IX. The Bakerian Lecture.—*On Repulsion resulting from Radiation.*—Part V.

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Contents.

INTRODUCTION.

220. In this Part I propose to give the results of some researches which, during the past twelve months, have occupied much of my time. The researches include a quantitative examination of the repulsion exerted by a standard flame shining on pith and mica disks, coated with various powders, chemical precipitates, &c., and suspended *in vacuo* in a torsion apparatus. The character of the incident radiation has been varied by straining it through water, alum, or coloured media; the action of good and bad conductors of heat has been compared; and the influence which favourable presentation of the experimental surface, by curvature or obliquity, has upon its movement has been investigated, with the result of throwing much light on some of the debated problems in molecular physics to which, by general assent, the repulsion resulting from radiation is held to be due. In every step of this investigation, theory and observation have gone hand in hand, and at each point gained it has been my endeavour to permanently record such experimental proof in the convenient form of an instrument, so as to have it available for further examination.

The reaction, along lines of greatest molecular pressure, between the experimental surface and the fixed case containing it, has been examined. Experimental proof has been obtained, not only of the existence of such a reaction, but of the direction in which it is chiefly exerted; and the apparatus devised during this inquiry, to put each step of the theory to an experimental test, has led to the construction of a modification of the radiometer named the *otheoscope*, in which the reacting surface is no longer the side of the glass case, but is specially made with a view of getting the greatest sensitiveness in the moving parts of the apparatus. Owing to the increased delicacy of the instruments now made, it has been possible to detect the existence of molecular pressure when radiation falls on a black surface, in air of normal density.

MULTIPLE DISK TORSION APPARATUS.

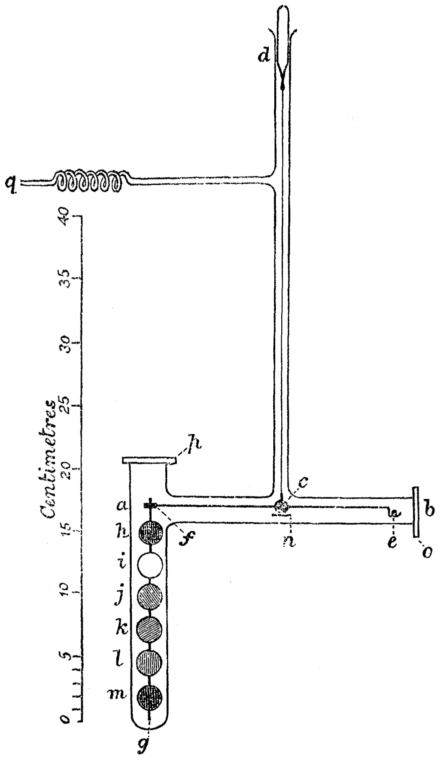
221. The apparatus used to get quantitative measurements of the repulsion produced by radiation on disks of various kinds, and coated with different substances, is similar in principle to the one described in Part IV. of these researches* (198, 208); but as it differs in many important details of construction it is here fully described. The torsion apparatus is represented in elevation in fig. 1.

a b is a horizontal glass tube containing the beam, which in this case is made of straw, so as to secure lightness with absence of flexure under the comparatively heavy weights it sometimes has to bear; glass was used at first, but it was found to bend too much. *c d* is a fine torsion fibre of glass (103), to which the beam is suspended;

* Phil. Trans., 1876, pt. 2, p. 365.

it is cemented at *d* to a well-ground stopper, so as to admit of adjustment. When in position, cement (83) is run round the stopper. At *c*, the point of junction between the torsion fibre and the straw beam, is a silvered glass mirror. At the end, *e*, of the beam is a small pan to hold the weights counterpoising the disks which are suspended to the other end. A flat stirrup of aluminium, at *f*, fits stiffly on the straw beam, and

Fig. 1.



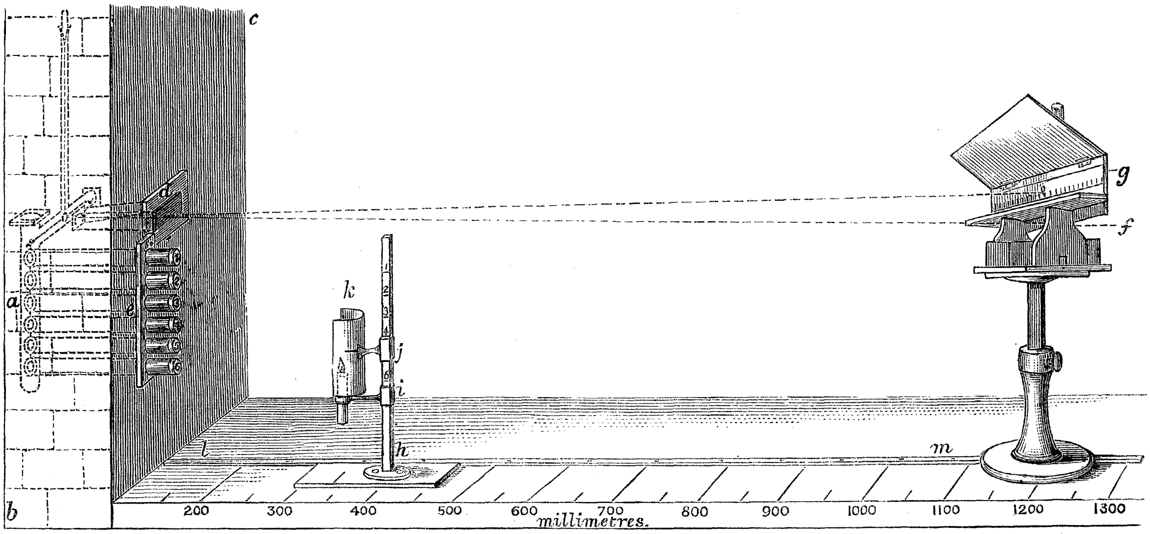
carries a flat glass fibre, *f g*, cemented to it so as to allow of no play; the straw beam, the aluminium hook, and the glass fibre being perfectly rigid. The experimental disks are fixed on the glass fibre by means of a touch of cement at the back. The vertical tube is arranged to hold six disks, the top one, *h*, being always the same standard lampblacked pith; the others, *i*, *j*, *k*, *l*, and *m*, being changed each time. A small magnet, *n*, attached to the central mirror, and controlled by a bar magnet outside, gives the power of bringing the beam to zero, should it happen to get out of adjustment, without having to melt the cement and alter the angle of the torsion fibre by turning the stopper *d*. Plate glass caps at *o* and *p*, cemented to the ground edges of the tubes, give access to the interior; *o* allows the counterpoises to be adjusted in the pan, and *p* allows the aluminium stirrup to be unhooked and the whole of the disks to be lifted out together. The apparatus is connected to the mercury pump by the arm and spiral *q*.

The weights and dimensions of the various parts of the apparatus are as follows :—

Weight of straw beam, mirror, magnetic needle, aluminium stirrup, and flat glass fibre, &c.	7·25 grains.
Average weight of six plain mica disks	2·40 ,,
Average weight of six plain pith disks	0·59 ,,
Length of straw beam, from centre of counterpoising pan to centre of disks	17·0 centimetres.
Length of arm, from centre of suspension to centre of pan	7·6 ,,
Length of arm, from centre of suspension to centre of disks	9·4 ,,
Glass torsion fibre (this was the same as I employed in the experiments described in my last paper, par. 199)—	
Length	23·0 ,,
Thickness	0·0013 inch.
Torsion, with the glass weight hanging from it (186, 199)	$\frac{1}{2}$ oscillation in 15·75 seconds.

Fig. 2 shows the apparatus fitted up for experimentation. The disks are shown in position at *a*; a brick wall, *b c*, has holes pierced through it in two places, as shown, one hole, *d*, being opposite the centre mirror, and the other, *e*, opposite the disks. The aperture *d* is lined with card, lampblacked inside, and the interstices between it

Fig. 2.



and the bricks are well plugged with cotton wool. A water cell at *d* prevents radiant heat from the lamp getting to the apparatus. Through the hole *e* pass six card tubes, lampblacked internally, 20 millims. diameter and 23 centims. long. The tubes are firmly cemented to the wall, so that each shall be exactly central with its corresponding disk, and the outer end of each is closed with a cork. The space between the tubes and wall is well stuffed with cotton wool. The apparatus, being once fixed in position, is surrounded on all sides, as well as above and below, with cotton wool. Outside this is a row of glass bottles filled with water, and in front of all is a wooden screen. When protected in this manner, the inside of the apparatus is found to be free from

disturbances caused by change of temperature. When the disks have to be changed, air having been let in through the pump, access is easily obtained to the glass cap *p* (fig. 1), and the cement being softened by heat, and the cap removed, the disks are lifted out together by seizing the aluminium stirrup with forceps. A fresh set of disks being introduced, the apparatus is again packed up, and re-exhausted.

A lamp at *f* throws a narrow beam of light on the mirror of the apparatus, through the aperture *d*. The ray is reflected to the scale *g*, where its deflection from zero shows the angular movement of the torsion beam when one of the disks is repelled by radiation. The scale is $1\frac{1}{2}$ metre from the reflecting mirror.

A standard candle (109) is supported on a heavy stand, *h*, and can be raised or lowered by means of the sliding piece, *i*. Another sliding piece, *j*, carries a pointed wire projecting from it. The upright rod of the stand is graduated and numbered, so that when the sliding piece *j* is at mark 1, the point of the wire is on the prolongation of the axis of tube and disk No. 1, and so on. Then by sliding the candle up till the most luminous part of the flame is level with the point of the wire, it is known that the light will shine full on the disk under experiment. A half cylinder, *k*, covered with black velvet, protects the candle from draughts. The candle stand, *h*, slides along a straight edge, *l m*, screwed to the bench, so graduated that by bringing a mark on the sliding stand to one of the divisions, it indicates the number of millimetres separating the surface of the experimental disk from the centre of the candle flame.

222. The experimental powders are laid on one surface of mica or pith disks, 17·6 millims. in diameter, the pith being 1 millim. thick. If unaffected by alcohol, the powders are ground up with this liquid in an agate mortar, and then laid on somewhat thickly with a camel-hair brush, so as to be certain that the whole surface of the disk is well covered. The back of the disk is left plain. If affected by alcohol, water is used ; but in any case no gum or other adhesive agent is added. When disks of mica or thin metal are used, they are punched out with the same tool employed for the pith, and care is taken to completely flatten the disk and to remove the burr. Where the material for the disks cannot be punched (*e. g.* charcoal, selenium, rock salt, &c.) they are cut or filed to shape. The upper disk, *h*, in the apparatus is never removed ; it consists of a pith disk, coated with lampblack, by painting with a thin cream of lampblack and alcohol, and after drying smoked over burning camphor (147). The other disks are attached to the flat glass fibre, *f g* (fig. 1), by a minute piece of cement at their backs, and the whole series is lowered into its place, as shown in fig. 2, and fixed in a vertical position. The cap *p* is then cemented on, and the air is rarefied by means of the pump to within one millimetre of a vacuum. It is kept at this exhaustion for about twelve hours, when the disks and powders become perfectly dry under the influence of the phosphoric anhydride which is in the drying tube of the pump (26, 51, 82, 355).* The lamp and scale are now adjusted, and the luminous index brought to zero, if necessary, by moving the control magnet.

* Proc. Roy. Soc., Nov. 16, 1876, No. 175, p. 306.

The standard candle being lighted and placed 500 millims. from No. 1 disk (standard lampblack), exhaustion by the pump is carried on till such a point of sensitiveness is reached that on removing the screen the standard disk is repelled so that the luminous index moves about 150 divisions on the scale. Under ordinary circumstances the standard candle is kept 500 millims. from the disk, but, when its force is enfeebled by interposed screens, the distance is diminished so as to increase the amplitude of swing of the luminous index.

223. It is necessary to carefully exclude aqueous vapour from the interior of the torsion apparatus, otherwise the sensitiveness will be diminished (105, 130). In all the series of experiments with different disks, the exhaustion, too, must be as nearly as possible uniform, otherwise the proportion between the standard disk and the others will not be identical. With a very good vacuum, when the apparatus is most sensitive, the amount of movement impressed on the experimental disks diminishes in greater proportion than that shown by the black disk; in other words, as the vacuum becomes very good, the sensitiveness of the black surface increases at a greater rate than does that of most of the other surfaces. In illustration I may take an experiment in which a pith disk coated with precipitated oxide of zinc was compared with the standard black disk. The candle being 900 millims. from the disks, the experiment was tried as soon as the exhaustion was good enough to cause a fair movement of the index ray. The ratio between the black and the white disk was as 100 to 55·5. On continuing the exhaustion for some time and then repeating the experiment, the ratio between the black and the white became as 100 to 42·5, and when the exhaustion was at the usual height at which the experiments were tried the ratio was as 100 to 35. In all cases, the actual amount of repulsion on the disks was greater at the higher than at the lower exhaustions. When sufficient air is present in the apparatus to visibly depress the gauge, the repulsion on the black and white surfaces tends to get still more nearly equal. These results are curiously analogous to those described in my third paper on this subject,* pars. 128, 155, 170, 171, where it is shown that the less refrangible rays of the spectrum cause black and white surfaces to be repelled to almost the same extent; the ratio between the black and the white increasing as the incident rays increase in refrangibility. In these instances, therefore, low refrangibility and low exhaustion produce similar results. The experiment described in par. 130 proves that at a high exhaustion the presence of residual aqueous vapour has the same effect in equalising the repulsive force of luminous radiation on black and white surfaces as is produced in dry air at a somewhat lower degree of exhaustion.

224. In the following Tables will be found the mean results of experiments with various powders laid on the surface of mica or pith disks.† The deflection of the

* Phil. Trans., Vol. 166, pt. 2, January 5, 1876.

