carrying the screens to be rotated on the axis, it will be seen that as one screen leaves the convex side of the vane, more of the positive rays of force are rendered active, whilst negative rays are cut off by the lower screen. Hence, as the screens are moved round, the fly will gradually rotate less strongly in the negative direction ; it will become neutral when the screens are in such a position that the opposing forces balance ; and ultimately it will rotate positively. This is what experiments prove to be the case (413).

I have tested this explanation by comparing with it the whole of the phenomena obtained with movable screens in various positions and at different pressures as described in pars. 391 to 413, and in no case does it fail. There is therefore high probability that it is true.

417. An apparatus (fig. 15) was constructed not differing in principle from the last, but having, in addition to the aluminium hemi-cylinder and movable mica screen, a small rotating fly made of clear mica, mounted in such a way that it could be fixed, by means of an exterior magnet, in any desired position inside the bulb ; the screen was also capable of adjustment by means of another magnet. The aluminium hemi-cylinder was in this apparatus immovable. The adjustible indicator, being very small in diameter, in comparison to the other parts of the apparatus, and being easily placed in any part of the bulb, was expected to afford information as to the intensity and direction of the lines of pressure when a candle was brought near the bulb.

It will be impossible within reasonable limits to give more than a few general results which I have obtained with this apparatus. Experiments have been tried :—

a. With the screen in different positions in respect to the hemi-cylinder ;

b. With the indicator in different parts of the bulb ;

c. With the candle at different distances from the hemi-cylinder, on one side or the other ; and

d. With the degree of exhaustion varying between wide limits.

These four conditions have been varied in numerous ways, and each time experiments have been tried both with and without an alteration in some or all of the other conditions. Although much time has been spent in this mode of experiment, it will be understood that, with so vast a number of possible combinations, only a few of the most obvious can be thoroughly investigated.

418. I will neglect the results at inferior exhaustions, and will confine myself to results obtained with a rarefaction of 12 **M**.

Fig. 15 gives a perspective view of the working parts of the apparatus ; a is the aluminium hemi-cylinder rigidly fastened to an arm fixed to the bulb ; $s\,s$ is the mica screen, drawn up close to the concave side of the hemi-cylinder ; $s'\,s'$ shows the same screen when moved some distance away. The screen can be moved right round the bulb, till it comes into position s'', where it is shown touching the convex surface of the

aluminium. The indicator i, which can be put into any part of the bulb, is a very small and light fly of a radiometer, the vanes being of clear mica not blacked on either side, and each being about 2 millims. square. They rotate under the influence of a very slight force, and the direction of rotation gives the direction of the force, and also shows on which side it is increasing or diminishing.

Fig. 15.
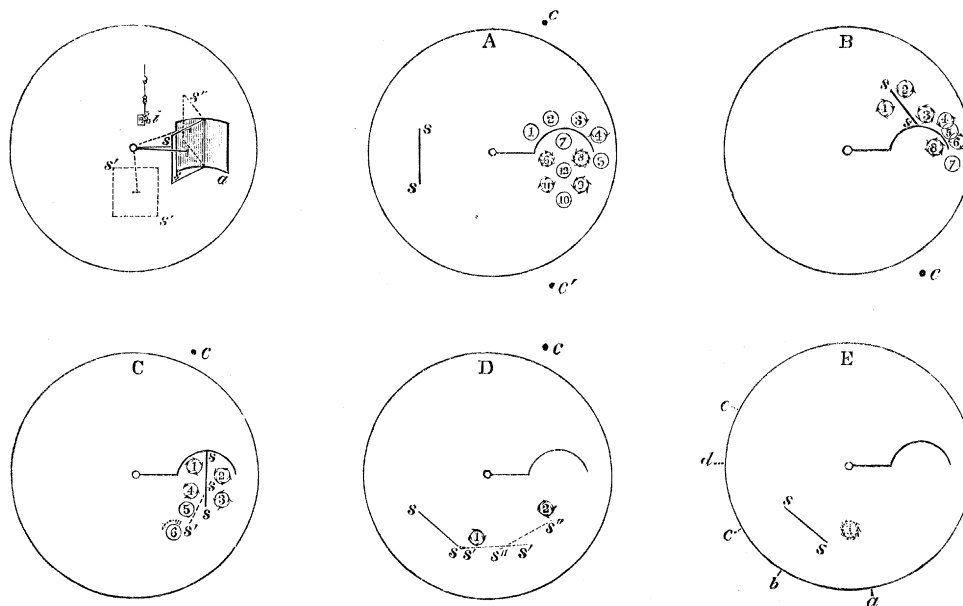
419. Fig. 15, A, is a plan of the hemi-cylinder a, with the mica screen $s\ s$ put as far from it as possible, so as to exert no appreciable influence on the movement of the indicator. The small circles, 1, 2, 3, &c., show the different positions in which the indicator was placed, the candle being at c when the indicator was (apparently) below the hemi-cylinder, and at c' when it was above—the object being to prevent the light from the candle, or the force from the heated glass near it, from falling direct on the indicator; my wish being that the indicator should be moved as much as possible by the force generated by the hot aluminium.

The direction of the arrow heads on the circles shows the direction of rotation taken by the indicator, and the number of arrow heads show the relative velocity. In positions 1, 2, 5, 7, 12, 10, there was no rotation. A reference to the hypothetical lines of force given in fig. 14, B, shows that along the line of positions 7, 12, 10, there would be equality of force on each side. At 5 also is another point of neutrality, the indicator being midway between the positive rays of force $a\ b$, fig. 14, B, and the negative rays $c\ d$, in the same figure. Positions 8 and 6 are those of greatest movement; this also is intelligible, as the indicator is struck almost entirely on one side. Position 8 is slightly the most favourable to sensitiveness; this is probably owing to that end of the aluminium hemi-cylinder being a little warmer than the other, from

the conduction of heat away along the arm. The direction of movement in 8 and 6 is also in accordance with theory. The slight action on the convex side of the curved metal plate is probably due to the lines of force acting here in both directions to and fro between the metal and the glass. This would cause the pressure here to be much greater than on the concave side, but at the same time would cause much less rotation. The slight movement in position 4, and its direction, is caused by the molecular disturbance generated on the surface of the aluminium, where it is nearest the glass, being struck back in somewhat greater quantity than at position 3, where the interval between the metal and glass is greater. In positions 1 and 2 the lines of force issuing from the convex surface strike each side of the indicator equally, the opposing face of the glass being too far off to cause a reaction.

420. Fig. 15, B, represents the position in which the mica screen, s s, was next placed, touching the convex side of the hemi-cylinder. The candle was at c, and the circles represent the successive positions of the indicator. The screen has now entirely altered the disposition of the lines of pressure. Position 3, where in the last experiment the indicator was almost stationary, is now the position of greatest speed. The indicator, in fact, has the rays which, in the absence of the screen, struck it on both sides, now acting on one side only, and the result is a rapid rotation in the direction of the arrows. No. 1 is the next best position, and then 2. The velocity and direction of movement in these two positions are clearly due to rays of force not acting so strongly on the side next the screen. As the indicator is moved in the other direction, away from the most sensitive position 3, the influence of the screen diminishes; at 4 the rotation is slight; and at 5 there is no movement. In position 6 the influence of the screen has almost disappeared, the motion now being opposite to that at No. 4. At 7 there is another position of neutrality, and at 8 the motion is again reversed. The movements in the last three positions correspond with those in similar positions when the screen was absent (fig. 15, A).

421. The screen was now moved round till it touched the hemi-cylinder on the concave side, as shown at s s in fig. 15, C. On comparing the direction taken by the indicator with that in fig. 15, A, it will be seen that no change is produced in positions 1, 2, and 3 (corresponding to 6, 8, 9, fig. 15, A), the speed only being reduced. In positions 4 and 5 the interference of the screen has caused the direction of rotation to change. The lines of pressure, being deflected by the mica, now radiate towards the centre of the bulb, and being stronger the nearer they are to the generating surface of aluminium, cause the indicator to rotate, as shown at 4 and 5. In position 6 there is no movement when the screen is close to the hemi-cylinder, but when it is brought into the position shown by the dotted line s' s', rays are deflected, and the indicator is rotated in the direction shown by the dotted arrow.

422. The screen thus renders evident the existence of active lines of force at great distances from the generating surfaces. A reference back to fig. 14, B, shows certain hypothetical lines of force stretching across the bulb from the generating hemi-cylinder

to d, and being obstructed by the screen. The present apparatus seemed capable of rendering those rays sensible. The indicator was accordingly placed in position 1, fig. 15, D, the screen being quite away from it and the candle being at c. The rays of pressure are here supposed to start from the hemi-cylinder, and strike both sides of the indicator equally ; the result is that no movement is produced. Without moving the indicator, the screen was brought into position $s\ s$. The indicator immediately rotated rapidly in the direction of the arrow heads. The action of the screen here is to strike back the impinging molecules, and thus cause a neutralisation of the pressure acting on the left side of the indicator. The line of pressure acting on the right side of the indicator passes on unimpeded, and therefore causes rotation. This explanation was verified by putting the indicator in position 2, and gradually bringing the screen nearer to it. With the screen at s, there was no movement. When the screen got to position $s'\ s'$, movement of the indicator commenced ; and when it reached position $s''\ s''$, the rotation of the indicator was rapid. A glance at the lines of force in fig. 14, B, will show how closely theory and experiment agree.

423. The action of heat applied to the bulb was now tried, the indicator being in position 1, and the screen at $s\ s$, fig. 15, E. A spirit flame was applied for a few seconds to the bulb at $a\ b$. There was rapid rotation of the indicator in the direction of the arrow heads, with strong negative rotation on cooling. When the action had ceased, the part of the bulb between c and d was heated ; the result was rapid rotation in the opposite direction to the arrow heads. These movements are perfectly explicable on the supposition that lines of pressure radiate from the hot internal surface of the glass, and, being partly cut off by the screen, strike the left or the right side of the indicator as the case may be. When the bulb is heated in such a part that the lines of force are entirely cut off, or are not at all obstructed by the screen, as at $d\ e$, or $b\ c$, no rotation of the fly is produced.

424. In the hope of deciding whether the force was capable of true reflection from a surface on which it impinged, or whether it was only deflected out of its course as a current of air would be, the apparatus represented in plan in fig. 16 was fitted up. A represents a plate of aluminium, lampblacked on each side, firmly fixed in the centre of a large glass globe capable of good exhaustion. B and B' are clear mica screens, a little larger than the aluminium plate, and capable of being held in any desired position by exterior magnets. A little exploring fly, as in the last experiment, shows the direction and strength of the lines of pressure. The positions into which this indicator was brought are shown by small circles. The candle was at c. It was found that similar results were obtained wherever the candle was placed, allowance being made for the interfering actions of the screens, but at c there was less interference than at any other part outside the bulb. The force is supposed to issue from the plate A in a direction normal to its surface. The dotted lines $a\ a'\ a''\ a'''$, $b\ b'\ b''\ b'''$, $c\ c'\ c''\ c'''$, show the direction taken by the lines of pressure, supposing specular reflection to take place from the surfaces of B and B'.

In positions 10 and 1 no rotation was produced; rotation in one direction was produced at 9, and in the other direction at 11; these results agree with those given with apparatus 15. In position 2, rotation was obtained in the direction of the arrow heads, and it was still stronger in the same direction at 3. These also agree

Fig. 16.

with theory. At 4 and 5 there was slow rotation in the direction of the arrows. Were the lines of force to follow the path shown by the dotted lines $b\ b'\ b''\ b'''$, &c., there should have been no rotation in these positions, but supposing the line $c'\ c''$ to have struck the indicator in position 5, there might be slow rotation in the opposite direction to what is here shown.

The black lines $d\ d'\ d''$, $e\ e'\ e''$, show the direction which the lines of pressure might take, supposing they were merely deflected out of their course by the screen B. On this supposition the movements of the exploring fly are quite reasonable. At 4 the force, striking one side only, would cause rotation in the direction as shown, and at 5 rotation in the same direction would also take place, but not with the same speed, owing to its being more surrounded by the stream. On moving away the screens, the fly remaining at position 5, the rotation stopped. The indicator was successively brought to a great many positions in respect to the screens, and the screens were also moved about to different parts of the bulb, and the results were in all cases easy of explanation on the de-flection theory, whilst they were sometimes contradictory on the re-flection theory. At 8 there was rotation due to the screen B cutting off some of the force from one side of the fly. At 6 and 7 there was no rotation, the screen B' having obstructed all the force.

The molecular pressure at the exhaustion found best for these experiments diminishes greatly as the distance from the plate A increases; it is not easy, therefore, to say whether a diminished speed, as in positions 2, 4, and 5, is due simply to increased distance, or to some action of the screens; but from the indications given generally by the exploring fly, I have come to the conclusion that the force is not reflected in the sense that light is reflected, but that it is merely deflected from a surface against which it strikes, as would be the case with a molar wind.

ACTION OF HEAT APPLIED INSIDE THE RADIOMETER.

425. In a previous paper it has been shown that phenomena, feeble and contradictory when caused by radiation external to the bulb, became vigorous and uniform when the radiation was applied internally by the agency of an electrically heated wire (336 to 384). It was hoped that some of the more obscure phenomena shown by the deep cups with movable screens in front (400, *et seq.*) might be intensified if set in action by a hot wire.

Fig. 17.
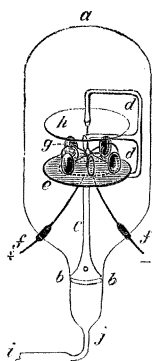
An apparatus was made similar to the one described and figured in a former paper (360, fig. 32, C D), but instead of the movable fly being of sloping mica vanes, it was composed of deep metallic cups with mica screens in front, capable of being brought by tapping any desired distance from the cups. This fly is similar to the one shown in fig. 8, paragraph 400, the complete instrument being shown in the annexed cut, fig. 17. It consists of a wide glass tube, *a, b b*, sealed off and blown round at *a*, and drawn off narrow at the end *b b*. Inside is a stem *c d d*, with branches. A disk of silver-flake mica, *e*, lampblacked on the upper side, rests on the platinum wire ring, the ends of which are joined to thicker platinum wires passing through the glass at *f f*. The disk *e* is pierced in the centre, through which passes the stem *c*, carrying a needle point on which the compound fly *g* rotates. Above the fly is a flat disk of clear mica, *h*, having a glass cap in its centre, and rotating on a needle point. The fly and the clear mica disk are supported independently of each other on separate needle points held in the glass rods *c, d d*. The tube *i* connects the apparatus with the mercury pump, and when the apparatus is exhausted to the requisite degree it is sealed off at *j*. The wire is heated by two GROVE's cells connected with *f f*, the current passing through a contact key, resistance coils, and galvanometer, to keep it constant, as explained in a former paper (359).

The plan of the adjustable fly with aluminium cups and mica screens is shown in a previous drawing (fig. 8, par. 400). The different positions of the screen are also

shown on the same figure, so I shall refer to the positions there given to illustrate the results here obtained.

426. The mica screen was in the first experiment adjusted in the position shown at fig. 8 A, or as close as possible to the convex surfaces of the cups. The rare-faction was brought to 12 M. Electric contact being made, the wire ring became red hot, heating the blacked mica disk which rested on it. The fly commenced to revolve in the negative direction $\overset{\text{\tiny ***}}{\mathcal{J}}$, at first slowly, then quicker, and afterwards slowly again, finally coming to rest after it had completed 34 revolutions. It now oscillated a little, and then remained quiet, although the battery contact was kept down, and the wire was glowing red. After remaining thus for a little time battery contact was broken. Instantly the fly acted as if released from a state of tension, and rotated in the positive direction $\overset{\text{\tiny ***}}{\mathcal{J}}$, coming to rest only after a con-siderable time.

427. The screens were now adjusted midway between the cups, as shown at fig. 8, E, and the foregoing experiment was repeated. As soon as the wire was made hot the fly commenced to rotate negatively, and after making $20\frac{1}{4}$ revolutions it stopped. Now, however, instead of remaining quiet as in the last experiment, the fly commenced rotating in the opposite direction $\overset{\text{\tiny ***}}{\mathcal{J}}$, and kept moving at an uniform speed of 50 revolutions a minute, as long as battery contact was maintained. On breaking contact the fly considerably increased its speed for some time, then gradually got slower, and finally came to rest.

428. In this experiment the screens were brought close to the concave faces of the cups, as in fig. 8, G. The fly made 15 revolutions in the negative direction $\overset{\text{\tiny ***}}{\mathcal{P}}$, it then stopped and rotated positively $\overset{\text{\tiny ***}}{\mathcal{P}}$ at a speed of 86 revolutions a minute, keeping at this rate as long as the wire remained hot. On allowing the wire to cool, the speed got much faster at first, and then declined till the whole apparatus was cold, when all movement ceased.

429. Experiments were now tried with the screens in various positions intermediate between those described in the foregoing paragraphs. The results differed in no material respect from those given above, the number of preliminary negative revolutions and the speed of the continuous positive revolutions being the chief variations.

430. An alteration was made in the fly, the clear mica screens being lampblacked on the sides facing the concavity of the cups. On repeating the experiments described in pars. 426 to 428, it was found that the blackening had caused a change in the order of the phenomena. When the screens and cups were in position A, fig. 8, and no lampblack was on the screens, the action of the hot wire was to cause the fly to remain at rest, after having revolved a certain time negatively (426). Now, however, with the mica screen lampblacked, and in the same position, i.e., close to the convex surface of the cups, the permanent rotation was at the rate of 30 a minute positively, after having made 22 preliminary negative revolutions. Again, when the blacked mica

screen was brought close to the concave surface of the cups, as at fig. 8, G, the preliminary negative revolutions were too rapid to count ; after a time they slackened and ceased, and the fly then refused to move till the current was turned off, when it seemed to be suddenly released from constraint, and revolved rapidly in the positive direction.   A reference to par. 428 will show that when no lampblack was on the mica screens there was permanent rotation in this position at a somewhat rapid rate, after the first preliminary turns had taken place.

431. The fly and screens were now altered in the several ways described in pars. 403, 404, 405, 406, 408, and numerous experiments were tried with them, the relative positions of cups and screens being altered each time.   To recapitulate the several results would be wearisome.   I will therefore shortly say that they confirm what has already been said as to the effect of the hot wire.   In all cases whilst the fly was receiving heat from the wire the direction of motion was negative.   When the fly had ceased to increase in temperature the continuous rotation was positive, but occasionally a position of fly and screens was met with at which no movement took place (426, 430). On breaking battery contact, and allowing the whole instrument to cool, the first effect was to cause the fly to move at a greater speed positively, gradually slackening till it had cooled down to the ordinary temperature, when all movement ceased.

Besides these I tried two other forms of fly, which yielded results of sufficient interest to be worth giving more in detail.

432. The first fly consists of a single arm, supported in the centre by a glass cap working on the needle point, and having at one extremity a small metal counterpoise, and at the other a single aluminium cup.   The cup is supported on the horizontal arm, which forms an axis traversing the centre of gravity of the cup through holes pierced in the sides.