† The action was about 50 per cent. stronger with mica disks than with pith disks (see Table XII., par. 237). But when reduced to the usual standard of lampblack=100, the differences ceased to be greater than might be due to experimental errors.

index ray of light was observed at intervals varying from a few hours to many weeks, several times with each powder, and the means were reduced to the standard deflection of the lampblacked disk = 100. The column headed "water screen interposed" is also reduced to the deflection of lampblack = 100. In comparing the two columns, it must be remembered that the actual amount of repulsion on the standard lampblacked disk when the water screen is interposed is only $\frac{1}{12}$th of the amount obtained when no screen is in the way, the distance of candle and other things being equal. In order, therefore, to compare one column with another the results in the column headed "water screen interposed" must be divided by 12.

TABLE I.—Black Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Iron reduced by hydrogen	101·1	107·2
Tungsten reduced by hydrogen	96·5	95·4
Palladium iodide	87·3	. . *
Mercury sulphide	84·0	94·6

225. TABLE II.—White Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Hydrated zinc oxide	40·5	14·0
Barium sulphate	37·4	4·2
Magnesia, ignited	37·2	8·4
Oxamide	36·0	10·7
Silica, precipitated	33·6	4·1
Lead carbonate (white lead)	32·5	9·8
Mercury sulphethylate	28·5	15·1
Calcium carbonate	28·5	3·9
Lead sulphate	27·6	4·7

The powerful absorption for the invisible heat rays which these white powders exercise is somewhat remarkable. Assuming that the ultra-red rays from a candle are almost entirely cut off by a water screen, the comparatively strong action shown in the first column must be mainly due to absorption of the invisible rays of heat, and when these are filtered off through water the action is diminished 48 times.† A similar examination of Table I. shows that a water screen only diminishes the action about 11 times.

In paragraph 201 of a former paper on this subject I gave the result of an

* When dots occur in a column, they mean that no experiment was tried.

† Omitting lampblack, the average of the first column is 33·5, and that of the second 8·3. But, as already stated, the action behind water must be divided by 12, which reduces it to 0·7, about $\frac{1}{48}$th part of 33·5.

experiment with lead carbonate tried in a somewhat similar way. The effect was then found to be only 13 as against lampblacked pith=100. The much stronger effect now obtained (32·5) is probably due to the different physical condition of the two samples of lead carbonate. The one giving the lower number, was prepared in the wet way by double decomposition, whilst the sample now used was prepared in the dry way by the corrosion of metallic lead by carbonic acid and air in the presence of moisture and acetic acid vapour, as in the manufacture of white lead. It is well known that lead carbonate thus prepared possesses great density and opacity.

226. TABLE III.—Red Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Amorphous phosphorus	40·4	38·0
Precipitated selenium	35·8	69·5
Ferric oxide	29·5	25·1
Mercury and copper iodide	22·4	11·7

The results given in this Table deserve notice. The very high action shown by precipitated selenium in the second column (water screen interposed) is one which, considered alone, might be supposed to belong to its elementary character, and this view would in some measure be borne out by the similar behaviour of reduced iron in Table I.; but other elementary bodies—*e.g.*, phosphorus in Table III. and tungsten in Table I.—do not act in this way. The averages of columns 1 and 2 are 33·1 with no screen interposed and 36·1 with a water screen; if selenium be left out as anomalous, the averages become 32·2 and 24·9. In subsequent Tables (242) other bodies will be seen to act like selenium, although not to the same extent.

227. TABLE IV.—Brown Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Thallic oxide	121·7	111·0
Lead peroxide	113·5	105·0
Platinum protochloride	77·8	84·0
Copper ferrocyanide	71·2	87·8
Thallium vanadate	50·4	69·2
Bismuth peroxide	21·5	10·2

The very high action exhibited by the thallium and lead peroxides is worthy of notice. Of all the substances I have yet examined these head the list, thallium peroxide being more repelled under the influence of radiation than any other body. The averages of the columns, *without* and *with* a water screen, are 92·7 and 94·5.

Brown powders therefore act most like black. The low action of bismuth peroxide is probably due to its pale brown colour, which acts therefore like a mixture of brown and white. It will be understood that in classifying all varieties of coloured bodies under a few headings, great differences in intensity and tint must be associated together in the same Table.

228. TABLE V.—Yellow Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Tungstic acid (hydrated)	57·9	26·9
Tungstic acid (anhydrous)	50·8	72·2
Persulpho-cyanogen	43·9	11·5
Ceroso-ceric oxide	38·7	14·1
Uranic oxide	33·8	11·8
Cadmium sulphide	32·6	10·6
Milk of sulphur	30·5	7·7
Sulphur, precipitated	25·6	19·8
Antimonic acid	22·6	8·1

The averages of the two columns are, without a water screen, 37·4, and with a water screen, 20·3. But anhydrous tungstic acid behind water is so different from the others that a fairer mean will be obtained by omitting this powder. The figures now become 35·7 and 13·8.

229. TABLE VI.—Green Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Green salt of Magnus (diammonio-platinous chloride)	89·5	103·5
Chromic oxide, pale green	71·5	20·2
,, bright green	63·4	49·8

These are too few in number to make it safe to draw any inference from the results. The great difference in action behind a water screen caused by a little change in colour of chromic oxide is worth notice, and will be again referred to.

230. TABLE VII.—Blue Powders.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Tungstic oxide	91·3	100·1
Copper carbonate	54·4	56·5
,, phosphate	52·0	52·1
,, tungstate	51·2	77·0
,, oxalate	30·1	40·2

These actions are of interest as showing a much stronger proportionate action behind a water screen than with no screen. The average of the first column with no screen is 55·8, whilst that of the water screen column is 65·2. At the conclusion of this tabulation of results I shall collect together the variations in the actions and comment upon them. The strong action on the oxide of tungsten is probably caused by its dark colour, the blue appearing almost black.

231. TABLE VIII.—Dyes and Colouring Matters of Organic Origin.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Bismark brown	52·7	42·6
Fluorescin	52·2	29·0
Magdala rose	47·0	32·5
Eosen	43·6	27·7
Saffranin	41·0	52·5
Product of the decomposition by acids of the green colouring matter of leaves (from Professor Stokes)	39·2	47·1
Aniline scarlet	37·0	21·7
Isatin	34·5	15·3

These organic substances do not show many striking variations. The saffranin, and the product of the decomposition of chlorophyll show an increased ratio of action when the heat rays are cut off by water. From the appearance of the spectrum of the chlorophyll product, Professor STOKES, who kindly prepared me the specimen, was led to believe that it would be little affected by invisible heat rays, but affected to a considerable extent by light. The figures in the two columns show that this theoretical reasoning is quite borne out by facts. The results obtained with the other organic colouring matters show that when the invisible heat rays are cut off, the action declines in proportion to that on the lampblack.

Leaving out saffranin and the chlorophyll product, the mean actions of the other substances are with no screen, 44·5; with a water screen interposed, 28·1. The results obtained for Bismark brown and aniline scarlet, behind a water screen, are not very satisfactory, and must only be considered approximations to the truth. It was difficult to get a definite position of rest for the luminous index, as after a certain time the oscillations increased in amplitude as the light continued to shine on the disk.

232. TABLE IX.—Metals.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Precipitated silver (on a pith disk)	57·8	58·3
Iron foil	48·4	5·1
Aluminium leaf (backed with mica)	28·7	45·0
Platinum leaf (backed with mica)	28·7	41·1
Platinum leaf	20·1	22·3
Lampblacked platinum leaf (black side exposed)	19·9	..
Gold leaf	19·3	51·0
Lampblacked silver leaf (black side exposed) .	17·7	..
Aluminium leaf	13·8	13·6
Gold leaf (backed with mica)	10·6	10·3
Palladium foil (saturated with hydrogen) . .	10·6	..
Gold leaf (lampblacked on reverse side) . .	7·3	..
Aluminium leaf (lampblacked on reverse side)	5·1	..

As metals move very slowly and do not come back to zero for a considerable time, satisfactory observations are not easily obtained. Except when testing precipitated silver, which was in fine powder, mica or pith disks were not employed as supports in this series. The gold leaf was not of the thinnest, but sufficiently thick to bear handling, weighing half a grain per square inch. The silver, platinum, and aluminium leaves were about double the thickness of the gold. The iron and palladium were thicker still.

The Table does not show any general relationship between the metals which I have tried, but before drawing conclusions, a much larger series of experiments should be undertaken. The extra weight of metallic disks prevented much experiment in this apparatus, but I hope to continue the experiments with metallic surfaces in an apparatus specially adapted to them. One or two points are here worth notice. The considerable movement of metallic iron with no screen interposed, and the slight action behind a water screen, show that the invisible heat rays are those chiefly absorbed by this metal; whilst the greatly increased proportional action on gold behind the water screen shows that with this metal, the luminous rays are more absorbed than the invisible heat rays.

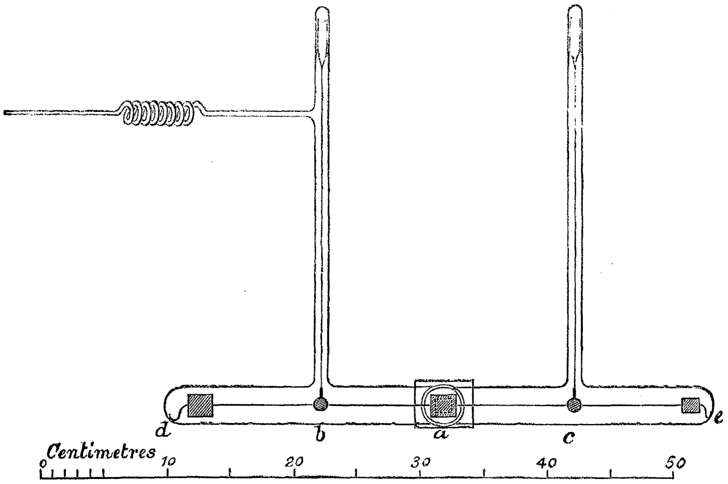
The films of metal employed are so thin that very little time is occupied in the conduction of heat from one surface to another. The rise of temperature, therefore, on the front surface, caused by the radiation from the candle, cannot be much greater than that on the back surface; and the resulting molecular pressure must exert itself on each side of the plate, the movement of repulsion being due to the difference of this pressure in favour of the front surface. Backing the metallic leaf with a thin plate of mica, by stopping the action of the molecular pressure on the reverse side, and throwing it all on the front, should therefore increase the amount of repulsion.

This reasoning is confirmed by the behaviour of the aluminium and platinum, but not by the gold, which is diminished in action by the mica backing. Gold, however, is seen to be acted on but little by the heat rays, and it is probable that these are the rays which most readily raise the temperature of the plate and cause molecular pressure to be exerted from the hinder surface. According to the same theory, if the transference of heat from the back surface be assisted by coating it with lampblack, the repulsion by rays falling on the unblacked surface should diminish. This is seen to be the case with aluminium and gold. The following Table will explain these actions :—

Metallic Plate.	Backing.		
	None.	Mica.	Lampblack.
Aluminium	13·8	28·7	5·1
Platinum	20·1	28·7	. .
Gold	19·3	10·6	7·3

The following experiment proves that when radiation from a candle falls on the surface of a metal plate, heat rapidly passes through and causes molecular pressure to be exerted from the back of the plate. A torsion apparatus was made similar to those used so frequently in these experiments but having a double suspension, and

Fig. 3.



two independent beams, as shown in fig. 3, each supported by a glass fibre, and having at each end a plate of platinum. In the centre of the tube, at *a*, is a plate glass window, through which radiation falls on the plate at the end of the beam *b*, which plate, being larger than the one at the end of beam *c*, and overlapping it entirely, cuts off direct radiation from it. Stops *d* and *e*, at the outer extremities of the beams, prevent

them moving so as to touch where they overlap in the centre. At the centre of each beam is a mirror, by means of which a luminous index is reflected to a scale, so as to render evident any movement of the beams. The instrument being in adjustment, light from a candle is allowed to fall on the large plate of platinum at the *a* end of beam *b*. Almost instantly the motion of the index ray of light from the mirror *c* shows that the smaller plate of platinum attached to the other beam, *a e*, is driven backwards, in the same way as it would be had the large plate in front of it been transparent instead of opaque. The beam *a d* is prevented from pushing the hinder plate at *a* by the stop at *d*.

233. The action on the palladium saturated with hydrogen is lower than might be expected. The saturation was effected by making the metal the negative electrode of a three-cell Grove's battery, decomposing water acidulated with sulphuric acid. After action had gone on for about half an hour, the palladium was washed, dried with a cloth, and introduced into the apparatus. During exhaustion it is possible that a little hydrogen might have escaped from the metal, but the loss could not have been great, as the rate of exhaustion was not materially reduced. When the proper exhaustion was reached, no escape of the gas from the metal was noticed, the gauge remaining stationary. It was thought possible that, on allowing radiation to fall on the palladium-hydrogen plate in the vacuum, the repulsion might be accompanied by a liberation of hydrogen. I could not, however, detect any action of this kind, either by a depression of the gauge or by a diminution in the sensitiveness of the other disks to the radiation, which would have occurred had hydrogen escaped into the vacuum. Moreover, it is probable that had the action of incident radiation been accompanied by a liberation of hydrogen, the repulsion would have been stronger than it actually was. On testing the palladium plate after removing it from the apparatus, it was found to be abundantly charged with hydrogen.*

234. TABLE X.—Silver Salts.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (*standard disk*)	100·0	100·0
Silver bromide	31·0	31·6
Silver chloride	20·9	14·7
Silver iodide, insensitive to light	20·9	9·2
,, ,, sensitive to light, washed	18·1	20·0
,, ,, ,, ,, not washed	11·6	1·5

The silver salts were prepared by double decomposition in a room feebly lighted by orange light. They were well washed on the filter, and then divided into two portions; to one was added a dilute solution of the precipitating salt (potassium iodide or bromide, or sodium chloride), and to the other a dilute solution of silver nitrate.

* This persistence of the palladium-hydrogen alloy was discovered by Graham. See Proc. Roy. Soc., June 11, 1868, vol. xvi. p. 422; or Collected Works, p. 284.