Fig. 18 shows this arrangement of fly ; a is the counterpoise balancing the cup b ;

Fig. 18.
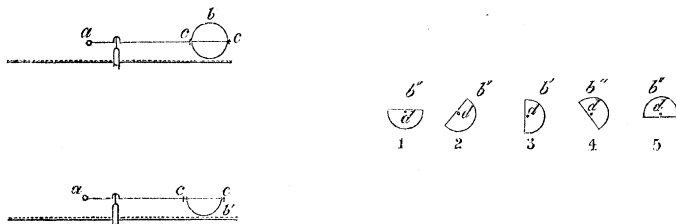
the axis passes through holes shown at d, on the side view of the cup b''.   Stops $c\,c$ on the axis keep the cup in position, and just sufficient friction is secured to retain the cup in any desired position, shown at b'', 1, 2, 3, 4, 5, into which it may be brought by tapping the apparatus.   The remainder of the apparatus, the black mica disk, the platinum wire ring, &c., is the same as before.

When the cup was set horizontally with the concavity upwards, as shown at b', and

also at b'' 1, no movement took place after exhaustion, when the platinum wire was ignited.   In the reverse position, the concavity being downwards, as at b'' 5, there was also no movement.

With the cup in position 2, there was no movement on igniting the platinum wire and keeping it hot.   When the current was cut off, and the wire and inside of the apparatus allowed to cool, good rotation took place in the direction ◿ .

When the cup was turned over a little less, so as to get it about halfway between positions 1 and 2, no movement was produced either on heating or cooling.

With the cup in position 3, heating the wire caused the fly to make 18 revolutions in the direction ◺ .   It then oscillated and came to rest, the wire remaining hot.   On turning off the battery current no further movement took place.

In position 4 the hot wire gave a rotation in the direction ◹ , at the rate of 150 a minute.   When still further turned over, till the cup was halfway between positions 4 and 5, the speed was 120 a minute in the same direction.

433. The other fly experimented with also consists of a single arm, with cap in the centre and counterpoise at one end.   Instead of an adjustable cup, the other end

Fig. 19.

A

supports rigidly a right-angled hollow mica prism, shown at fig. 19 in end view and perspective.

After exhaustion the current was turned on, and the fly immediately rotated in the direction shown by the arrows, keeping up continuously as long as the wire remained hot.

This experiment, I think, proves that the direction of the pressure is not wholly normal to the surface on which it is generated.   Were it so, no movement would have taken place, as the base of the prism was in a parallel plane to the blacked mica disk. A tangential direction of the lines of force will, however, exert more pressure on the perpendicular face of the prism than on the hypotenuse, and will drive the fly round, as shown at fig. 19, A, in the direction given by experiment.

THE TURBINE RADIOMETER.

434. Experiments tried with the apparatus described in a former paper (336, 345, 354), where thin mica vanes, inclined at an angle of 45° to the horizontal plane, form the fly of the radiometer, show that this form of fly possesses advantages in cases where the incident radiation falls at an angle on the instrument ; and the favourably-

presented radiometers, when tested with the hot metal rings applied equatorially and at the poles (298 to 305), showed that the action of radiation was in some cases entirely different, according as it fell on the vanes horizontally or nearly vertically. The experiments just described with the sloping adjustable cup (432) show still more forcibly the great difference in speed of rotation caused by a little alteration in the angle presented by the vanes to the direction of pressure. These experiments were, however, tried with somewhat complicated apparatus. A simpler form of instrument, in which full advantage is taken of the peculiarities of sloping vanes, was exhibited before the Royal Society on April 5, 1876, under the name of the turbine radiometer.

Fig. 20.
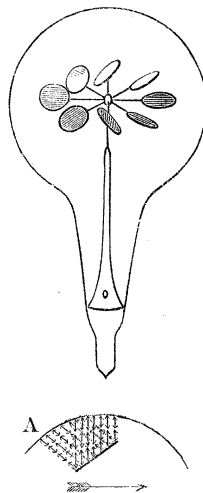
In the earlier radiometers of this kind the vanes were of mica, blacked on both sides, and inclined at an angle like the sails of a windmill, instead of being in a vertical plane. These are not sensitive to horizontal radiation, but move readily, in one or other direction, to a candle held above or below. If one side only of each vane is blacked, the fly becomes more sensitive to radiation falling on the black side, but is not sensitive when radiation strikes it on the other side. In the ordinary form of radiometer, the number of disks constituting the fly is limited to six or eight, a greater number causing interference one with the other, and obstruction to the incident light. In the turbine form of fly there is no such difficulty; the number of vanes may be increased to a considerable amount without overcrowding, and with corresponding advantage. The action of the vanes is evident. Fig. 20 shows the turbine vanes; light falling from above generates molecular pressure between the surface of the vanes and the top of the exhausted bulb, and this pressure, acting as at A, drives the fly round in the direction of the arrow. A vertical light gives the strongest action, but rotation takes place whatever be the incident angle, provided the light is caught by one surface more than by the other. If the finger, or any warm substance, touches the top of the bulb, so as to generate pressure from the inner surface of the exhausted bulb, the fly is strongly driven round in the direction shown at fig. 20, A

(which I will call *positive*). The lower half of the bulb grasped in the hand causes pressure to be exerted on the vanes from below, and the resulting rotation is *negative*.

435. Ether dropped on the top of the bulb to chill it causes rapid negative rotation. If the radiometer is floated in a vessel of ice-cold water, and exposed to the air of a warm room above, it rotates rapidly in the positive direction, acting as a heat-engine, and continuing so to act until the rotating fly has equalised the temperature of the upper and lower portions of the bulb.

By reversing the cycle of operations—by floating the radiometer in hot water, and cooling the upper portion of the bulb—the fly instantly revolves in the negative direction.*

436. The turbine fly mounted vertically works equally as well horizontally. In this form it is supported on a double pointed needle, working horizontally in glass caps. A little care is required in balancing the vanes, otherwise one side tends to fall to the lowest point, and there is a difficulty in first starting the movement. This *windmill* form is very sensitive to radiation falling on it parallel with its axis of rotation, and it has the peculiarity of continuing its movement in any position. When once started it may be turned round, upside down, or on either side, without interfering with the rotation of the fly so long as the sloping vanes catch the light.

If mica vanes are used in the turbine radiometer they should be oval, the arms of the support passing through the minor axis, so that when viewed from the direction in which the light should fall on them their appearance will be circular.

437. The cause of the movement of the radiometer being pressure between the driving surface and the glass case of the instrument, it would follow that, other things being equal, the fly should revolve faster in a small bulb than in a large one.† This

Fig. 21.
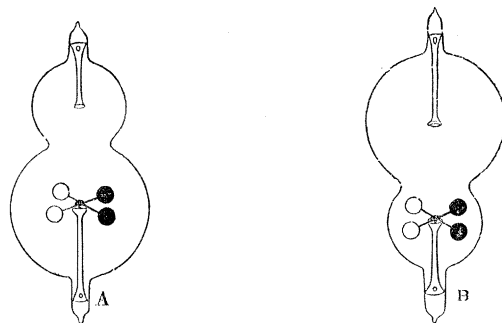
cannot well be tested with two different radiometers, as the weight of the fly and other essential points would not be the same in each, but I have constructed a double radiometer which shows this fact in a very satisfactory manner. It consists of two

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* Radiometers working in this manner were exhibited, with appropriate descriptions, at the soirée of the Royal Society, April, 5, 1876.

† Proc. Roy. Soc., November 16, 1876.

bulbs, one large and the other small, blown together so as to have a wide passage between them, as shown in fig. 21. In the centre of each bulb is a cup, held in its place by a glass rod, and in the bulb is a small four-armed fly with roasted mica vanes blacked on one side. The fly can be balanced on either cup, so as to admit of experiments being tried in position A or position B. In the larger bulb there is about half an inch between the vanes and the glass, whilst in the smaller bulb there is a space of a quarter of an inch. When exposed to the same source of light under identical circumstances, the mean of several experiments shows that in the small bulb (position B) the fly rotates about 50 per cent. faster than it does in the large bulb (position A).

438. [The following experiments show very clearly the influence of an alteration of density in the residual gas on the movement of a radiometer.

A small sensitive radiometer was fitted in a bulb $1\frac{1}{2}$ inch diameter, and a large bulb 3 inches diameter was connected to the lower limb of the radiometer by a narrow glass tube. The whole was then exhausted to about 35 M, and sealed off.

The large bulb was then placed in an air bath so arranged that it could be raised or lowered in temperature without altering the temperature of the radiometer, except by convection or conduction through the connecting glass tube. A candle was placed 3 inches from the radiometer, and observations of speed were taken whilst the temperature of the large bulb was raised or lowered. The mean of several observations showed that the speed of the radiometer was always reduced by heating the supplementary bulb, the expansion of the residual gas contained in it causing increased pressure in the radiometer bulb. On cooling the bulb, the speed of the radiometer increased. Taking the speed at the lowest temperatures at 10 a minute, the variations are as follows :—

Temperature.	Revolutions per Minute.
0°	10·
15°	10·
200°	6·9
300°	5·

W. C., November 21, 1878.]

439. Advantage has been taken of the fact, elicited in the experiment described in par. 437, in the construction of radiometers having flies of a spiral form.* By cutting a thin disk of aluminium into the form of a spiral, then drawing it out corkscrew fashion, and suspending it on a needle point in a tube in the usual way, the spiral rotates very quickly on exposure to light after proper exhaustion. The upper surface of the spiral is blacked, and it is kept of as large a diameter as will conveniently go in the tube. In this form, as in the turbine form of radiometer, the black surface is always exposed to the incident light instead of being alternately in light and in darkness. The driving surface is greater in this form than in the usual kind of fly,

* Proc. Roy. Soc., November 16, 1876.

and the distance between the reacting surfaces may be very small with corresponding advantages of increased speed.

Spiral flies of mica are much more sensitive than those of aluminium, but are less easy to make. A very sensitive spiral radiometer may be made by threading flat mica disks on a thin aluminium wire. The blackened surfaces must in all these instruments make an angle with the inner surface of the glass tube, or there will be no tangential action of the molecular pressure.

440. The following experiments were tried with an aluminium spiral radiometer exhausted to the most sensitive point. It was completely immersed in water at 20° C., and when quite still it was suddenly plunged into water at 60° C. Rapid negative* movement took place, continuing for a few minutes ; the fly then became still. When it was quiet in the hot water the radiometer was suddenly plunged into cold water (20° C.). Rapid positive movement took place, stopping when the temperature was uniform.

The radiometer was now heated with a lamp over the upper half of the tube ; the spiral immediately rotated positively, and continued so to do till quite cold. Heat applied in a similar manner to the lower half of the radiometer case caused the spiral to rotate rapidly in the negative direction. Whilst so rotating negatively, a lighted candle was brought near ; the fly stopped and then turned positively, resuming its negative rotation when the candle was removed, and continuing it till the tube and fly were cold. When the lower half only of the radiometer was immersed in hot water, the upper half being allowed to remain cool by radiation to the air, the negative rotation of the fly continued at an almost uniform speed, not coming to rest till the water was nearly cold.

These positive and negative movements of the spiral fly under the influence of partially applied heat are in strict accordance with the explanation already given, that when the glass case is heated its inner surface becomes the generating surface for the molecular pressure, which then acts as if it were a molar wind, repelling whatever happens to be within the sphere of its action (218, postscript).

441. In the foregoing experiments the results have in all cases testified to the truth of the theory that the glass case of the radiometer is essential to the movement. It was of interest to ascertain whether the substitution of another kind of surface for that of polished glass would have any effect on the motion of the fly. A radiometer was accordingly constructed with a four-vaned mica fly, the disks being blacked on one side. The case of the radiometer was made so that it could readily be opened and sealed again when a change of contents had to be made. Round the inner surface of the case an equatorial band of aluminium was fixed a little wider than the diameter of the disks on the fly, and coated with lampblack on the inner side. Fig. 22 shows the instrument complete. It was attached to the pump and

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* In all cases the positive direction is that in which the fly moves when exposed to candle or day-light ; the reverse direction being negative.

exhausted. A candle was placed 2 inches from the glass, and sufficiently above the level of the band to allow the rays to pass over it on to the fly. The exhaustion was continued until the maximum sensitiveness was obtained. Air was let in, and the speed at the pressure of greatest sensitiveness was taken several times ; it was

Fig. 22.
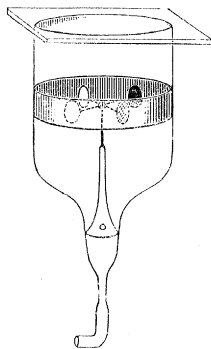
found to be 40 revolutions a minute, becoming less if the exhaustion exceeded or fell short of the most sensitive point.

The aluminium band was now removed and the experiment again repeated. At the pressure of maximum sensitiveness the revolutions of the fly were only 8·5 revolutions a minute, diminishing on each side of this pressure.

The black aluminium band was replaced, and a fly, with clear mica vanes, not blacked, and favourably presented (273), was suspended in the instrument. The experiments were now repeated as in the last case, and the result was as before— that the fly rotated more quickly with the aluminium band in, than when it was absent.

The increased speed in these experiments must not be entirely attributed to the fact that the blacked aluminium band presents a better reacting surface for the rebounding molecules than does the polished glass. In the first place, the introduction of the metal band slightly diminished the distance between the fly and the reacting surface ; and in the second place, the rays from the candle not only shone on the fly, but also on the opposite hemi-cylinder of black aluminium, and warming it converted it into a driving surface. Each of these actions would cause an increase of speed in the fly ; but added together, they could only account for a part of the jump from $8\frac{1}{2}$ to 40 revolutions. The diameter was only to a slight extent diminished, and it has been shown that a much greater reduction of diameter (437) had only power to add 50 per cent. to the speed. The effect which the light of the candle shining on the blackened hemi-cylinder would have on the speed was ascertained by placing the candle in such a position that it would illuminate the inner half of the aluminium band, while its direct action on the fly was cut off by screens. The driving action of the pressure from the cylinder was shown in this way to be only equal to about $13\frac{1}{2}$ revolutions a minute.

ROTATION OF THE CASE OF THE RADIOMETER.

442. Granting the existence of pressure acting between the fly and the case of the radiometer, it follows that one being held fast the other must move. Usually, the bulb is fixed and the fly rotates, but if the conditions are changed and the fly fixed while the globe was free to move, the latter must rotate. On March 30, 1876, I brought before the Royal Society an experiment in which this was shown to be the case. I quote the following opening sentence from the short note of this experiment which was published at the time*:—" During the discussion which followed the reading of Professor REYNOLDS's and Dr. SCHUSTER's papers at the last meeting of the Royal Society, I mentioned an experiment bearing on the observations of Dr. SCHUSTER. I have since tried this in a modified form, and as the results are very decided, and appear calculated to throw light on many disputed points in the theory of these obscure actions, I venture to bring a description of the experiment, and to show the apparatus at work before the Society."

The experiment was as follows : A radiometer was employed, the fly of which carried a magnetised needle. The radiometer was floated in water, and four candles were brought near. The fly immediately rotated, carrying round the magnetic needle. A powerful magnet was held over it, when the rotation of the fly was arrested, and the glass envelope rotated in the opposite direction to that in which the fly had been moving, the rotation keeping up as long as the candles were burning.

443. I have tried numerous forms of radiometer in the endeavour to ascertain the best kind for showing this rotation of the envelope. Turbines with pith or with metal flies, and arranged to rotate when floated on hot or cold water, did not give good results ; neither did any variety of radiometers with metallic cup flies. By far the most sensitive form is one in which the fly carries four silver-flake mica disks, lamp-blacked on both sides. Over the glass cap carrying the fly, another fly stifly works, carrying four other disks made of clear mica. A reference to fig. 4, par. 392, will explain the arrangement, it being understood that the instrument now described is four-vaned instead of two-vaned, and the opaque mica disks are blacked on both sides instead of on one side. The arms carrying the clear mica screens also carry a magnetic needle. By tapping the instrument the screens can be brought close to the black vanes on either side. When exposed to light, rapid rotation is produced, the exposed side of the lampblacked vanes being repelled. By altering the position of the screens, so as to obscure either one or the other black surface, rotation can be produced in either direction. By increasing the distance between the screens and the blacked mica, the rotation is made slower ; and by putting the screens midway between the vanes rotation ceases. Reference to par. 392 shows that the present results entirely confirm those there given. Shots are sealed in the lower part of the case to act as ballast and keep it upright when in water.

* Proc. Roy. Soc., No. 168, March 30, 1876.

444. The radiometer was floated in water contained in a large beaker, and a cover was placed over it to prevent interference from air currents. The screens were brought close to one side of the vanes, and the whole was exposed to sunlight. The force of repulsion at once overcame the power of the magnet, and the compound fly rotated rapidly. A strong magnet was then brought near the bulb, the motion of the fly was arrested, and immediately the bulb rotated in the opposite direction, making about 6 revolutions a minute. So strong was the force of rotation that when the cover was removed, and a paper arrow 3 feet long was cemented to the top of the bulb, as long as the sunshine lasted this paper index was swung round the room 3 times a minute. On tapping the screens to the other side of the vanes, rotation took place equally well, but in the opposite direction.

445. The radiometer was brought into a dark room, and four candles placed near, the outside control magnet being in position. The bulb rotated about 3 times a minute. When its speed was uniform the control magnet was removed, liberating the fly, which then revolved under the influence of the internal pressure, the case and the vanes going opposite ways. After the bulb had made one-third of a revolution it stopped, and went back for about the same distance. Then it again stopped and made one-third of a revolution in the original direction. These oscillations kept on for a con-siderable time ; they seemed to get gradually less and less, but I did not observe that they stopped altogether. The motion of the bulb in the opposite direction to the fly was always more rapid than when it went with the fly. The movement of the fly kept up at a uniform speed as long as the experiment lasted.

446. It would seem that this oscillatory movement was due in whole or in part to internal friction, either of the steel point on the glass socket or of the vanes against the residual gas, or to both these causes combined. To ascertain what power this friction possessed the candles were removed, and as soon as the whole instrument had come to rest, a bar magnet was moved alternately from one side of the radiometer to the other, so as to cause the fly to rotate as if it had been exposed to light. The fly rotated rapidly, and the internal friction carried the glass envelope round in the same direction at the rate of about 1 revolution in 3 minutes, in opposition to the friction of the water against its sides.

447. The rotation of the envelope, the fly being fixed by a magnet, was also effected in another manner. Oblique mica vanes were fixed round the inner horizontal circum-ference of the bulb, and the movable fly, which carried a small magnet, was furnished with metallic vanes favourably presented (273), so that molecular pressure acting between them and the envelope should cause the fly to rotate. Inside the fly, coiled round the supporting glass stem, but not in contact with the fly, was a platinum wire spiral, the extremities of which were connected with thicker wires passing through and sealed into the glass bulb. By connecting these terminals with a battery the spiral was ignited, and the heat warming the metallic fly caused pressure to be exerted between the fly and the outer envelope, and produced rapid rotation. The

whole instrument was floated in water, and one of the outer terminal wires was caused to dip into a mercury cup at the bottom of the water, whilst the other terminal dipped into a ring-shaped trough of mercury surrounding the upper part of the bulb.   Battery wires were connected with the two mercury cups, when the fly rotated rapidly. On arresting the movement of the fly by means of a magnet, the bulb was seen to rotate in the opposite direction.   The movement, however, was feeble, and with difficulty could be kept up for any length of time, owing to the friction of the platinum wires in the mercury cups.   Having demonstrated the fact of rotation, further experiments seemed unnecessary.