Silver chloride, precipitated in the presence of a slight excess of sodium chloride, and subsequently washed, is a white powder which slowly darkens to a slate colour when exposed to daylight. When the precipitation takes place in the presence of an excess of silver nitrate, the chloride darkens more rapidly on exposure to light, and the depth of colour depends in great measure on the amount of free silver nitrate left with the silver chloride, and not subsequently washed out.

Silver iodide varies in colour according to the mode of preparation. If the potassium iodide is in excess, the silver iodide falls as a very pale yellow, almost white, precipitate; whilst, if precipitated in the presence of an excess of silver nitrate, it is of a decided straw-yellow colour. In the former case, it is not visibly affected by exposure to light, even to the sun. But the straw-yellow iodide formed in the presence of excess of silver salt is very sensitive to light. This sensitiveness is not rendered evident by much change of colour, since exposure to full day or even sunlight only causes it to change to a pale brown colour. If the *sensitive* silver iodide is exposed for one or two seconds to daylight, and then brought into a room faintly illuminated with orange light, no change of colour is visible; but on pouring over it a mixture of silver nitrate and a reducing agent, immediate blackening takes place, showing that a very strong, although invisible, change has been produced in the silver iodide by the momentary exposure to light.

In its behaviour to light, silver bromide may be considered intermediate between silver chloride and iodide. Its visible darkening, when exposed to daylight, is much less than that of silver chloride; whilst it also shares with the silver iodide, although in a less degree, the power of assuming a *latent* change capable of subsequent development. In all cases the presence of free silver nitrate increases the sensitiveness to light, and as this salt is washed away the sensitiveness diminishes. The rays of light which produce this photographic action are chiefly the indigo and violet rays, the red, orange, and yellow having no action. The most sensitive salts of silver can therefore be safely prepared in a room illuminated by a candle shining behind orange glass.

I experimented with all varieties of the three silver salts. They were dried, then ground up with pure water to a paste, and carefully painted on disks of mica, as described at par. 222. In the case of the silver bromide and chloride (prepared in the dark, and not exposed to light before the standard candle of the apparatus shone on them), no material difference of action could be observed between the sensitive and non-sensitive varieties. The figures in the table are therefore the mean of all the results, which were fairly concordant. With the silver iodide, however, the case is different: the almost white, insensitive variety is most affected; next comes the sensitive variety, from which, however, much of the free silver nitrate has been washed, so as to considerably reduce the sensitiveness. Lastly comes the silver iodide most sensitive to light; this is less affected mechanically by radiation than any other powder hitherto tried. The incident radiation from the candle, instead of causing molecular pressure on the surface, and driving back the silver iodide,

spends itself in chemical action, and causes a molecular change to take place in the structure of the silver iodide. When no latent change is produced, mechanical action is represented by 20·9; on slight latent change, the mechanical action is 18·1; but when strong latent disturbance in the molecular structure of the silver iodide is caused by the incident radiation, the mechanical action sinks to 11·6. The amount of repulsion behind a water screen, as shown in the second column, corroborates this reasoning as far as the non-sensitive and the most sensitive varieties of silver iodide, but it fails in the intermediate case. For this anomalous action I am unable to account.

235. The same series of silver salts which are given in Table X. were now subjected to further experiments. Without removing them from the apparatus, or interfering with the adjustment, the disks were first exposed for one minute to the light of burning magnesium, and then faint sunlight was reflected on to them for two minutes; owing to the direction along which the ray had to pass, three reflections were necessary. After each of these exposures to light, the apparatus was completely closed up and kept in darkness till the molecular disturbance induced by the light had passed off. Experiments were then tried with a standard candle in the usual way, and the amount of repulsion of each disk recorded. Lastly, air was let in, the disks were carefully lifted out of the tube by the flat glass fibre on which they were cemented (222) and exposed to bright daylight for half an hour; all the disks except the insensitive silver iodide were visibly darkened. They were then re-introduced into the apparatus, the whole was exhausted, and the experiment repeated. The results of these experiments are given in the following table:—

TABLE XA.—Silver Salts after Exposure to Light.

	Original repulsion before exposure.	Repulsion by candle light after exposure to			
		Magnesium light.	Faint sun.	Daylight. Without screen.	Daylight. Behind water screen.
Lampblack (standard)	100·0	100·0	100·0	100·0	100·0
Silver bromide	31·0	33·0	35·1	58·7	88·8
,, chloride	20·9	21·0	24·3	69·8	98·1
,, iodide, insensitive	20·9	19·9	20·0	23·0	12·3
,, ,, sensitive, washed	18·1	19·0	23·2	27·3	40·1
,, ,, sensitive, not washed	11·6	22·6	29·8	38·5	75·5

This table shows very clearly how readily a change in the state of the surface is detected by an increased amount of repulsion under the influence of radiation. With the exception of the insensitive silver iodide in the second column (probably due to unavoidable errors of experiment), every exposure to light has left the silver surface in a condition more sensitive to radiation. The silver chloride, which darkens

most by light, is ultimately most repelled, whilst the bromide follows next in sensitiveness. As might be expected, the insensitive iodide is less acted on by light; the washed sensitive iodide is little affected by the magnesium light, and never attains any great sensitiveness to the mechanical action of radiation. The most sensitive silver iodide has its capacity for molecular change almost exhausted by the first exposure to the light of burning magnesium, and after the sudden jump from 11·6 to 22·6, is comparatively little affected by subsequent exposure to daylight or sunlight.

236. TABLE XI.—Selenium, Crystalline and Vitreous.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Selenium disk, crystalline, No. 1	21·1	18·6
,, ,, ,, No. 2	19·1	17·0
,, ,, vitreous	15·0	..

The selenium disks were suspended direct in the apparatus, without being attached to mica or pith disks as were the previous substances experimented upon. They are 17 millims. diameter, and about 0·5 millim. thick. The disks were kindly prepared for me by Mr. R. J. Moss, who, in conjunction with Mr. H. N. DRAPER, has been for some time investigating the action of light on selenium in different physical states.* Disks of vitreous selenium were first prepared; they were heated for one hour to 100° C., and then for one hour to 210° C., which left them in the condition in which Mr. Moss and Mr. DRAPER find selenium most sensitive to *light* action. Two disks of crystalline selenium thus prepared were experimented with; and at the same time a third disk of selenium, in its ordinary vitreous condition, was exposed in the apparatus for purposes of comparison.

Mr. Moss finds† that exposure of selenium in a Sprengel vacuum causes it to acquire a film of mercury selenide, which increases its conducting power for electricity. As it was likely this alteration might cause the molecular disturbance on the surface of the selenium, under the influence of radiation, to vary, extra care was taken to keep the vapour of mercury from penetrating to the selenium by interposing between the pump and the apparatus additional tubes filled with sulphur, copper, and closely packed gold leaf (355).

When the crystalline selenium was under experiment, an effect already noticed in previous cases was very marked. On cutting off the light, and watching the index ray in its passage across the graduated scale, it was observed that the ray did not readily return to zero. Experimenting many times in rapid succession, this sluggishness could be accumulated. In other instances in which this action has been noticed, I

* 'Proceedings of the Royal Irish Academy,' vol. i., ser. ii. (Sci.), p. 529.

† 'Proceedings of the Royal Society,' May 11, 1876, vol. xxv. p. 22.

explain it by the fact that the disk is a very bad conductor of heat; consequently the molecular disturbance is retained on the front surface, and does not sink so rapidly as it would were the heat rapidly conducted through to the other side of the disk. In the case of the crystalline selenium this action is very strongly marked, and without denying that some of the sluggishness to return to zero may be due to the bad conducting power of selenium for heat, the greater portion of this action is explained by the fact of the sensitiveness to light of this form of selenium. It would seem as if the impact of light on the surface produced a persistent disturbance, which keeps up a similar disturbance in the adjacent gaseous molecules, and takes some time to subside. It is known that the change in electric conducting power of crystalline selenium, when it is transferred from light to darkness, takes some time to effect.

The vitreous selenium does not show this strongly marked sluggishness to return to zero, and it is decidedly less acted on by radiation. This may be due to its non-sensitiveness to light, or to its shining surface reflecting more of the candle rays than does the crystalline surface.

237. TABLE XII.—Miscellaneous Substances—Pith, Mica, Charcoal, Glass, &c.

	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (standard disk)	100·0	100·0
Pith, plain white	17·7	0·4
Pith, lampblacked on one side, white side exposed	0·0	0·0
Amadou, lampblacked on one side, black side exposed	57·5	53·6
Amadou, lampblacked on one side, white side exposed	21·0	12·2
Amadou, not blacked	20·5	7·6
Mica, silver flake, lampblacked on one side, black side exposed	151·0	125·5
Mica, roasted, blacked on the opaque side, black side exposed	111·7	89·3
Mica, roasted, blacked on the clear side, black side exposed	87·5	78·5
Mica, silver flake	12·5	2·1
Mica, roasted, clear side exposed	6·7	0·0
Mica, roasted, blacked on clear side, black turned away from light	6·8	3·5
Mica, roasted, blacked on opaque side, black turned away from light	7·6	8·9
Mica, silver flake, blacked on one side, black turned away from light	9·8	8·8
Charcoal, wood, parallel to the grain	18·4	14·7
Charcoal, wood, across the grain	15·2	10·7
Charcoal, cocoa-nut shell	11·6	3·7
Microscopic glass, quite clear	6·5	0·5
Microscopic glass, having the portion of the glass tube behind it coated internally with lampblack	6·0	0·0

The complicated nature of these actions is well shown by an examination of the results given in the first three lines. Lampblack on a pith disk being 100, plain white pith without any lampblack is 17·7. But when lampblack is applied to the back of the pith, and the plain white surface is again exposed to radiation, the action sinks to zero. The repulsion exerted on the white pith must be the same in each case, but the presence of lampblack behind it has caused an absorption of heat by the back surface, producing molecular pressure just sufficient to neutralise the pressure in front. It is not sufficient therefore to take into account the kind of powder exposed to radiation; its conducting power for heat, as well as that of the disk which serves to support it, and the absorbing and radiating powers of the back surface for heat, together with its distance from the bounding surface of the glass vessel, all have to be taken into consideration. For these reasons too much weight must not be attached to the results given in the foregoing tables. They convey a fair general idea of the variations in the power according to the colour and physical condition of the substances exposed to radiation, and considering the enormous difficulty in getting results which have any approach to quantitative accuracy, they are very satisfactory; but it must be remembered that they are only comparable one with another under the exact conditions in which they were tried, and it is not unlikely that a repetition of the series, with an alteration in some apparently unimportant item, such as an increased diameter of glass tube, a thicker disk of pith, or the substitution for pith of a substance which will better conduct heat, might give a different series of numbers. The proportion between them, however, would probably remain the same as at present.

In an ordinary radiometer, such as I described in my last paper on this subject, (145), the disks are of pith, lampblacked on one side. The present results show that the whole of the force of radiation exerted on the black surface is utilised in turning the fly round.

238. The experiments were tried with mica to test a suggestion by Professor STOKES, that roasted mica, lampblacked on one side, would combine in a pre-eminent degree the conditions needed for the fly of a radiometer, namely,—

1. Good absorption on one face.
2. Good reflection on the other, for heat as well as light.
3. Bad conduction.
4. Absence of organic matter.
5. Extreme lightness.

I had already used mica both plain and roasted, but had never tested them systematically. The "silver flake" mica is a natural mineral occurring in the United States. It is of a brilliant silvery lustre, and splits into exceedingly thin fibres, which are as coherent and tough as ordinary mica, whilst they have the bright reflecting surface of mica artificially calcined. The mineral is probably produced

from ordinary clear mica, through the agency of volcanic or other natural heat. The results show how well Professor STOKES's theoretical reasoning is confirmed by experiment. With a radiometer, the fly of roasted mica lampblacked on one side, the power of radiation to cause rotation will be 111·7 on the black, and −7·6 on the white side, or a total of 119·3, as against 100 with lampblacked pith. The employment of silver flake mica is still more advantageous, as here the blacked side is repelled with a force of 151, whilst the bright side is (apparently) attracted with a force of 9·8, making a total force to turn the fly round of 160·8. The negative action, or apparent attraction, seen when radiation falls on the clear face of a mica disk lampblacked behind, is caused by the heat passing through the thin plate and warming the hinder surface of lampblack. The thinner the mica the greater is this action, up to the point when the lampblack begins to show through. With a thick piece of silver flake mica no negative repulsion takes place, but it becomes positive, increasing in power until it reaches 12·5, which is the amount given by silver flake mica with no black behind it. Taking the action on the blacked silver flake mica as 151, and that on the same mica unblacked as 12·5, the action exerted on the black surface is seen to be 12 times greater than that on the white surface. In some experiments on roasted mica radiometers, published by Professor E. WARTMANN,* the action on the black face is found to be 11·9 times stronger than that on the white face.

On heating clear mica in the blowpipe flame, the side on which the flame plays becomes opaque and silvery, whilst the other side retains its glassy reflecting surface. The employment of one or the other side as the lampblacked surface exerts a considerable difference on the results.

239. The very low results given by the three kinds of charcoal I explain thus:—Radiation falling on the front surface is absorbed and converted into thermometric heat (107, 195), which warms the front side of the charcoal. Although charcoal is one of the worst known conductors of heat, there is no doubt that the vibration caused by heat on the surface of a plate of charcoal is quickly communicated to the layer beneath, and thus a very short time suffices for the conduction of heat through a disk only half a millimetre thick. Having arrived at the hinder surface, the heat which there becomes sensible causes negative repulsion to take place, as in the case of the roasted and blacked mica (238), and the numbers 18·4, 15·2, and 11·6 are simply the differences between these two opposing actions.

This explanation is proved by an experiment. A reference to Table XII. shows that the action of radiation on plain pith is equal to 17·7, whilst that on cocoa-nut shell charcoal is only 11·6. Now were this amount of 11·6 the total action of radiation instead of the difference only, lampblacking the front surface of the charcoal should bring it up to 100, and a radiometer made of cocoa-nut shell charcoal lampblacked on one side should work better than one made of lampblacked pith. On making such an instrument it was however found to be almost insensitive, the feeble

* Société de Physique et d'Histoire Naturelle de Genève, Séance du 2 Mars, 1876.

rotation produced being simply due to the slightly superior absorption which the lampblack possesses over the solid surface of charcoal.