448. The fixed vanes in the apparatus just described appearing to act in a very decided manner, further experiments were tried in this direction, as it was thought that the results might throw further light on the theory of the movement.

Fig. 23.
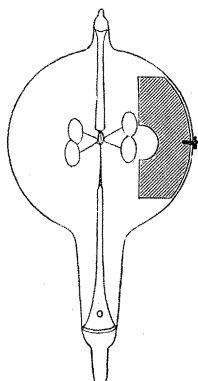
A radiometer was furnished with a fly, the four vanes of which were cut from thin transparent mica, and were mounted symmetrically with the axis of rotation, not being favourably presented.   At the side of the bulb, in a vertical plane, a plate of mica was fastened in such a position that each clear vane in rotating should pass it, clearing it by about a millimetre.   The mica screen was cut away in the middle to allow the vanes to pass, as shown in fig. 23.   The screen is a double one, formed of two plates of mica about a millimetre apart, the outer surface of one being lampblacked, the other being clear.   On bringing a candle near, and allowing the light to shine on the clear side of the mica screen, no effect is produced.   If by means of a shade the light is allowed only to shine on the clear mica vanes, there is still no action; but if the light shines on the blacked side of the mica screen, the fly rotates rapidly as if it were blown round by a wind issuing from the black surface, and keeps on moving as long as the light is near.

A similar instrument contained a mica screen, blacked on both sides.   The fly carried four bright aluminium cups (318).   On shading the light of a candle from the blacked mica screen, and allowing it to shine only on the cups, the fly rotates positively, the convex sides retreating from the light.   If the candle is allowed to shine only on the

black mica screen, the cups being unexposed, the fly is driven rapidly round in one direction or the other, according to which black side is illuminated, the cups going with almost equal readiness whether the convex retreats, as in an ordinary cup radiometer, or the concave retreats, as in ROBINSON'S anemometer. When the light shines on both screen and cups the rotation of the fly is always positive ; but the speed is much greater when the molecular pressure from the black screen conspires with, than when it opposes the positive motion of the fly.

449. It was suggested to me by Professor STOKES that it might be possible to get rotation in a radiometer with a perfectly flat fly, alike on both sides, by throwing the obliquity from off the fly on to the case. Following out the suggestion, three vertical partitions of thin clear mica were fixed in the bulb of a radiometer, with their planes not passing through the axis of rotation, but inclined, as shown in fig. 24, and slightly

Fig. 24.

Elevation of Partition and Fly.
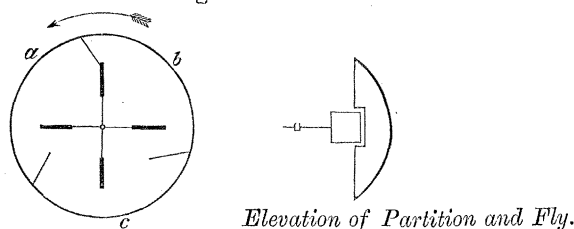
cut away to let the fly pass closely. The fly had four aluminium vanes, polished alike on both sides. Candles at *a*, *b*, *c* make the fly revolve rapidly in the direction of the arrow. Indeed, one candle is sufficient to produce rotation. Breathing gently on the bulb causes negative rotation. A hot glass shade inverted over the instrument causes strong negative rotation, changing to positive on cooling. When the fly is furnished with clear mica, or with silver-flake mica vanes, the same results are obtained as when aluminium vanes are employed. The strongest action is produced by warming the bulb.

THE OTHEOSCOPE.

450. The experiments on the rotation of the envelope (442 to 447) show that the surface generating the molecular pressure need not be the one which rotates. The apparatus shown in fig. 23, as well as the one described in a former paper (360), prove that it is an advantage to have the driving surface stationary. In the radiometer the surface which produces the molecular disturbance is mounted on a fly, and is itself driven backwards by the excess of pressure between it and the sides of the containing vessel. Regarding the radiometer as a heat-engine, it is seen to be imperfect in many respects. The black or driving surface, corresponding to the *heater* of the engine, being also part of the moving fly, is restricted as to weight, material, and area of surface. It must be of the lightest possible construction, or friction will greatly interfere with its movement; it must not expose much surface, or it will be too heavy ; and it must be a very bad conductor of heat, so as to retain the excess of pressure on one side. Again,

the part corresponding with the *cooler* of the engine (the side of the glass bulb) admits of but little modification. It must almost necessarily be of glass—one of the worst materials for the purpose; it is obliged to be of one particular shape; and it cannot be brought very near the driving surface.

451. To get the best results the *heater* should be stationary; it might then be of the most suitable material, of sufficient area of surface, and of the most efficient shape, irrespective of weight. The moving portion should be the *cooler*; it should be as near as possible to the *heater*, and of the most suitable size, shape, and weight for utilising the force impinging on it. The *heater*, or driving surface, acts as if a molecular wind* were blowing from it (276), principally in a direction normal to the surface (312). By having the heater of large size, and making it of a good conductor, such as silver, gold, or copper, a very faint amount of incident radiation would suffice to produce motion.

In April, 1877, I communicated to the Royal Society a preliminary note on a new instrument which I had made in accordance with these indications, and as it was essentially different in its construction and mode of action to the radiometer, I proposed to identify it by the distinctive name of *Otheoscope* (ὠθέω, I propel). Whilst the radiometer admits of but few modifications, such an instrument as the otheoscope is capable of an almost endless variety of forms. The glass envelope is an essential portion of the machinery of the radiometer, without which the fly would not move; but in the otheoscope the glass vessel simply acts as a preserver of the requisite amount of rarefaction. Carry a radiometer to a point in space where the atmospheric pressure is equal to, say, 1 millim. of mercury, and remove the glass bulb, the fly will not move, however strong the incident radiation; but place the otheoscope in the same conditions, and it will move as well without the case as with it.

452. The instrument described in a former paper (360), and repeated here with some alterations (425, fig. 17), fulfils the essential conditions of the otheoscope, and by allowing light to shine on the blacked mica plate instead of heating it with the platinum wire and battery, the vanes may be set into good rotation.

An instrument was made of this kind, leaving out the electrical portion so as to work entirely by radiation. It is represented at fig. 25, A. A plate of mica, *a a*, is attached firmly to the support *c*, and is lampblacked on the upper side; a fly, *b b*, with polished aluminium vanes, set at an angle of 45°, is supported by a glass cap on a needle point passing through *a a*, so that when rotating the lower edge shall be about a millimetre from the mica plate. Light shining on the black surface generates molecular pressure, which reacting on the sloping vanes drives them round

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* This movement of the molecules may be compared to the movement of the oxygen and hydrogen molecules when water is decomposed by an electric current. In the water connecting the two poles there is no molar movement whatever, although eight times as much matter is passing one way as the other.

with considerable speed.   The black disk is here the driving surface, the glass envelope not being active.

A more sensitive form of this construction is made by having a fixed copper disk lampblacked on the upper side, and making the vanes of mica for the sake of light-
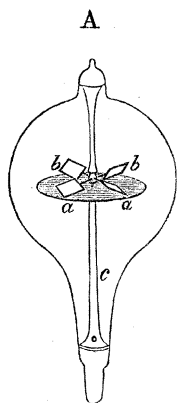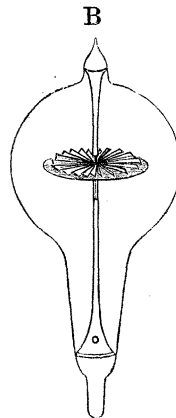
Fig. 25.

A

Fig. 25.

B

ness, fig. 25, B.   The vanes are as numerous as can be conveniently put together, and being set at an angle, the pressure from the copper plate drives them round with great speed when set in action with even a faint light.   Another form consists in suspending on the fly aluminium cups, turned at an angle of 45°, with the concave side downwards, as shown in fig. 18, No. 4 (432).   This form likewise proved very sensitive.

453. The pressure being exerted chiefly at right angles to the driving surface, it was thought that power was lost by the tangential action of the pressure in the above form of otheoscope.   Other instruments were therefore made with the driving surface of thick copper, cut into 16 equal portions by radial lines stopping short of the centre.   Each of the 16 sectors is then bent round to form an angle of 45° with the original plane of the disk.   This driving wheel is lampblacked and fixed to the support in the centre of the bulb.   Immediately above, and suspended on a needle point, is another disk cut into sectors, and bent at an angle exactly the same as the lower disk.   As the upper and lower sectors face each other, being in parallel planes, a force acting at right angles to the driving surface will also strike the movable fly at right angles, and drive it round in a more direct manner.   Experience shows that this form is attended with advantage.

These otheoscopes are very sensitive to heat externally applied.   If those shown in fig. 25 be warmed at the upper part above the movable fly, the fly is driven round in the negative direction ; the pressure which acts on the vanes from above giving the opposite rotation to that produced when pressure acts from below.

If the lower part of the case is warmed, no action is seen at first ; gradually,

however, the heat is communicated to the fixed driving wheel, and the fly then rotates positively.

When plunged into hot water the fly revolves negatively, and then stops as soon as the temperature is equalised. On removing it from the water positive rotation sets up, and continues with considerable speed till quite cold.