240. The experiments with clear microscopic glass, given in Table XII., were tried in order to test the theory advanced in my paper of Feb. 5, 1876 (194, 195), that the "apparent viscosity of a vacuum"* was due to the absorption, and subsequent slow communication of heat from the substance on which the light fell to the adjacent gaseous molecules. That this effect does occur to an appreciable extent has been proved by the results obtained with aluminium and gold backed with lampblack (232), and with mica and pith backed with lampblack (237). Mr. JOHNSTONE STONEY suggested that this might be tested in a different way by coating the inner side of the exhausted tube with lampblack opposite to the disk of glass. Upon allowing light to fall across the vacuum on this blackened surface, the disk should move towards the light. The results show that such an action does not take place to an appreciable extent. Being fully convinced that the theory is correct, I have carefully examined the apparatus, and thought over the conditions under which the experiment was tried, in the hope of discovering the cause of the anomaly and thereby reconciling this result with the numerous array of proofs ranged on the opposite side. I think a sufficient explanation is to be found in the behaviour of the glass disk when it is exposed to radiation behind a water screen. When the total radiation from the candle falls on the thin glass, both the light and heat are acting, and the movement of 6·5 may be due to either of these or to both combined. By interposing a water screen I practically cut off all the invisible heat rays, and any action which now takes place must be due to the luminous rays. But behind water the repulsion is only 0·5, in comparison to lampblacked pith behind water =100, or not more than (0·5÷12=) 0·04, in comparison to the repulsion of 6·5 when the water screen is away. The luminous rays are therefore 162·5 times less active on thin glass than are the heat rays, and may consequently be left out of consideration altogether; they pass through

* This must not be confounded with the *viscosity of the residual gas*, in the sense in which I speak of it in the preliminary notice published in the 'Proceedings of the Royal Society,' No. 175, 1876. What I meant by the "apparent viscosity of a vacuum," spoken of in par. 195, is rendered clear by the description of the experiment, which I will quote from par. 194:—"A candle held close to the screen, and the shutter momentarily opened and closed, sent the index with some violence to the extreme limit of the scale. It then slowly came back to zero, and there stopped. . . . . . The movement of the beam . . . . . . seemed as if it were held in check by a force acting the whole time of its movement, and not only for the time the light acted. The impression conveyed was that the beam was swinging in a viscous fluid. . . . . . I then gave the apparatus a sudden twist round, so as to cause the beam to knock against the side of the tube. This set it swinging through a large arc, and the oscillations kept up with perfect freedom for several minutes, declining in amplitude at each oscillation, till the beam ultimately came to zero. This perfectly free movement is in strong contrast to the constraint under which the beam moves when the initial blow is given by a ray of light instead of by a mechanical push."

In an earlier experiment of the same kind, described in Part II. of this research, I express the same idea thus:—"(107.) This behaviour points to the return movement taking place under the influence of a force which remains active after the original radiation is cut off, and which is only gradually dissipated."

the glass unchanged, and can therefore do no work on its surface. With the ultra-red heat rays, the case is different; to these glass is almost opaque, and their energy, being arrested, is transformed into thermometric heat, or heat of temperature which raises the temperature of the glass. But before arriving at the disk of thin glass under experiment, the radiation from the candle meets the obstruction offered by the front wall of the glass tube in which the disks swing. The heat rays from the candle are mostly stopped by this glass and raise its temperature. The warm glass then becomes the point whence the lines of molecular pressure radiate; and it is this molecular force which repels the plate of thin glass, and not the reaction of molecules which are set into activity by a rise of temperature of its own surface. The luminous rays from the candle pass unchanged through the front wall of the tube, through the thin glass disk, and strike the lampblack with which the hind wall is coated. Here they are quenched, and, as I think has been sufficiently proved, they increase the temperature of the lampblacked surface and cause molecular pressure in the adjacent gas. The disk of thin glass suspended in the centre of the tube is therefore acted upon by two opposing forces, one from the front and one from the back wall of the tube, and its movement is in accordance with the stronger of the two. The front force is due to the direct heat of the candle, whilst the back force is due to the light falling on the lampblack and being degraded into heat. Were the heat and the light originally equal in amount, the original heat would ultimately largely exceed that produced from the degraded light; but, as is already proved (197), much of the action of a candle is due to the ultra-red rays, and it may therefore be reasonably supposed that, in comparison to the strong action of the repulsion from the front wall of the tube, that from the back of the tube is inappreciable. That such an action as is here sought really occurs is abundantly proved further on, but the present form of apparatus is not suitable for showing it.

ACTION OF SCREENS.

241. When the experiments described in the foregoing paragraphs were first commenced, I used several screens besides water (109, 200, 201), and tabulated the results with each kind. They consisted of plates of glass of various colours, and glass cells filled with coloured solutions, such as potash bichromate, copper sulphate, iodine dissolved in carbon disulphide, &c. But the time required to take a sufficient number of observations in order to get a satisfactory mean with each substance tried behind each screen, was more than I could give; I was therefore obliged to content myself with a single screen. For several reasons I decided upon water in a clear glass cell. First, it is almost perfectly opaque to the invisible heat rays, consequently its employment facilitates discrimination between actions due to heat and to heat and light combined. Secondly, it is colourless, and, having no selective action on any visible ray of light, can be used in conjunction with any coloured

powder, without complicating the results. Coloured glasses, or very thick masses of colourless plate glass, generally act in proportion to the amount of light they apparently cut off; whilst coloured solutions act like water, with a special action superadded, due to the colour. A very considerable thickness of glass offers less obstruction to the motion-producing rays than does a very thin layer of water. A clear plate of alum is very similar to water in its effects, and a solution of alum is almost identical with the same thickness of water. Copper sulphate solution offers great obstruction when artificial light is used. These facts show that glass is not so opaque to the ultra red heat rays as is water; that the lowest visible red rays are likewise powerful heat rays; and that by cutting off these also, by adding copper sulphate to water, a considerable fraction of the rays which produce repulsion when artificial light is used will be cut off.*

Seeing the very strong absorptive action which gaseous ammonia exerts on rays of radiant heat,† as measured by a thermo-pile, I endeavoured to detect any diminution in the intensity of the repulsion on pith, lampblacked and plain, lampblacked mica, as well as on other bodies, when the rays from the candle were allowed to pass through a layer of pure ammonia gas, 6 inches in thickness. I was, however, unable to detect the slightest diminution of action which could be ascribed to the absorption of heat by the ammonia gas (200).

DIFFERENT ACTIONS OF RADIANT HEAT AND OF LIGHT.

242. An examination of the preceding tables shows that the substances used in experiment can be divided into two classes: 1, *negative*, those in which the repulsion behind water is greater, in proportion to the standard, than when no screen is present; and 2, *positive*, those in which the repulsion, in proportion to the standard, is less behind water than when no screen is interposed. From these tables a few illustrations are selected:—

Table XIII.

Class 1.

	No screen.	Water screen.	Difference.
Lampblack (standard disk)	100·0	100·0	0·0
Copper tungstate	51·2	77·0	−25·8
Saffranin	41·0	52·5	−11·5
Precipitated selenium	35·8	69·5	−33·7
Copper oxalate	30·1	40·2	−10·1

* In some rooms lighted by gas, a layer of water is interposed between the light and the lower part of the room, with the view to cut off the heat. This device answers very well, but the absorption of heat could be greatly augmented by adding to the water a very little copper sulphate, whilst the colour of the light would at the same time be improved.

† 'Contributions to Molecular Physics in the Domain of Radiant Heat.' By J. Tyndall, LL.D., F.R.S., p. 80.

CLASS 2.

	No screen.	Water screen.	Difference.
Lampblack (*standard disk*)	100·0	100·0	0·0
Chromic oxide, pale green	71·5	20·2	+51·3
Persulpho-cyanogen	43·9	11·5	+32·4
Hydrated zinc oxide	40·5	14·0	+26·5
Barium sulphate	37·4	4·2	+33·2
Calcium carbonate	28·5	3·9	+14·6

In class 1, the behaviour behind water shows that the substances experimented on are much more affected by light than by invisible heat; whilst the behaviour of the bodies in class 2, behind water, shows that these are much more acted on by the ultra-red heat rays than by the luminous rays. To render these differences of action more comparable, the figures in the second column (water screen) must be divided by twelve (par. 224). Uniting the two classes together, the figures then become as follows:—

243. TABLE XIV.

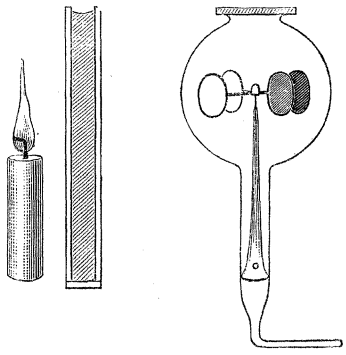
	No screen.	Water screen interposed (5 millims.).
	°	°
Lampblack (*standard disk*)	100·0	8·3
Chromic oxide, pale green	71·5	1·7
Copper tungstate	51·2	6·4
Persulpho-cyanogen	43·9	1·0
Saffranin	41·0	4·3
Hydrated zinc oxide	40·5	1·2
Barium sulphate	37·4	0·3
Selenium, precipitated	35·8	5·8
Copper oxalate	30·1	3·3
Calcium carbonate	28·5	0·3

EXPERIMENTAL VERIFICATION OF THEORY.

244. At the end of a long investigation with complicated apparatus, it is a great satisfaction to find that an easy way of proving the general accuracy of the results offers itself; more especially if the numerical results show many discrepancies, which may be due to errors of experiment, or on the other hand may be anomalies, pointing in the direction of further discoveries. A glance at the above table shows that the results can be proved by balancing one powder against another in a radiometer. A bulb was blown on the end of a wide tube, as shown at fig. 4. The top of the bulb was opened and turned over to form a lip; this was ground smooth and polished so as to be readily closed by cementing on it a piece of plate glass. A glass stem supports a fine

needle in the centre of the bulb, and on this rests a glass cap, to which is attached four radial arms of aluminium. To these arms disks of mica or pith can be fastened, so as to form the moveable fly of a radiometer. The disks can be changed by uncementing the glass top, and lifting the fly out with tweezers. The lower part of the

Fig. 4.



tube is drawn out for connexion with the mercury pump. The powders used for experiment were carefully painted on the opposite sides of pith or mica disks, only water or alcohol being used (222).

245. The first pair of substances tested in this apparatus were chromic oxide and precipitated selenium.* In a tabular form, these stand as follows (243) :—

	No screen.	Water screen.
Chromic oxide	71·5	1·7
Selenium, precipitated	35·8	5·8
Difference	+35·7	−4·1

A radiometer therefore made of these powders, on alternate sides of pith disks, should rotate in one direction when no screen is interposed between it and the light, and in the opposite direction when behind a water screen—the positive rotation taking place with a force of 35·7, and the negative rotation with a force of 4·1.

When the apparatus was exhausted up to the point of maximum sensitiveness, a glass cell full of water was placed in front of it and a lighted candle brought near. Negative rotation immediately commenced, the selenium being repelled. On drawing away the screen the rotation stopped, and positive rotation commenced, which could

* The selenium was precipitated as a brilliant scarlet powder, by boiling commercial selenium in fine powder, in solution of cyanide of potassium, and then supersaturating with hydrochloric acid. Selenocyanide of potassium is formed, and I showed in 1851 that this salt is decomposed by almost any acid, with precipitation of selenium. (Chem. Soc. Journ., iv., 1852, p. 13.)

be changed to negative by interposing the water screen. The positive rotation was much the stronger of the two.

Exposed to the candle radiation behind a screen of black talc, perfectly opaque but diathermous, positive rotation ensued.

The candle was removed, and a hot glass shade* put over the bulb and fly. Negative rotation took place; on removing the hot shade and letting the instrument cool, there was no reversal of rotation (161, 165, 167, 168).

246. The fly was then removed from the apparatus, and the pith disks replaced by others coated on opposite sides with the following powders :—

	No screen.	Water screen.
Chromic oxide	71·5	1·7
Copper tungstate	51·2	6·4
	+20·3	−4·7

When properly exhausted, the instrument was exposed to candle light behind a water screen, as in the previous experiment; quick negative rotation took place, the copper-tungstate being repelled. Whilst the fly was in full rotation, the water screen was drawn away, the candle still remaining; the negative rotation got slacker and slacker till the fly just moved round, but it did not stop entirely, or revolve positively, as it should have done according to the indications of the above table. By holding a second candle, temporarily, close to the chromium side of a disk, the movement could be stopped, but on taking away the second candle the slow negative rotation recommenced. So far, the results only half agree with theory: the negative rotation behind water is correct, but the positive rotation to the direct light is not seen. The candle was then removed, and the fly allowed to come to rest. When quite still and cold, the lighted candle was again brought up to the apparatus, when the fly at once moved, the chromic oxide being this time repelled, and positive rotation, in accordance with theory, keeping up for several revolutions. After a little time, however, the positive rotation slackened, then stopped altogether, and finally gave place to a very slow negative rotation.

From these experiments it appears that the superior repulsion, exerted by radiation from a naked candle, on chromic oxide over copper tungstate, is due to the former being more sensitive to ultra-red heat rays: this, in fact, is in accordance with the results behind water. When dark heat rays are thus filtered off, the copper tungstate is four times more sensitive to the residual luminous rays than is the chromic oxide. But the peculiar behaviour in the last experiment carries the proof a step further. The candle, shining on the glass bulb, gradually raises its temperature, and the glass begins to radiate dark heat in all directions, on the chromic oxide and copper tungstate

* A hot glass shade is used as a convenient means of heating the bulb, by immersing it in a hot air bath, without the liability of introducing action of rays other than those emitted by hot glass.

equally. Now, I have already shown (128, 144, 155, 156, 157, 161) that dark heat, radiated from glass, has a very different action on a lampblack and pith radiometer from that of the luminous rays; and at pars. 170, 171, 172, reasons are adduced for believing that, to rays of low refrangibility radiated from hot glass, white pith and lampblack change places, the pith becoming black and the lampblack acting as a light substance.

It is therefore legitimate to carry out the same line of reasoning in the case of chromic oxide and copper tungstate. To the total radiation from the candle, unfiltered except through the thin glass wall of the bulb, the chromium compound is the more sensitive; the chromic oxide is black, and the copper tungstate white. But when exposed to the heat rays of low refrangibility emitted by warm glass, the two powders change places, and chromic oxide becomes white, whilst copper tungstate absorbs them powerfully, and behaves as a black powder. The difference between the action of dark heat and that due to the other rays is sufficient not only to overcome the *plus* action of 20·3, but to give a slight negative action.*

When covered with a hot glass shade, negative rotation takes place, the copper tungstate being repelled; on removing the shade and letting the instrument cool, reverse rotation takes place, the fly now moving positively. The theory just discussed is therefore corroborated.

247. The next powders experimented with were persulpho-cyanogen and copper oxalate; in a tabular form these stand thus:—

	No screen.	Water screen.
Persulpho-cyanogen	43·9	1·0
Copper oxalate	30·1	3·3
	+13·8	−2·3

Showing a positive rotation of 13·8 to the naked flame, and a negative rotation of 2·3 behind a water screen. When properly exhausted and exposed to the candle behind water, negative rotation was produced, and continued steadily as long as the experiment was tried. Without moving the candle the water screen was now taken away. The direction of rotation instantly changed, and gave place to a rapid positive rotation. The speed, however, soon diminished, and in a little time, when the bulb had become warm, there was great difficulty in the copper oxalate passing the candle, and sometimes a disk would stop on the dead centre. A gentle tap on the bulb always sent it on, and then rotation would continue for a short time longer, the persulpho-cyanogen always being the powder most repelled by the naked flame.

When the fly was cold a hot glass shade was inverted over the bulb; positive rotation immediately commenced, which, when the hot shade was removed and the apparatus was cooling, changed to negative rotation.

* I may here remark that this anomalous action is strongly marked in the case of most copper salts, which act as if they were nearly white to light, but black to heat of low refrangibility.

The phenomena observed with this couple are similar to those commented on in the case of the chromic oxide and copper tungstate (246). The explanation there given will apply equally well to the present case.

248. Another couple was now tried, namely—

	No screen.	Water screen.
Persulpho-cyanogen	43·9	1·0
Saffranin	41·0	4·3
	+ 2·9	−3·3

Tested in the same way as the others the results were in conformity with the figures. Positive rotation (persulpho-cyanogen being repelled) was obtained when exposed to the naked flame, and negative rotation (saffranin repelled) when water was interposed. In either case the movement was feeble, and was not continuous with only one candle. With two or three candles the rotations were strong.

249. Another couple (saffranin and hydrated zinc oxide) were now selected, which were nearly equal to the naked flame but different behind water. The figures are—

	No screen.	Water screen.
Saffranin	41·0	4·3
Hydrated zinc oxide	40·5	1·2
	+ 0·5	+3·1

Tested as in the other experiments, no motion could be detected with the naked flame of one candle, and only slight repulsion of the saffranin when five candles were used. Behind water, however, there was good rotation with one candle, the saffranin being repelled.

Upon inverting a hot glass shade over the bulb no movement of the fly was produced.

250. A couple was now selected which should give rotation to the naked flame, but none behind water. They were—

	No screen.	Water screen.
Barium sulphate	37·4	0·3
Calcium carbonate	28·5	0·3
	+ 8·9	0·0

With no screen, good rotation was produced, the barium compound being repelled. No movement whatever was observed when a water screen was interposed.

Covered with a hot glass shade rotation was produced, the barium sulphate being repelled. There was slight reversion of movement on cooling.

251. The following couple—

	No screen.	Water screen.
Thallic oxide	121·7	9·2
Green platinum salt of Magnus	89·5	8·8
	33·2	0·4

also acted to the naked flame and behind water in accordance with theory, giving good rotation in one case and no movement in the other.

Covered with a hot glass shade the platinum compound was repelled, producing rotation. On removing the source of heat, and allowing the bulb to cool, reversion of movement took place.

252. In addition to these couples, experiments were also tried in the apparatus with other substances likely to give valuable results. Metallic iron and gold, rolled together to thin foil and well polished on each side, were punched into disks and mounted on the fly, the gold facing one way and the iron the other. After exhaustion the iron was most repelled by a candle flame, rotation being produced. When the bulb was grasped in the warm hand or covered with a hot shade the gold was repelled, producing rotation, which reversed on cooling.

253. Platinum and gold in thin foil, heated till the gold just fused to the surface of the platinum and then rolled flat, were tried in the same way. Exposed to the light of a candle the gold was slightly repelled, and with three candles continuous rotation was produced. Covered with a hot shade the platinum was slightly repelled.

254. Zinc and copper were rolled together and tried in the same manner in the apparatus. One candle gave good rotation, the zinc being repelled. Heated with a hot glass shade the zinc was still repelled, rotation being produced, and the motion reversing on cooling. Behind water no movement was produced by the light of three candles.

ANOMALIES EXHIBITED BY SELENIUM.

255. The most sensitive couple experimented on is the chromic oxide and scarlet selenium (245), and accordingly I put these powders together in the form of a radiometer both for the sake of further experiments and for the convenience of retaining the actual apparatus in a permanent form for future illustration or research. Thin pith was used for the disks, and the powders were thickly painted on alternate sides, so that the same powder should always follow or lead, according to the direction of rotation. The radiometer was well exhausted and then sealed off. The experiments are sufficiently instructive to warrant my giving them somewhat in detail, as they illustrate in a striking manner the extremely complicated actions involved in these repulsions, and also serve as a warning against hasty generalisations.

It should be remembered that the experiments collected together in this paper have extended over more than twelve months; each experiment was fully described

at the time in my note book, and it is my custom to verify everything of importance. The record of experiments given in paragraph 245 was written in May last. The repetition now described took place in October.

When a lighted candle was placed $1\frac{1}{2}$ inches from the bulb continuous rotation was produced, but instead of the chromic oxide being repelled the selenium was repelled. Another candle was lighted, and the two only made the abnormal rotation stronger. After a time the bulb became warm and the rotation got slower till it stopped. The candles were blown out, and when the bulb had cooled, a water cell was interposed and one candle was lighted. Good rotation now took place in the same direction as when no water intervened; the radiometer, in fact, behaved just like an ordinary lampblack and white pith one, the scarlet selenium representing the black surface. The results were not quite so strong as when lampblack is used, but they were so definite that had it not been for the previous observations I should unhesitatingly have assumed that the true action was as now recorded. But knowing that my former results were just as carefully worked out as the present ones, and not admitting "experimental errors" as explanations of anomalies, I sought long and anxiously for a physical cause of these two diametrically opposite results. Every circumstance which could influence the result was the same in the two experiments, yet in May I found a candle repelled chromic oxide more than it did selenium, whilst in October I found the selenium decidedly the more repelled of the two, positive rotation occurring in one case and negative in the other.

256. Next day I repeated the experiment by placing a lighted candle near the radiometer, and the fly at once rotated, *the chromic oxide being repelled.* Nothing had been moved, nothing had changed since the previous day except the candle. Here was a clue which, followed up, explained everything. The candle used in May was a large wax candle, four to the pound; that used in October was a sperm candle of a smaller size, six to the pound, and having a whiter flame. I found I could always get the chromic oxide repelled by using the wax candle, and the selenium repelled by using the sperm candle; the difference between the two is evidently due to a variation in the proportion of light to heat. The sperm has a very white flame, whilst the wax candle burns with a yellower flame: for equal amounts of light, therefore, the wax candle gives more heat; and according to theory heat is principally required to repel chromic oxide, whilst light chiefly repels selenium. To test this by experiment was easy. A spirit flame was brought near the bulb; decided repulsion of the chromic oxide with quick rotation followed. A Bunsen burner, with the air holes covered (giving a luminous flame), brought near the bulb caused repulsion of the selenium, but scarcely strong enough to give continuous rotation. On uncovering the air holes and making the flame non-luminous the chromic oxide was strongly repelled, giving rapid rotation.

The radiometer was exposed to the light from two candles behind a transparent plate of alum, 5 millims. thick; continuous quick rotation ensued, the selenium being

repelled. A spirit flame was now brought up about six inches from the opposite side of the radiometer, nothing intervening. The rotation gradually slackened, and then stopped. On bringing the spirit flame nearer, the heat overbalanced the candle-light and the chromic oxide was repelled, whilst on removing the spirit flame further off the light overcame the heat, and the selenium was repelled. The balance between the heat from the spirit lamp and the light from the candles was perfect, the fly obeying the stronger force as delicately as if it were a magnetic needle under the influence of two opposite currents.

257. The very strong action exerted by solution of copper sulphate on the rays which are usually most powerful in causing repulsion in a vacuum, has already been mentioned (139, 153, 241). The radiometer was exposed to the light of the same two candles, a cell containing a saturated solution of copper sulphate, 5 millims. thick, being interposed; rotation in this case was also produced, the selenium being repelled with a force only a little less than it would have been behind water or alum.

A colourless gas flame from a Bunsen burner was coloured intensely green by thallium, and the radiometer brought near it. To the eye, by this light, the chromic oxide looked nearly white, and the selenium black. The rotation due to the repulsion of the chromic oxide was, however, apparently as strong as when the non-luminous flame was used. This is a proof that the train of argument I have employed on former occasions is correct—viz., that certain substances have an opposite absorptive action on rays of dark heat to what they have on light, and that an optically white body may be thermically black, and *vice versâ* (170, 171, 172, 246). Here, for instance, chromic oxide is optically white and thermically black, whilst scarlet selenium is optically black and thermically white.

258. The experiments with the Bunsen flame show that the behaviour of scarlet selenium in a vacuum is closely allied to the variations in the electrical resistance of crystalline selenium when exposed to similar flames. During some researches undertaken to determine whether the change in the electrical resistance of selenium is due to radiant heat, light, or chemical action, Professor W. G. ADAMS* tried the effect of exposing the selenium to a Bunsen burner alone, in its ordinary state, and when it is rendered luminous by stopping the air holes. I quote the following passages from his printed paper:—

"Exposure to the ordinary Bunsen flame for several seconds only caused a slight deflection of about 10 divisions of the scale.

"On making the flame luminous, the needle was suddenly deflected off the scale with great rapidity.

"With the 10 shunt to the galvanometer, there was no deflection on exposure to the ordinary Bunsen flame; but with the luminous flame there was a sudden deflection, which increased to 250 divisions of the scale in a few seconds.

* "On the Action of Light on Selenium." Proc. Roy. Soc., June 17, 1875, vol xxiii. p. 535.

"The illuminating power of these sources of light was compared by means of the Bunsen photometer.

"The light of the ordinary Bunsen flame could scarcely be measured, but was somewhere about $\frac{1}{200}$th part of a candle, and of the luminous Bunsen flame about 10 candles.

"The heating effects of these sources were compared by means of the thermo-electric pile and delicate astatic galvanometer.

"At a distance of one foot from the face of the pile, the deflection produced by the ordinary Bunsen flame was $46\frac{1}{2}°$, and by the luminous Bunsen flame was 52°.

"These experiments clearly show that very little effect is produced by the radiation of obscure heat, but that the effect is due almost entirely, if not entirely, to light.

"These experiments show that the action on the selenium is due principally, if not entirely, to radiations belonging to the visible part of the spectrum."

These passages might almost have been written by myself to describe the repulsion produced by obscure and luminous radiation on scarlet selenium, so closely do they express the actions which I have been elucidating.

259. Professor ADAMS concludes his paper by suggesting two hypotheses as possible explanations which may help as guides in further experiments, but which he thinks cannot be accepted as proved without further evidence. These hypotheses are :—

(1.) That the light, falling on the selenium, causes an electro-motive force in it, in the same direction as the battery-current passing through it, the effect being similar to the effect due to polarization in an electrolyte, but in the opposite direction.

(2.) That the light, falling on the selenium, causes a change on its surface, akin to the change which it produces on the surface of a phosphorescent body, and that in consequence of this change the electric current is enabled to pass more readily over the surface of the selenium.

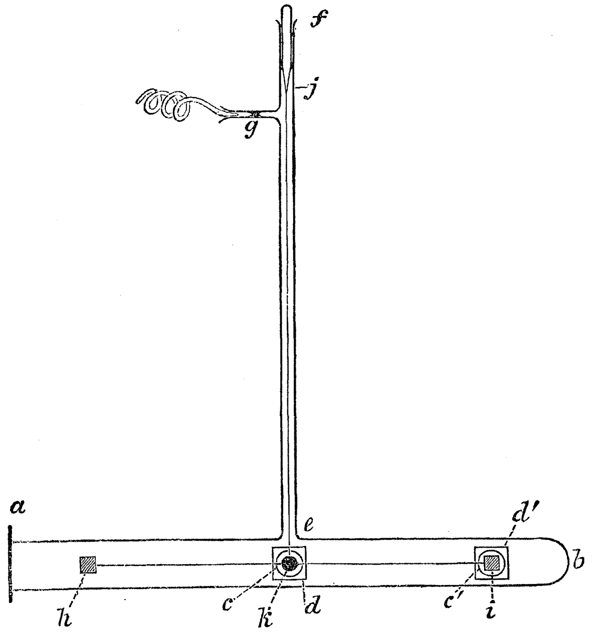
I think there is little doubt that my own experiments show that the second of these two hypotheses is more likely to be correct. The change on the surface, which diminishes electrical resistance in Professor ADAMS's experiments, sets the molecules of the selenium into such a state of vibration that this vibration is communicated to the adjacent molecules of residual gas, and causes them to exert molecular pressure, which drives back the selenium. In comparing the two series of experiments, it must be borne in mind that in testing plates of crystalline selenium which were in the state most sensitive to light from Professor ADAMS's point of view (236), I failed to detect any special action; whilst the variety of selenium found to be most sensitive to the luminous rays is a scarlet, amorphous powder, precipitated from a cold solution, and very different, physically, from the crystalline variety produced by long continued heat on the ordinary vitreous selenium.