454. It was suggested by Professor STOKES that a disk might be made to revolve on its axis, and the following instrument was made in accordance with the design proposed. The disk is horizontal, mounted like the fly of a radiometer, and for lightness sake is of mica, blacked above. Fixed to the bulb above the disk are four flat pieces of clear mica; each extends from the side of the bulb to near the centre and ends below in a straight horizontal edge, leaving just space enough for the disk to revolve without risk of scraping. The edge is in a radial direction, and the plane of the plate inclined about 45° to the horizon, in the same direction for them all. Exposed to the light of a candle the rotation is against the edge, the same as in the instruments last described.

Fig. 26.

It was found on experimenting that a much more sensitive instrument could be made by slightly modifying this form. Fig. 26 shows the best construction of otheoscope with rotating disk. *a a* are six vanes of copper foil, oxidised by heating to redness in the air; they are attached to arms, and are inclined at an angle of 45° to the horizon, as in the forms of driving vanes previously described. These are fixed to the support. Through the centre passes a needle point balancing a glass cup; this carries a thin clear disk of mica, *b b*, freely rotating about a millimetre above the top edges of the copper vanes. When exposed to light, the mica disk rotates with great speed against the edges. If the lower part of the envelope is heated so that the pressure from the warm glass strikes against the vanes before reaching the disk, the direction of rotation is negative owing to the deflection of the pressure on passing between the vanes. As soon as the copper vanes have become warmed, they become the driving surfaces, and the rotation changes to positive.

The upper part of the mica disk in one of these otheoscopes was divided into sectors, each of which was painted with one of the component colours of white light. When exposed to sunshine the speed was so great as to cause the colours to blend together into a neutral grey.

The pressure which drives the movable fly round reacts equally on the driving surface (442). By suspending the driving vanes as well as the fly on needle points, so as to allow both to revolve freely and independently (345, 360), they both rotate under the influence of light in opposite directions. Otheoscopes have been con-structed of the forms shown in figs. 25 and 26, in which the upper and lower vanes
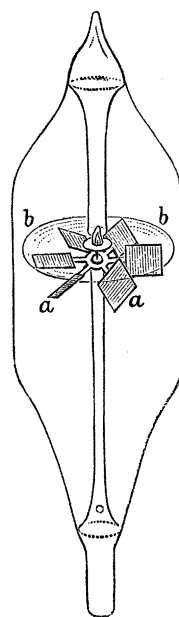
or disks are capable of rotation.   When exposed to light the movements take place in accordance with theory.

THICKNESS OF THE LAYER OF MOLECULAR PRESSURE.

455. Whilst experimenting with the otheoscope it was found that, for a given exhaustion, the nearer the reacting surfaces were together the greater was the speed obtained.   This was in accordance with previous results (437).   In a note on the theory of the radiometer which I had the honour of communicating to the Royal Society in November, 1876,* I briefly described a piece of apparatus by which I was able to measure the thickness of the layer of molecular pressure generated when radiation impinged on a blackened surface, enclosed in an atmosphere the rarefaction of which could be varied at will.

The apparatus which is represented in fig. 27 (plan and elevation), consists of a torsion balance, fitted with a glass suspending fibre and reflecting mirror, as already

Fig. 27.
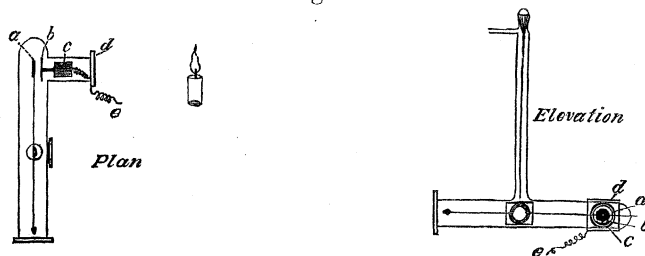
described in previous papers (102, 186, 198, 221, 259).   To one end of the beam is attached a disk, a, of silver-flake mica (238), lampblacked on the face.   The portion of the tube in front of this disk is opened out, and a short piece of wider tube is sealed on at right angles to the beam, as shown in the plan.   The outer end of this additional tube is ground flat, and closed with a piece of clear plate glass, d, cemented on.   In front of the blacked disk is a thin and perfectly clear disk of mica, twice the diameter of the black disk.   This is connected by a rigid arm with a lead plate, c, curved to fit the inside of the tube, and capable of sliding freely to and fro.   The clear mica screen, b, is easily and accurately adjusted any desired distance from the blacked disk, a, by gently tapping the under part of the glass tube on one side or the other of the lead weight.   The space between is measured with a millimetre scale.   The torsion beam is controlled by an outside magnet acting on a small magnetised needle attached to the reflecting mirror of the beam.

456. The friction of the lead plate when sliding to and fro in the glass tube, especially

* Proc. Roy. Soc., No. 175, 1876, vol. xxv. p. 310.

at high exhaustions, produced slight electrification, which caused the two disks to be drawn together.   This was remedied by connecting the lead to earth by a fine wire, e.

A candle was used as the source of radiation; it was set a measured distance from the blacked disk.   Its rays were cut off by water and opaque screens, except at the time of trying an experiment; and all extraneous radiation, or interference from the warmth of the body, was cut off by water screens and black velvet placed around.

The scale to receive the reflected index of light was 3 feet from the mirror.   A movement of the blacked disk to the extent of 1 millim. produced a deflection of 32 divisions on the scale.

457. Preliminary experiments showed that it was not necessary to rarefy the air in this apparatus to get repulsion.   By moving the control magnet sufficiently far off to secure great sensitiveness, and putting the candle 120 millims. from the blacked disk, the following results were obtained at ordinary atmospheric pressure :—

T. = Tension in millimetres of the gas in the apparatus.

C. = Distance in millimetres of the candle from the blacked disk.

S. = Distance in millimetres separating the screen and disk.

F. = Force of repulsion represented by the degrees on the scale covered by the first swing of the luminous index.

T.	C.	S.	F.
millims.	millims.	millims.	
748	120	1	36·7°
,,	,,	2	20·7
,,	,,	4	11·0
,,	,,	8	3·5

Plotted on a curve, the results in columns S and F give the line shown in fig. 28.

Fig. 28.
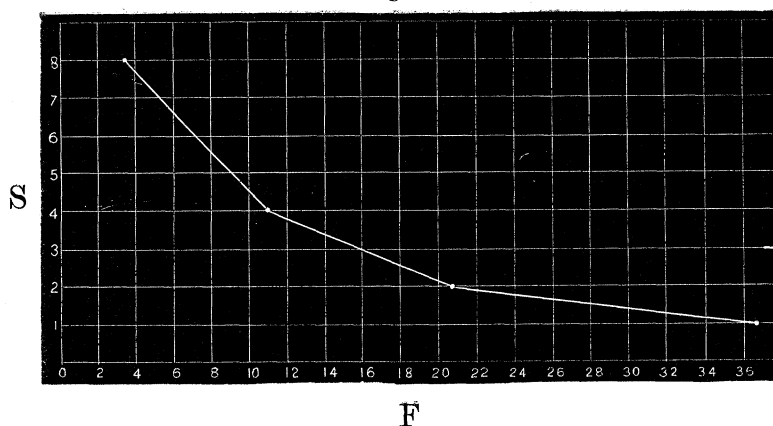
458. The repulsion being so decided at atmospheric pressure, the apparatus was

made less sensitive by the control magnet, and the candle was placed 200 millims. off. Exhaustion was then commenced, and observations were taken as recorded in the following table, each result being the mean of several observations :—

T.	C.	S.	F.
millims.	millims.	millims.	°
129	200	1	4·
,,	,,	2	2·1
,,	,,	3	1·
89	,,	1	5·
,,	,,	2	3·
,,	,,	3	1·
64	,,	1	6·5
,,	,,	2	3·
,,	,,	3	2·
42	,,	1	6·
,,	,,	2	3·
,,	,,	3	2·
27	,,	1	12·
,,	,,	2	6·5
,,	,,	3	3·
14	,,	1	17·
,,	,,	2	9·
,,	,,	3	5·
9	,,	1	23·5
,,	,,	2	16·
,,	,,	3	11·
4	,,	1	41·
,,	,,	2	34·
,,	,,	3	30·

Fig. 29 shows the curves formed when the tension in millimetres and the force of repulsion at the three distances of the screen are taken as abscissæ and ordinates.
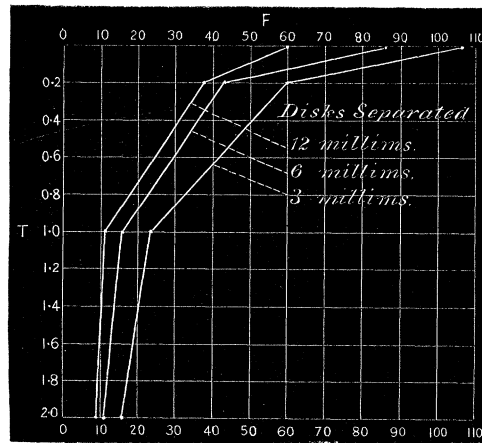
Fig. 29.
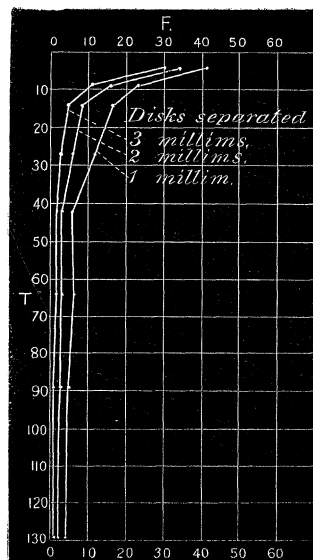
459. In the next experiments the candle was placed 400 millims. off, and the screen and blacked disk were separated 3, 6, and 12 millims. :—

T.	C.	S.	F.
millims.	millims.	millims.	°
2·0	400	3	16·
,,	,,	6	11·
,,	,,	12	9·5
1·0	,,	3	24·
,,	,,	6	16·
,,	,,	12	11·
0·2	,,	3	60·
,,	,,	6	43·
,,	,,	12	38·
0·01	,,	3	107·
,,	,,	6	86·
,,	,,	12	60·

Fig. 30 shows the curves given by these figures, using, as in the last diagram, T and F for abscissæ and ordinates.