EXPERIMENTS WITH POLARISED LIGHT.

259. I have long endeavoured to carry out a suggestion made by Professor MASKELYNE during the discussion of the first part of my paper "On Repulsion resulting from Radiation," at the Royal Society, the evening of December 11, 1873, viz.—that I should suspend a plate of tourmaline in a vacuum, and see if different amounts of repulsion were produced by allowing light to fall on it after passing through another tourmaline, which could be rotated so as to alter the plane of polarisation of the incident light.

Three separate sets of experiments were tried. The results are the same in each, and as they have been obtained under different circumstances, and are interesting from a theoretical point of view, I will briefly describe each apparatus.

Fig. 5.



The apparatus first used consists of an ordinary torsion apparatus in an inverted **T** tube, as shown at fig. 5, *a, b, e, f,* made of glass tubing cemented together at *e*, and ground flat at the end *a*. In the centre is blown a circular hole *c*, and another hole, *c'*, is at the end; the edges of these holes are also ground quite flat. *a, c,* and *c'* are sealed up by cementing plates of glass *a, d, d'*, on them. *g* is the connexion to the mercury-pump. The beam *h i* is of glass drawn from square glass tube; *j k* is the glass torsion fibre; *k* is a silvered glass mirror. The plate of tourmaline is attached to the beam at *i*, and a glass counterpoise is fixed at *h* to balance the tourmaline.

In the first experiments a plate cut from a crystal of tourmaline was used at *i*, but it was found that it became so electrical when a ray of light fell on it in the vacuum

that no observations of any value could be taken, the crystal being attracted to one side or the other of the glass tube. A thin plate of artificial tourmaline (herapathite or iodo-sulphate of quinine) was then used at *i*, instead of the tourmaline, and with this no inconvenience was observed from electrification.

A few experiments showed me that the red and heating rays of the spectrum were most active in repelling this artificial tourmaline, so a platinum spiral, heated to full redness by a 2-cell Grove's battery, was used as the source of radiation.* A large silvered reflecting mirror was placed behind the hot spiral and a lens in front of it, so as to form a highly luminous image of the spiral on the tourmaline. Close to the window *c′* a large slice of real tourmaline† was mounted as a polariser in a frame, so that it could be easily rotated. The apparatus was covered with black velvet, and care was taken to allow no light to get to the artificial tourmaline except what had passed through the polarising tourmaline.

A luminous index, reflected from the mirror *k* to a graduated scale, showed the movement of the beam. The contact key was pressed down, and the spiral heated for time sufficient to allow the index to get to the extremity of the first oscillation. The number of degrees on the scale at which the index stopped was noted. Observations were sometimes taken with the tourmalines crossed and parallel alternately, and at other times a series of observations was taken with the polarising tourmaline one way, and then a series with the tourmaline turned the other way. The means of each set of observations, which were fairly concordant, are given below :—

	Artificial and natural tourmalines.	
	Parallel.	Crossed.
	°	°
Group 1	18·0	17·8
,, 2	11·5	13·5
Mean . .	14·75	15·65

Observations were now taken by keeping the battery key down for exactly five seconds :—

	Artificial and natural tourmalines.	
	Parallel.	Crossed.
	°	°
Group 3	3·5	3·5
,, 4	3·4	3·5
,, 5	3·5	3·5
Mean . .	3·47	3·50

These results look as if there were no difference between the actions; but the

* A platinum ball, heated to redness by a gas flame, was at first tried, but the heat from the gas was too great.

† I am indebted to Professor MASKELYNE for the loan of several plates of tourmaline of very large size.

apparatus was not very sensitive, and with so small an amplitude as 3·5° much accuracy could not be expected. It was therefore put aside, and the experiments were not resumed for nearly four years.

Apparatus No. 2 is the same in construction as No. 1 (fig. 5), made, however, more delicately, suspended by a finer torsion fibre, and sealed on to a pump with which I can easily bring the exhaustion to the most sensitive point. Instead of a hot platinum spiral, a standard candle is used. The polariser is the same large plate of real tourmaline used in the previous apparatus. With this, a large series of observations were made; the means are given below, arranged in groups :—

	Artificial and natural tourmalines.	
	Parallel.	Crossed.
	°	°
Group 1	24·8	25·2
„ 2	13·5	19·0
„ 3	14·0	16·0
„ 4	18·5	18·5
„ 5	17·0	21·5
„ 6	18·0	18·0
„ 7	16·0	16·0
„ 8	16·0	18·0
„ 9	17·0	17·0
Mean . .	17·2	18·8

260. So far the results show a very slight difference in favour of the crossed tourmalines. The artificial tourmaline being very small, and exposing some bare glass round its edge, it was removed from the apparatus, and a thin slice from a natural crystal of tourmaline was suspended in its place. To avoid the inconvenience of electrification, I adopted a device suggested by Mr. C. F. Varley, which answered perfectly—viz., binding the crystal very loosely with the finest platinum wire, so as to form a gridiron-shaped grating about half a millimetre from its surface, the wires being about a millimetre apart. As polariser, a large Nicol's prism was used, for the loan of which I am indebted to Mr. Spottiswoode.

With this arrangement a large number of observations were taken, with the following results :—

	Nicol's prism and natural tourmaline.	
	Parallel.	Crossed.
	°	°
Group 1	18·0	16·5
„ 2	20·5	16·0
„ 3	20·5	17·
„ 4	21·	17·
„ 5	21·	16·5
„ 6	21·5	17·
Mean . .	20·4	16·7

The difference in this case is on the other side. It would now seem that there was more repulsion when the polarised ray passed through the crystal. There was, however, great difficulty in bringing the beam and index ray of light back to zero; the platinum grating was successful in preventing the tourmaline from flying to one or other side of the glass tube and there sticking, but there seemed to be a residual action which kept the suspending fibre in a state of torsion and interfered with the free movement of the crystal.

Another apparatus was therefore made, introducing every refinement which experience suggested, and employing a still finer torsion fibre. A minute portion of a magnetised sewing needle was attached to the beam at the centre, so as to allow the beam each time to be brought to zero by a control magnet outside. The natural tourmaline was discarded, and a large and very perfect crystal of artificial tourmaline suspended in its place. The standard candle was kept two inches from the polarising tourmaline, and sheets of glass enclosing an air space between, and a water cell 5 millims. thick, were interposed to cut off radiant heat. The apparatus was well packed with cotton wool, except in the actual paths of the light.

The means of several observations are collected below into groups. The apparatus was allowed to come to perfect rest between each observation, and the lighted candle was only brought near it just before the screen was removed to take each observation.

	Artificial and natural tourmalines.	
	Parallel.	Crossed.
Group 1	15°·	15°·5
" 2	16·5	15·
" 3	15·5	16·5
" 4	16·5	16·
" 5	15·	15·5
" 6	15·5	15·5
" 7	16·	16·5
" 8	16·	16·5
" 9	15·5	..
Mean . .	15·7	15·9

Here the difference has vanished to within the limits of accuracy of which the apparatus is capable.

261. Finally, the control magnet was removed further off so as to get greater amplitude of swing. The sensitiveness of the apparatus was thereby considerably increased.

The following are the means of three groups of observations taken with it so arranged:—

	Artificial and natural tourmalines.	
	Parallel.	Crossed.
Group 1	40°·	46°·
„ 2	38·	36.
„ 3	36·	30·
Mean . .	38·	37·3

Here the difference is in favour of the parallel tourmalines, but it is so slight that, like the former result, I do not consider it as the expression of a natural law.

262. The idea when these experiments were first tried was that a slice of tourmaline, being black to a ray of light polarised in one plane, and white to a ray polarised in the other plane, would be repelled when the incident light was quenched by it, and not affected when the incident light passed through it. The idea was a perfectly reasonable one some years ago; but recent researches have proved that the repulsion resulting from radiation is almost entirely a surface action, whilst the action of a tourmaline on a ray of polarised light is one in which thickness is necessary.

The above experiments prove that the special action originally thought possible does not exist in a degree appreciable with the present experimental means.

263. That a polarised ray of light can produce repulsion in a vacuum as well as a ray of common light is proved by the fact that radiometers move readily when exposed to candle light which has passed through Mr. SPOTTISWOODE's large prism. A torsion balance with black pith at one end was also exposed to candle light, two tourmalines being interposed between the candle and the pith. When the tourmalines were crossed there was no repulsion, but when parallel the pith was driven back against the side of the glass tube.

EFFECT OF SHAPE IN INFLUENCING THE AMOUNT AND DIRECTION OF REPULSION.

264. In a preliminary note on the theory of the radiometer, which I had the honour of experimentally illustrating at the meeting of the Royal Society, November 16th, 1876,* I described an experiment in which the vanes of a radiometer were made of gold leaf, lampblacked on one side. The apparatus in which this and most of the succeeding experiments in this division were tried, is the one shown at fig. 4, par. 244. Through the open top, access can readily be obtained, and disks, plates, &c., can be quickly tested by being fixed to the extremities of a pair of aluminium arms with a glass cap in the centre, rotating on the needle point. On submitting the pair of blacked gold leaf disks to experiment in this apparatus, after exhaustion, I found an anomaly in the action. A candle repelled the black surface of one of the disks, but it seemed to repel with almost equal energy the metallic surface of the other disk; one

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

disk moving positively* and the other negatively, according to the one on which the light was allowed to shine. The disk which moved the negative way was somewhat crumpled, and on examining the action more closely I found that the slight curvature of the gold leaf thereby produced was the cause of the anomalous action. By means of screens with small apertures in front of the candle, and by concentrating a small image of the candle flame on various parts of the crumpled disk by means of a lens, motion could be produced in either direction; repulsion being produced when the light fell on a convex, and attraction when it shone on a concave portion of the disk. The gold disk which behaved abnormally happened to be slightly turned up at the edge next the tube, so as to present a bright convex surface to the candle.

265. Experiments were now commenced with a view to clear up this interfering action due to the shape of the vanes. As the experiments are very numerous and only differ from one another in small modifications or details, which have been successively introduced in order to ascertain what are the accidental and what the necessary accompaniments of the phenomena, I will only describe the first in detail, and will give the others of the series as briefly as possible consistent with clearness.

Plates 12 millims. square, cut from thin aluminium foil, were mounted diamond-wise on arms and supported on the needle point inside the bulb shown in fig. 5. The plates were lampblacked on sides facing opposite ways, and the apparatus was well exhausted. The vanes behaved like an ordinary metal radiometer in respect to light

Fig. 6.

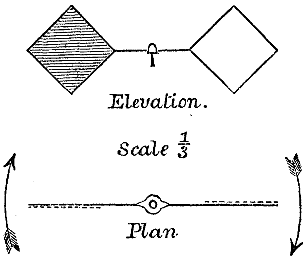
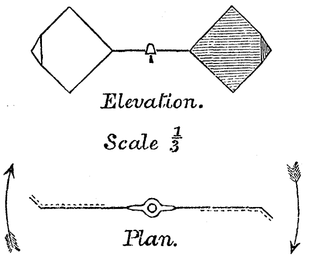


Fig. 7.



and radiant heat. Fig. 6 shows the elevation and plan of the fly, the dotted side representing the one which was lampblacked. The arrows show the direction of positive rotation† when exposed to the light of a standard candle 3·5 inches off. The exhaustion in this and in all cases, except where otherwise specified, was carried to the point at which the fly moved most rapidly to the candle.

266. The outer corners of the aluminium plates were now turned up at an angle of 45°, 4 millims. of the two sides being turned up, leaving 8 millims. flat, as shown in fig. 7. They were lampblacked on the inside, as shown in the figure by dots. A lighted candle, 3·5 inches off, caused very slow and feeble positive rotation. On

* I call the rotation *positive* when the black or driving side is repelled, and *negative* when the side which, under ordinary circumstances, would be the driving side, moves towards the light.

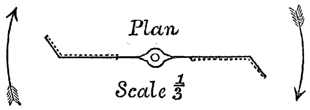
† In the experiments illustrated by figs. 6 to 11 (pars. 265 to 272), the direction of *positive* rotation is shown by the arrows.

shading the light from the black side the bright side was repelled, causing positive rotation, and on shading the light from the bright side the black was repelled, causing negative rotation; but the positive repulsion was rather stronger than the negative repulsion, and consequently when both sides were illuminated the force was only that due to the difference of these repulsions.*

A hot glass shade inverted over the bulb (245, *note*) produced negative rotation, changing to positive on cooling. Both these rotations were stronger than that given by the candle.

267. Instead of 4 millims. of the sides being turned up, 6 millims. were turned up, as shown in fig. 8. The candle gave moderately good positive rotation. On shading

Fig. 8.



the light from the black surface by means of a screen, and letting it shine only on the bright face, there was no movement. On shading the light from the bright side, and letting it shine on the black side, there was apparent *attraction*† with positive rotation, the speed being about half what it was when the light shone on both vanes simultaneously. A hot shade gave negative rotation, that is, in the opposite direction to that caused by light, changing to positive as the vanes cooled.

268. The plates were now folded across the vertical diagonal, as shown in fig. 9.

Fig. 9.

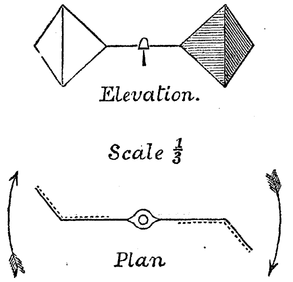
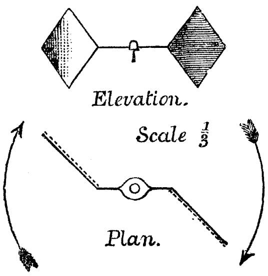


Fig. 10.



The candle gave strong positive rotation in the direction of the arrows. When a screen was interposed so as to allow the light to shine only on the black side, the positive rotation was kept up with scarcely diminished speed, the direction being that of attraction. When the light shone only on the bright surface no rotation took place. A hot glass shade gave good negative rotation, changing to the positive on cooling.