Fig. 30.

460. An examination of these tables and diagrams shows that the law of increase of the force with the diminution of the distance between the disks does not remain uniform at all rarefactions. At the lowest exhaustions the mean free path of the molecules of the attenuated gas is less than 1 millim., as rendered evident by the force of repulsion diminishing rapidly as the distance increases. At exhaustions higher than 9 millims. this condition alters; and as the gauge approaches barometric height, the pressure tends to become uniform through considerable distances, the mean path of the molecules now being comparable with the greatest distance separating the surfaces between which they act. As the distance between the disks increases, the tangential action between them and the sides of the glass comes more into play, and tends to interfere with and augment the direct pressure between the two surfaces.

REPULSION AT ATMOSPHERIC PRESSURE.

461. The attraction or repulsion exerted between surfaces at atmospheric pressure or low exhaustions has always exhibited contradictions, the air currents caused by the heating of the glass envelope, and those generated inside by the heating of the movable indicator, being sufficient to neutralise, wholly or partly, any repulsion which was occasioned by true molecular pressure. It was thought that by special arrangements the effect of air currents might be separated from that of molecular pressure, and the following apparatus was accordingly fitted up.

It consists of a torsion balance, similar to the one last used (455, fig. 27), but instead of the adjustable mica screen and blacked disk, the experimental end of the

Fig. 31.
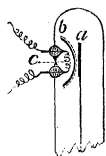
torsion beam was arranged as shown in fig. 31. a is a clear mica disk suspended on the end of the torsion beam; b is a shallow cup of platinum, lampblacked on the convex side; c is a platinum wire spiral, connected with thicker platinum terminals passing hermetically through the glass. By heating the spiral the platinum cup is warmed, and the approach or retreat of the disk a is measured by an index ray of light reflected on to a screen in the usual manner.

The strength of the voltaic current used to heat the spiral is kept constant by the system of resistance coils and galvanometer described in a previous paper (359). Two LECLANCHÉ cells, giving a tolerably constant current, were used to heat the spiral; the heat never got up to redness. The scale was kept 3 feet from the mirror.

462. The apparatus was exhausted to dry it, and then filled with dry air which had passed through a tube packed with phosphoric anhydride. The disk was adjusted so as just not to touch the platinum cup.

When the spiral was heated, the disk was immediately attracted to the cup. The mica disk was now put at different distances from the cup. On heating the spiral, strong attraction always took place, the disk rushing across to the cup, rebounding from it, and rapidly settling in close contact. A wet finger* placed on the opposite side to the cup, when it had got cold, drew the disk away.

463. Exhaustion was now proceeded with, observations being taken at intervals. The control magnet was moved so as to let the disk lightly touch the cup; the scale was moved till the index ray of light stood at −140. The magnet then brought the torsion beam back till the index ray of light stood in the centre of the scale, at zero. As now adjusted, the mica disk is several millimetres from the cup, and can move

* Wetted to avoid electrification by friction,

towards it till the index ray of light marks −140, when the disk and cup touch; a positive movement to the right signifying repulsion, and a negative movement to the left signifying attraction. Electrical contact was made by pressing down a key. The current was kept on during the whole time of each experiment.

464. *Pressure* 260 *millims.*—When the current is turned on the index ray moves to +2; it then swings back to −140, the disk touching the cup, and being held there for some time after contact is broken.

465. *Pressure* 240 *millims.*—On making contact the movements of the index are the same as at 260, the first movement, however, being +3 divisions.

466. *Pressure* 210 *millims.*—The same as above, but the first movement being +4.

467. *Pressure* 160 *millims.*—On making contact the first movement of the index is +4·5° repulsion. It then swings back to −139, the plate just failing to touch the cup by one division. There was no permanent attraction, as in former cases, but the beam swung quite freely.

468. *Pressure* 125 *millims.*—The index moved on making contact +6°, repulsion; it then returned to −136°, attraction, being 4 degrees short of contact.

469. *Pressure* 110 *millims.*—When contact was made the first movement was +9, repulsion; the return movement was to −135°, attraction, or 5 degrees short of contact.

470. *Pressure* 90 *millims.*—The first movement was +15, repulsion; the return movement was −131°, or 9 degrees short of contact.

471. *Pressure* 60 *millims.*—The first movement was +22, repulsion; the return movement was to −115, or 25 short of contact.

472. *Pressure* 55 *millims.*—The first movement of the index on heating the spiral was +34, repulsion; the return swing was to −94.

473. *Pressure* 15 *millims.*—On heating the spiral the index ray showed repulsion, going to +145. It then oscillated a little to and fro, but did not show any attraction.

474. *Pressure* 10 *millims.*—As soon as battery contact was made, strong repulsion ensued, the index ray going off the scale (250°+), and the mica disk being driven against the side of the tube and remaining there. This being the case, no further experiments could advantageously be tried with the apparatus.

Between each of the latter experiments the index took a long time to return to zero, owing to the mass of heated metal inside, which had to get quite cold.

475. Fig. 32 shows the results of the above experiments drawn as curves. The attraction, which is very strong at pressures between atmospheric and 210 millims., begins to decline after that degree of exhaustion is passed, until it disappears at 15 millims. At the same time, the repulsion, which begins to be apparent at 250 millims., increases as the attraction diminishes. It is probable that the attraction is the effect of air currents caused by the permanent heating of the surface in front of the mica disk, and that if the first action of the molecular pressure, which I assume is practically instantaneous, could be still further separated from the more slowly acting air currents, we should succeed in getting decided repulsion at still higher pressures,

Fig. 32.
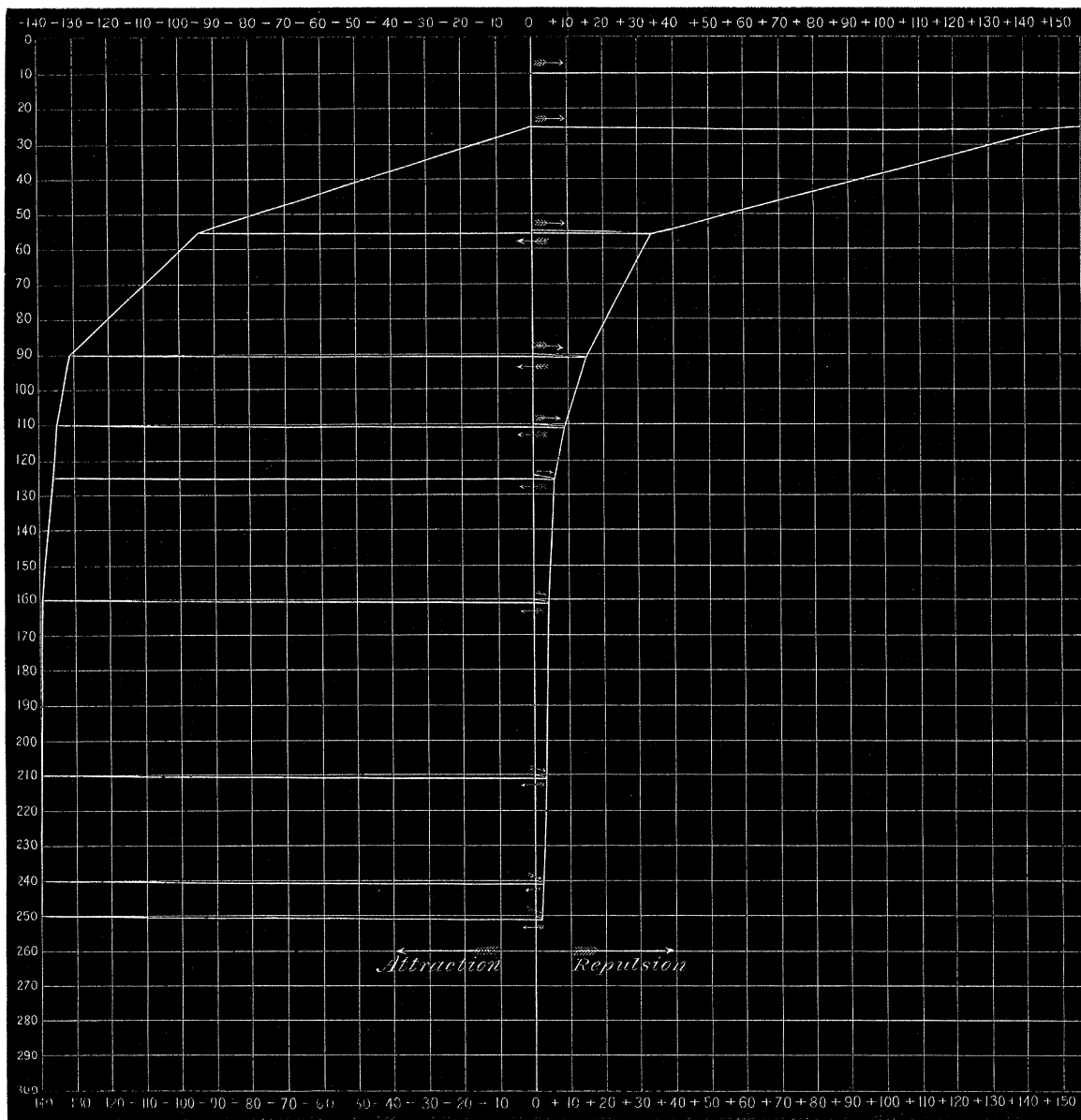
476. An experiment tried three years ago with the bar photometer (described in Part III. of this research, par. 135*) bears so closely on these results that I condense the following description from my note book.