* A radiometer similar to this, but not turned up to quite the same extent, is insensitive to light shining on it in the ordinary way.

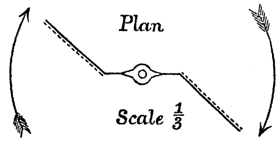
† I use the word *attraction* in these cases for convenience of expression. What appears to be attraction is really due to a *vis a tergo*. See par. 312.

269. The above experiment was repeated, the only change being that the plates were folded across their horizontal diagonal, the crease being in a line with the supporting arm. The movements to a candle and a hot shade were the same as in the last experiment (268), but considerably weaker.

270. Flat plates were now used, attached to the arms at an angle of 45°, as shown in fig. 10. They were blacked on the insides, away from the bulb. Exposed to candle light, there was slight repulsion on each face, that on the bright surface being rather the stronger, but not enough to commence rotation. On starting rotation by shaking the bulb, it kept up very slowly in the direction of the arrows. A hot shade gave good rotation in the same direction. There was no reverse movement on cooling.

271. As in the last experiment (270), the plates were mounted at an angle, but they were blacked on the outsides as shown at fig. 11. A candle gave rapid positive

Fig. 11.



rotation. A hot shade gave negative rotation with good reversal of movement on cooling. This form is the most sensitive yet experimented with.

272. Radiometers made of silver flake mica being more sensitive than those made of pith or metal (238), it was deemed of interest to ascertain whether this extra sensitiveness would be retained when the vanes were mounted at an angle, as in the last experiment. This was found to be the case; radiometers constructed with silver flake mica vanes set at an angle, as shown in fig. 11, and blacked on the outside, prove the most sensitive for light hitherto constructed.

SPECIAL EXPERIMENTS WITH SLOPING-VANED RADIOMETERS.

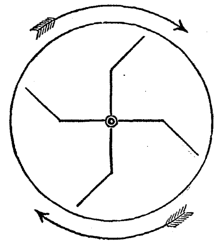
273. From the foregoing experiments it appears that the favourable presentation of the surface of the vanes to the inside of the bulb, has more influence on the movement than has the colour of the surface. A series of experiments was instituted in the hope of clearing up many anomalous results which had attended the application of heat either by hot shades or by hot water to radiometers. The results hitherto obtained had been contradictory, and it was now seen that there might be an antagonistic action between the effect of shape and that of colour of surface, the two actions sometimes acting together and sometimes in opposition.

Five radiometers were made exactly alike in size of bulb, shape of vanes, and degree of exhaustion, and only differing in the material of which the vanes were composed. No. 1 was made of mica, 0·003 inch in thickness.* No. 2 of mica,

* Measured by a Whitworth's measuring machine.

0·0005 inch in thickness.* No. 3 of pith, 0·05 inch in thickness.* No. 4 of aluminium, 0·002 inch in thickness.* These four radiometers were plain on each side, no lampblack being applied. Their appearance is shown in plan in fig. 12. No. 5 was made of aluminium, identical with No. 4, but the vanes were lampblacked

Fig. 12.



on each side instead of being bright. Had the vanes pointed radially, there could have been no tendency for any one of the flies to move either way, but being inclined, the normal movement, on exposure to radiation, should be in the direction of the arrows—a direction which I will call the *positive* direction.

274. The radiometers were tested with a candle. They all moved positively, but with very different rates. With the candle 3 inches off, no movement took place at first; after a little time repulsion was observed, but rotation could not be started. By following up the retreating vane with the candle, rotation was set up, and on then removing the candle 3 inches off, rotation continued in the case of the pith and the two aluminium instruments, but not with the mica. The black aluminium was the easiest to move, then the pith. The bright aluminium fly was more difficult to start than the thick mica fly, but when once set going it moved the quicker of the two. The thin mica fly was the most sluggish of all.

These radiometers are evidently affected much more by the heat from the candle than by the light. I explain the above actions in the following manner.

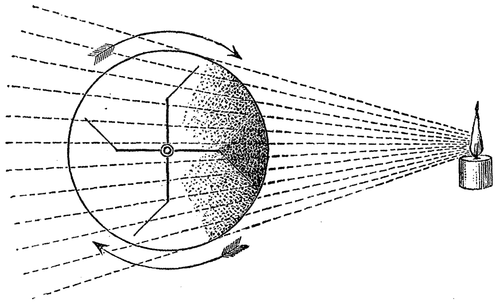
275. I assume that the glass bulb is transparent to the *light* of the candle, but offers considerable obstruction to the ultra-red *heat* rays which accompany the light (246), and that the dark heat rays which are arrested raise the temperature of the glass, which thereupon gives out dark heat. The side of the bulb exposed to the air radiates dark heat outwards, and the inner side of the bulb in contact with the highly rarefied gas, generates molecular pressure, which reacts in all directions (218 postscript), but most powerfully in a direction normal to the surface (312).

276. To explain the action more easily I will first discuss the action of the mica-vaned radiometers exposed to the candle. In fig. 13, the candle is represented shining on the bulb. The rays of light pass through the first wall without action. They then meet the mica, and that also being very transparent, the rays pass through it likewise, and then escape through the opposite side of the bulb, as is shown by

* Measured by a Whitworth's measuring machine.

dotted lines, without absorption and consequently without doing work. But in addition to light, the candle is radiating ultra-red dark heat rays. These in great measure are arrested by the glass, and raise its temperature. The inner surface of the bulb then becomes the surface on which molecular pressure is generated,* as shown

Fig. 13.†



by the shading at the side next the candle. This molecular disturbance presses on the mica vane which is in front of it, and drives it round in the direction of the arrows, as if it were subjected to a bombardment of small shot. The vane, in fact, may be said to be blown round by what may be likened to a wind, which however is not *molar* but *molecular*, inasmuch as there is no wind in the sense of an actual transference of gas from one part of the bulb to the other.

277. One of the flies of the mica radiometer is much thinner than the other (273), and moves less readily to a candle. The reason is this :—

Mica is not perfectly transparent to light and heat; a small portion is arrested, and is converted into heat of temperature. This causes molecular disturbance on the surface of the mica, and thereby assists the motion, as the pressure from the glass and from the mica acts in the same direction. The thick mica naturally obstructs more of the incident rays than does the thin mica, and it also holds more heat. More molecular pressure, therefore, comes from the thick than from the thin mica, and the thick will move better to a candle. A reference to fig. 13 will show why the mica radiometers will not rotate unless the candle is moved round to drive the vane before it. Imagine the fly moving slowly round in the direction of the arrows. When it has moved a few degrees further than is here represented, the advancing vane comes within the layer of pressure, and the retreating vane is emerging from it. Both will therefore be receiving the push, but in opposite directions. The more favourable presentation of the retreating over that of the advancing vane, will not carry the fly round, but it will only cause it to come to rest at such a point that the retreating vane is further from the candle than the advancing vane. If a certain amount of impetus

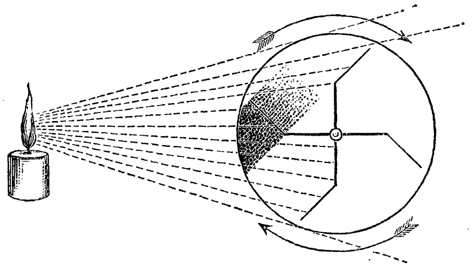
* This may for shortness be called the *driving surface*.

† This fig. and figs. 14, 20, 21, 24, 25, 26, 27, are simply explanatory, and are not to scale. The instrument is shown in plan, but the candle is in elevation and much diminished in size.

were acquired by the fly, if more candles than one were at work, or if sufficient molecular pressure were generated on the face of the mica vanes, there would be no difficulty in getting over the dead centre, and rotation would take place; in default of these conditions the fly soon comes to rest.

278. I will now describe the action of the candle on the aluminium radiometer. When a candle is brought near, the dark heat rays are stopped by the glass, and cause molecular pressure to react from it, as explained in the case of the mica radiometer (276). The luminous rays, which in the former case mostly passed through the vanes and bulb, are now arrested by the aluminium, some being reflected and some absorbed. I have been unable to find an account of experiments on the proportion of incident rays absorbed by aluminium, but considering that highly polished speculum metal absorbs 36 per cent. of the light falling on it, I am not far wrong in estimating that ordinary aluminium foil absorbs nearly 50 per cent. of the incident light. Therefore about half the light falling on the aluminium vanes is absorbed and converted into heat of temperature. Molecular pressure is thus produced on both surfaces of the plate, for the aluminium is so thin, and is so good a conductor of heat, that the two surfaces almost immediately become of the same temperature. In fig. 14 I have

Fig. 14.



endeavoured to represent part of the action which takes place when the candle shines on the aluminium radiometer. The molecular pressure generated on the hot surface of the glass opposite the candle is omitted, as it will be the same as with the mica radiometer shown in fig. 13, and its representation would only complicate the drawing. The light passing through the bulb falls on the aluminium plate, and, raising its temperature, causes pressure to be exerted on all sides. The pressure from the face away from the bulb is mostly dissipated, and may be disregarded, but the molecules rebounding from the face next the glass, cause increased molecular pressure on that side, and produce movement in the direction of the arrows, or positive rotation. As each vane passes the candle it takes up heat, and acquires extra *driving* energy. As it swings round, the opposite side of the glass acts as a *cooler*, and by the time the vane has completed the circle and has radiated away some of its extra heat, it is ready to recommence the cycle of transformation—light, heat, molecular pressure, motion.

Unlike mica, which generates very little pressure on its surface, the aluminium

fly carries sufficient driving power to enable it easily to pass the dead centre opposite the candle. Therefore, as soon as the candle has shone on the aluminium radiometer long enough to warm the vanes a little, rotation readily continues.

279. The action of the pith radiometer is similar to the aluminium. On referring to Table XII., par. 237, it is observed that white pith is repelled with a force of 17·7 by rays which are not cut off by water; that is, by dark heat rays which have escaped the absorbing action of the side of the glass tube in which the experiment was tried. The rays quenched by the pith will reappear as heat, and the slice of pith being of a sensible thickness, and almost a non-conductor, nearly all the molecular pressure will act on the first surface. The action of the candle on the pith radiometer will therefore be similar to that on the aluminium, represented in fig. 14, except that the dissipation of pressure from the back surface of the pith will be almost *nil*. The pith, moreover, being sensitive to the heat rays, and being a non-conductor, may be expected to move quicker than the aluminium, which requires time to get warm throughout. This is found to be the case.

280. The aluminium vanes blacked on both sides, as might be expected, act like the plain aluminium vanes, but in a much stronger degree.

281. The agreement between theory and observation, so far, seemed exact. In the endeavour to clear up the discrepancies I had so frequently met with, I now tried numerous experiments with dark heat applied in various ways to these five radiometers.

282. In par. 245 it is shown that, when I wanted to try the effect of dark heat on a radiometer, I covered it with a hot glass shade, a convenient means of warming the bulb uniformly by heat rays which would not pass through the glass in a radiant form, and thus avoiding the interference of other rays on the material composing the fly. On trying this experiment with the five sloping-vaned radiometers, the results proved very contradictory (273). Generally the effect of the hot shade was to produce negative rotation. Sometimes, however, the movement was positive, and occasionally no rotation at all could be obtained. The vanes would go round once or twice, then quickly stop, and reverse their movement, as if under the influence of two nearly equal opposing forces, sometimes obeying one and sometimes the other. Thinking that the hot shade might have become electrified on handling, I heated it in hot water, and inverted it dripping wet over the radiometers, still with the same contradictory result.

283. To immerse the radiometers in water of about 70° C. appeared a better means of heating the bulbs uniformly on all sides, without producing electrical disturbance. Heated in this manner, the thick mica radiometer moved slowly in the negative direction, and after a short time came to rest.

The radiometer was now removed from the hot water, and allowed to cool. Positive rotation commenced, and after continuing for about a minute it stopped, and then gave one or two turns negatively.

284. The thin mica radiometer behaved differently. When first immersed in hot water, it gave one turn in the negative direction, and then changed to positive, rotating positively for some time at a good speed. It finally came to rest.

When removed from the hot water and allowed to cool, the thin mica radiometer rotated negatively for a considerable time.

285. The bright aluminium radiometer, on immersion in hot water, rotated rapidly in the *negative* direction, and soon came to rest.

When cooling in the air, this radiometer rotated *positively* at a considerable speed.

286. The aluminium radiometer, blacked on both sides, behaved like the plain aluminium one, but in a stronger degree, rotating *negatively* on heating and *positively* on cooling.

287. The pith radiometer, when dipped into hot water, moved in an undecided manner, first a little one way and then a little the other—the tendency, however, being in the *positive* direction.

On cooling, the pith radiometer moved continuously, but slowly, in the *negative* direction, and kept up the movement for a considerable time.

288. The thick mica radiometer was heated over a Bunsen burner till the glass approached its softening point. It was then turned upside down, and allowed to cool till the temperature of the bulb was about 150° C. The cooling having gone on for some time, and taking place entirely by radiation from the outside of the bulb, it was certain that the fly inside was somewhat hotter than the bulb. On now inverting it, so that the fly rested on the needle point, the vanes immediately commenced to rotate in the *positive* direction. When the temperature of the outer bulb was appreciably the same as the room, the vanes stopped, then gave two or three turns the *negative* way, and finally came to rest.

289. Thinking it probable that the kind of dark heat might vary in refrangibility according to its source, and that the rays from hot water, hot glass, and hot metal might affect the materials composing the vanes in a different manner, and being absorbed by one body and transmitted by another might cause the positive or negative rotation, I repeated the experiments, varying the source of heat.

290. The five radiometers were immersed in boiling water; after cooling, they were immersed in water only a few degrees above the temperature of the room. In each case the results were of the same kind as already described with water of 70° C.

291. The five radiometers were covered successively with hot shades of English, French, and German glass, of different thicknesses, and at different degrees of temperature. They were sometimes dry, and at others wet and filled with steam. The results were even more contradictory than with the hot water, and no law could yet be disentangled from the individual results.