The bulb was filled with dry air at atmospheric pressure, and the movement of the bar being observed by an index ray of light on a graduated scale, a candle was uncovered at different distances.

With the candle six inches from the bulb, the index first showed repulsion 4 divisions, and then strong attraction, going quite off the scale, more than 500 divisions.

* Phil. Trans., 1876, Vol. 166, part II., p. 333,

With the candle 1 foot off, there was at first repulsion 10 divisions, immediately followed by attraction 100 divisions.

With the candle 2 feet off, there were 10 divisions repulsion, and 85 divisions attraction.

With the candle 4 feet off, the first movement was repulsion 35 divisions, and then attraction 10 divisions.

At 6 feet off the candle only gave repulsion 50 divisions, and no attraction.

At 8 feet off the candle gave repulsion 10 divisions, with no subsequent attraction.

The bar of the photometor was of pith, one-half plain, and the other half lamp-blacked. The repulsion is much stronger on the black than on the white half. The warm bulb attracts much more powerfully than radiation repels, therefore by increasing the distance of the candle from the bulb, heating is avoided and the action of radiation becomes apparent.

477. The candle was now placed 10 inches from the bulb of the photometer. A glass cell full of water, and having parallel sides, was interposed, near the candle, and a thick sheet of plate glass was put close to the bulb. The light was screened off till an experiment was to be tried, and the exposure was continued only as long as was requisite to get the result. The index ray of light and the scale were the same as before.

Tried in air (pressure 745 millims.) there were 10 divisions repulsion with no subsequent attraction, showing that the water and glass screens prevented the heating of the bulb.

478. The bulb was then exhausted with the SPRENGEL pump, observations being taken from time to time.

At 330 millims. pressure there was repulsion $=12°$

,,	225	,,	,,	,,	,,	11
,,	115	,,	,,	,,	,,	9
,,	85	,,	,,	,,	,,	5
,,	80	,,	,,	,,	,,	3
,,	72	,,	,,	,,	,,	2
,,	68	,,	,,	,,	no movement	
,,	60	,,	,,	,,	,,	
,,	45	,,	,,	,,	,,	
,,	40	,,	,,	,,	repulsion 3°	
,,	35	,,	,,	,,	no movement	
,,	25	,,	,,	,,	,,	
,,	10	,,	,,	,,	,,	
,,	2	,,	,,	,,	repulsion 2°	
,,	1	,,	,,	,,	,, 25°	

In this series I obtained no attraction. The gradual diminution of action to 72 millims. pressure, its absence (with one exception) till the gauge was within 2 millims. of barometric height, and its rapid increase after that, may, however, be

regarded as fair reasons for suspecting that the repulsions at high and at low pressures are not entirely due to the same cause.

MEASUREMENT OF THE FORCE OF REPULSION.

479. The following experiments were undertaken with the view of getting measurements of the actual amounts of force exerted by radiation in causing repulsion.

A horizontal torsion balance was employed similar in construction to the one described in a previous paper* (209, 210, 211). A somewhat stiffer torsion fibre was employed, and the part corresponding to the pan of the balance was a clear mica disk 16 millims. in diameter. A similar disk was fastened to the tube in which the beam oscillated, in such a position that when in equilibrium the pan should be 1 millim. above the fixed disk. This fixed disk was lampblacked on the upper surface, and had beneath a thin platinum spiral connected with terminals sealed in and passing through the glass, as in apparatus fig. 31 (461). When this spiral is heated by an electric current, the blacked mica disk fixed above it becomes heated, and the molecular pressure thereby generated between it and the mica pan causes the latter to rise. The glass thread attached to the beam is now twisted by means of the graduated circle, and the number of degrees through which the thread has to be twisted, in order to bring the beam back to equilibrium, is noted. This gives a measurement of the pressure exerted in torsional degrees. To convert these degrees into grains it is only necessary to ascertain through how many degrees the glass thread has to be twisted, in order to balance a known weight placed on the pan. A piece of iron weighing 0·01 grain was used, and it was found that to restore the beam to equilibrium with this weight on the pan, 3 complete revolutions and 34°5 additional, or 1114·5 degrees of torsion, were required. The force with which the glass fibre tends to untwist itself, being directly proportional to the number of degrees through which it has been twisted, the value in grains of any number of torsional degrees is readily calculated. A ray of light reflected from a mirror in the centre of the beam is used as an index, being brought to a definite mark on a scale for zero.

The battery power was kept constant by the means already described (359, 461).

480. In the following table the degrees of exhaustion are given in millionths of an atmosphere, and the force of repulsion is given in fractions of a grain, calculated from the degrees of torsion.

* Phil. Trans., 1876, Vol. 166, part II., p. 371.

Exhaustion.				Grain.
2237· M,	force of molecular pressure			= ·000126
1316· M,	,,	,,	,,	= ·000206
424· M,	,,	,,	,,	= ·000368
259· M,	,,	,,	,,	= ·000511
153· M,	,,	,,	,,	= ·000718
94· M,	,,	,,	,,	= ·000987
64·7 M,	,,	,,	,,	= ·001086
32·9 M,	,,	,,	,,	= ·001140
26·0 M,	,,	,,	,,	= ·001076
20·0 M,	,,	,,	,,	= ·000987
13·9 M,	,,	,,	,,	= ·000727
12·1 M,	,,	,,	,,	= ·000646
9·3 M,	,,	,,	,,	= ·000682
9·1 M,	,,	,,	,,	= ·000619
6·0 M,	,,	,,	,,	= ·000520
1·3 M,	,,	,,	,,	= ·000269
0·7 M,	,,	,,	,,	= ·000224

481. In fig. 33 these results are plotted as a curve, taking the abscissæ in units of the hundred-thousandth of a grain, and the ordinates in millionths of an atmosphere. The maximum action would not be far from 40 millionths, increasing slowly up to that exhaustion, and diminishing suddenly after that point.

482. In the Proceedings of the Royal Society for November 16, 1876,[*] I gave a similar curve of the variation of the force of repulsion in air at different degrees of exhaustion. The source of radiation was a candle, and the body repelled was blackened mica. In that curve the maximum action is very near 40 millionths of an atmosphere, rising slowly and sinking rapidly.

483. Another similar curve, obtained in quite a different way, is given in the fifth part of this research (par. 334).[†] The instrument here experimented with was a cup-shaped aluminium radiometer, and the source of light was a candle. In this case also the maximum action occurred close upon an exhaustion of 40 millionths of an atmosphere, increasing slowly and dying away rapidly.

484. In the same paper (par. 383)[‡] I have given a third curve of the variation of the action of a candle on a blacked mica surface in an air vacuum. Observations are wanting between 59 and 14 millionths of an atmosphere, but by continuing the curve passing through the other points, it is seen that here, likewise, the maximum would not be very far from 40 millionths of an atmosphere.

485. These agreements must be more than accidental coincidences. Care must, however, be taken not to consider them as expressions of more than a partial law, for in the diagram containing the curve last referred to (483, 383), is another curve
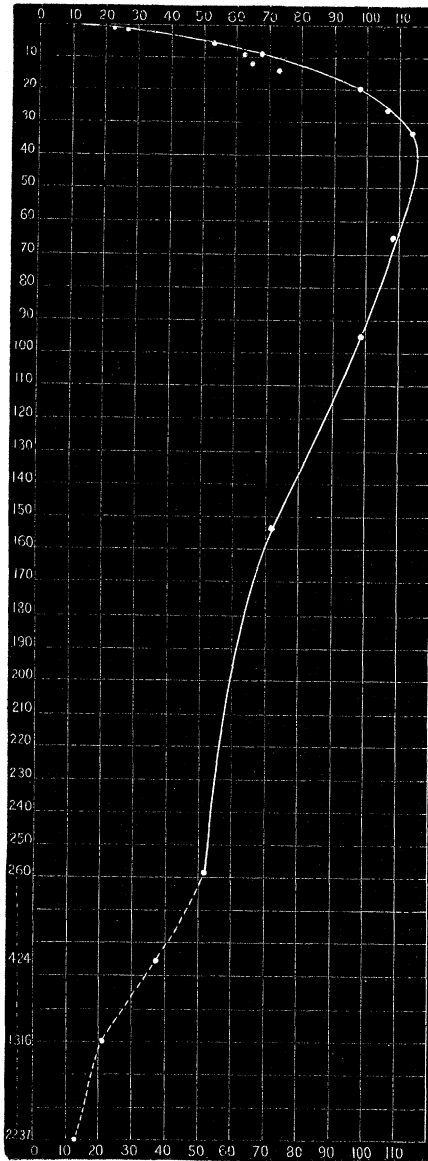
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[*] Vol. xxv. p. 305.

[†] Phil. Trans., 1878, part I. (The Bakerian Lecture), p. 301.

[‡] *Loc. cit.*, p. 316

taken under somewhat similar circumstances to the curve in fig. 33 (480), a hot platinum wire being used as an internal source of radiation, which shows a still increasing power of repulsion up to as high an exhaustion as 0·4 millionths of an atmosphere.

Fig. 33.

In concluding this series of papers "On Repulsion resulting from Radiation," it is a pleasure for me to state that during the six years they have been in progress I have been materially aided by my assistant, Mr. C. H. GIMINGHAM, whose extra-ordinary mechanical dexterity and skill in glass manipulation have been called almost daily into service.