292. Heating the bulbs with a gas or spirit flame gave less uniform results than those obtained with the hot shades.

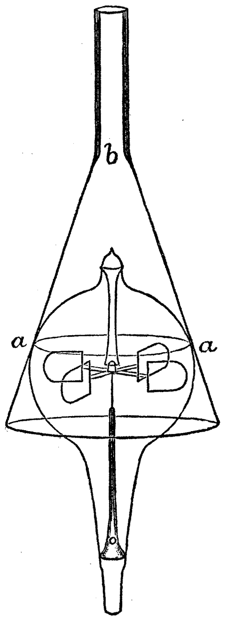
293. A funnel was heated in boiling water, and then allowed to rest on the five

radiometers in succession. They all moved in the *positive* direction, except the bright aluminium radiometer, which remained stationary. When the funnel was removed, the two aluminium and the thick mica radiometers rotated *positively* till they were cold.

294. The funnel was allowed to cool. It was then inverted over a radiometer, and steam was passed through for a second or two. The same experiment was repeated with each radiometer. The results were now equally uniform with those of the last experiment, but the rotation was *negative;* the bright aluminium fly moving the best of all, and the pith fly the least.

295. Order now began to evolve itself from the mass of contradictions I had hitherto encountered. Let fig. 15 represent the funnel covering one of the radiometers; and first let it be supposed that the funnel has been heated in hot water, and then inverted over the bulb. The funnel touches the bulb in a ring at *a a*, in a nearly equatorial position, and therefore this ring of the bulb gets hotter than any other part, as radiant heat from hot glass has much inferior warming power to actual contact with hot glass. Next, imagine the funnel to be cold, and steam passed in for a second or two. The upper portion of the funnel, *a a b*, together with the *north pole* portion (if I may use the expression) of the bulb gets warm, whilst the equator is cold.

Fig. 15.

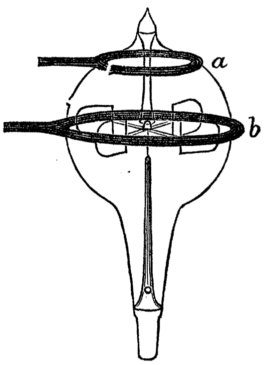


296. The rule appears to be that when the equatorial part of the bulb of the radiometer is warmed, positive rotation takes place, and when the polar portion is warmed negative rotation takes place.

297. Further experiments soon showed that this law was likely to be the true one. The radiometers were dipped into hot water one-third of the way up the bulb. Strong *negative* rotation took place in each case.

298. A thick brass ring was selected with an internal diameter about half that of the bulb, fig. 16, *a*. It was heated to about 400° C., and then put on the five radiometers in succession at *a*. All moved in the *negative* direction at a tolerably good speed.

Fig. 16.



On removing the hot ring from the two aluminium radiometers a reversal of movement took place and faint positive rotation was observed. With the thin mica and the pith radiometers no change of direction could be detected on cooling, the negative rotation keeping up for a considerable time.

299. A thick brass ring, a little larger in diameter than the bulbs (*b*, fig. 16), was heated to 400° C., and then held round the centre of the bulb of each radiometer in succession in the position *b*. All the flies revolved in the *positive* direction. The thick mica fly went at a maximum speed of 60 revolutions a minute, the thin mica fly made 36 revolutions a minute, the pith 15 revolutions a minute, the bright aluminium 11 a minute, and the blacked aluminium 1 revolution a minute.

300. When the equatorial hot ring was removed, and the bulbs were allowed to cool, no reversal of movement took place with the thick mica or the two aluminium flies. The thin mica and the pith flies showed decided reversal on cooling.

301. To still further test the question of the change of direction on cooling, the experiments with the two brass rings were again tried on the five radiometers. The rings, this time, were made red hot, and were held in position till the flies were in rapid movement. The rings were removed, and as soon as the hot part of the bulb was cool enough to bear handling, it was dipped into cold water, so as to chill the glass quickly, and still keep the fly warm. Tried in this way very decided results were obtained, which will be better understood in the form of a Table.

Material composing the fly of the radiometer (*favourably presented.*)	Hot ring applied above.		Hot ring applied equatorially.	
	Heating.	Cooling.	Heating.	Cooling.
Thin mica	—	—	+	—
Thick mica	—	?	+	+
Bright aluminium	—	+	+	+
Blacked aluminium . . .	—	+	+	+
Pith	—	—	+	—

The thin mica and the pith when cooling, after being heated above, kept rotating negatively for a long time. The others soon came to rest. The movement of the thick mica on cooling, after being heated above, was contradictory, some experiments giving it + and some —. The other movements were very decided.

Applying the hot ring below had exactly the same effect as applying it above, and when the radiometers were heated above and below, the equator being kept cool, the rotation in the negative direction was very strong and rapid.

302. Having described the various phenomena, I will show how far the theory explains them, and as the radiometers differ in construction and action, I will first discuss the movements common to all.

It will be observed that when heat is applied round an equatorial ring of the bulbs (294, 296, 299, 301), the rotation is always in the *positive* direction. The hot ring of glass generates molecular disturbance, which presses towards the centre and strikes the sloping vanes, driving them round as if a wind were blowing on them (276). In fig. 17 I have tried to represent this action. The positive movement is inde-

pendent of the material of which the fly is made, and is only slightly increased or diminished according to the conducting power of the fly for heat. The lighter the weight of the fly to be driven round the easier it moves, and the heavier the fly the longer it keeps in motion after it is once started.

Fig. 17.

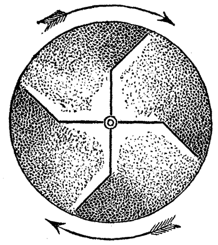
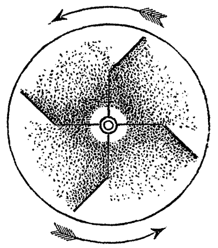


Fig. 18.



303. When heat is applied to either pole of the bulb the action is of a different character, *negative* rotation taking place (295, 296, 298, 301). A moment's consideration will show that the molecular pressure proceeding from a hot pole of the bulb will strike the *inner* surface of the sloping vanes, and driving them before it, will cause a rotation which appears *negative* to an observer, although it is really *positive* to the direction of pressure. It is not easy to represent the lines of force on a flat diagram, but fig. 18 will sufficiently illustrate the mode of action. The heat is supposed to be applied near the centre, and the molecular pressure radiating on all sides presses the vanes chiefly on the inner surfaces.

This action, like the positive rotation when the bulbs are heated equatorially, is in great measure independent of the material of which the vanes are made and of its conducting power for heat.

304. The anomalous results obtained when the radiometers were heated with hot glass shades or hot water (282 to 293), the vanes sometimes rotating one way and sometimes the other, but chiefly in the negative direction, are now completely accounted for. Polar heating gives negative, and equatorial positive rotation, and therefore when both are heated together by immersion in hot water the direction of motion is governed by the stronger of these two forces. A much larger surface of the bulb is effective in producing negative than positive rotation, and therefore the tendency of hot water is to drive the vanes negatively. If, however, the lower part only of the bulb is dipped into hot water (297), strong negative rotation takes place. Owing to accidental conditions, such as the shape of the bulbs, the size of the vanes, and their position in respect to the centre, the two opposing forces may be more or less evenly balanced, and a very little will cause one or the other to preponderate. A hot shade, for instance, if it is very large, may heat the bulb uniformly all over and give negative rotation, whilst if it is tall and narrow, the equator of the bulb receives most heat, and positive rotation ensues.

305. When explaining the action of light from a candle on the radiometers

(276 to 280), I showed that the glass heated by the ultra-red rays became hot, and acted as the driving surface, generating molecular pressure and causing the sloping vanes to turn in the positive direction. I also showed that another action took place at the same time, the vanes got warm and became themselves sources of molecular pressure. Now the amount of molecular pressure thus generated depends on the capacity of the material of the vanes to absorb heat. Thin mica, owing to its thinness, will hold very little; thick mica will hold more; and aluminium, on account of its superior mass and good conducting power, will hold most. This extra capacity for heat causes more molecular pressure to proceed from the aluminium and thick mica than from the thin mica, and generates a proportionate amount of driving power on the surfaces of the vanes, turning them, as shown in paragraph 278 and fig. 14, in the positive direction, and supplementing the action of the equatorial ring of hot glass (302).

306. When these radiometers are heated at the poles they go *negatively*, and when heated at the equator they rotate *positively*. On allowing them to cool, the flies being inside must lag behind the glass bulb in losing heat, the vanes will therefore be hotter than the outer bulb; two forces are now at work tending to move the flies in opposite directions. These forces are—

(*a*.) The increased temperatures of the vanes and consequent generation of molecular pressure from their surfaces. That from the inner surface need not be taken into account, but that from the outer surface produces pressure between it and the glass bulb, and tends to produce positive rotation.

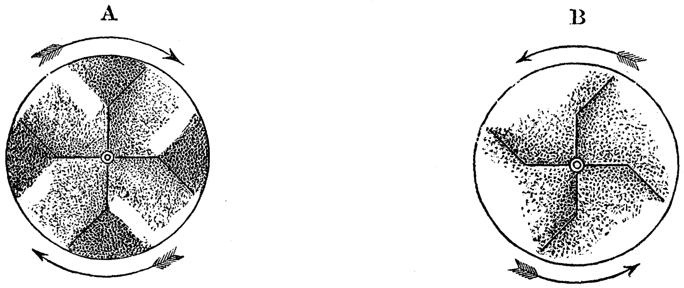
(*b*.) The radiation of heat from the inner fixed parts of the radiometer, such as the supporting stem, the needle, the upper glass tube, &c. This causes a stream of molecular pressure to strike against the inner surfaces of the vanes, and gives them a tendency to negative rotation.

307. Of these two forces, the latter (*b*), will be practically constant in intensity, whatever be the material constituting the vanes. The former force (*a*) will, however, vary considerably, being very slight in thin mica and pith, and strong in aluminium. With thin mica and pith, therefore, force *b* will preponderate, and the fly will rotate negatively; whilst with aluminium the force *a* will preponderate, and the fly will rotate positively.

308. As the thickness of the mica increases, force *a* will gain strength, and the phenomena exhibited by the thick mica radiometer will be produced, namely, tendency to rotation in an undecided manner, first one way and then the other, according as one force or the other gains temporary ascendancy.

In fig. 19, A and B, I have attempted to represent an aluminium and a mica radiometer, cooling from a high temperature, the aluminium fly, under the preponderating influence of force *a*, going positively, and the mica fly under the preponderating influence of force *b*, going negatively.

Fig. 19.



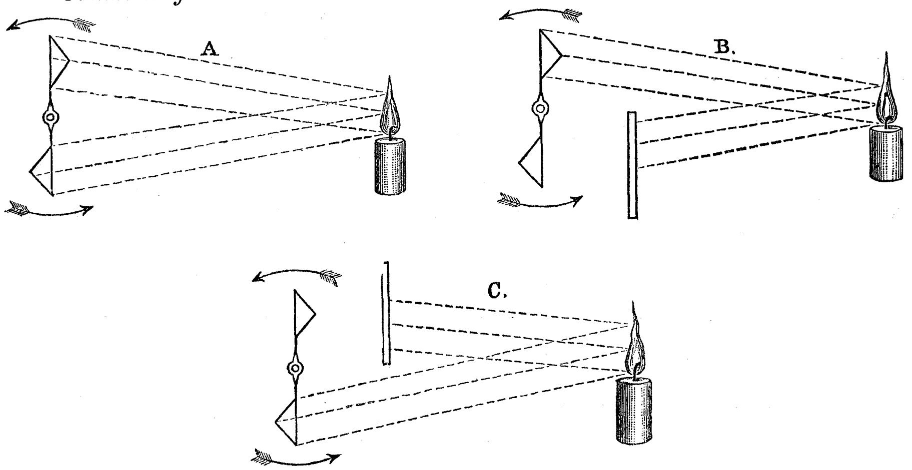
Aluminium. *Mica.*

ACTION OF RADIATION ON CONES, CYLINDERS, AND CUP-SHAPED VANES.

309. Having investigated the simplest form of favourably-presented vanes, I turned my attention to more complex shapes, hoping thereby to obtain verifications of the laws which have been described in the previous pages. A pair of thin aluminium disks, cut half across the diameter, were bent into cones and mounted on two arms as a radiometer, the cones facing opposite ways. Preliminary experiments having shown that an effect of attraction, already noticed at pars. 267 and 268, was strongly marked with these cones, the following experiments were also tried. A standard candle was placed with the centre of its flame 3 inches from the centre of rotation of the arm carrying the cones. The exhaustion having been brought to about 20 millionths of an atmosphere, the revolutions under the influence of the lighted candle were timed. With no screen in front, as in fig. 20, A, the arms made 21·8 revolutions a minute in the positive direction,—the mean of eight closely concordant observations.

Fig. 20.

Candle only in Elevation.



A screen was then interposed between the candle and the concave cone, as in fig. 20, B, so that the radiation should only fall on the convex surfaces of the cones, as they emerged successively out of the shadow of the screen. The rotation became

slower, and when the speed was uniform, on timing the revolutions I found the mean of seven observations to be 11 revolutions a minute in the positive direction.

The screen was now placed as in fig. 20, C, so as to cut off the light from the retreating cones, and allow it to fall only on the concave cones as they were approaching the light. A very slight diminution in velocity took place, but the rotation continued in the same direction as in the two previous instances. The speed was 9·6 revolutions a minute. Finally the candle was blown out, and when the cones were still, and the bulb cold, the candle was again lighted, the arrangement remaining as at C. Rotation immediately commenced, the hollow cone advancing towards the light, and the speed rapidly increasing till it became uniform at 9·5 revolutions a minute.

These results show that the speed of rotation produced when the candle shines on the advancing and retreating cones simultaneously, is practically made up of the sum of the speeds attained when the radiation is allowed to fall on either side of the cones separately. Adding the speed in position B (11 revolutions a minute) to the speed in position C (9·6 revolutions a minute), will give 20·6 revolutions a minute: a speed which, allowing for the imperfection of the candle, is sufficiently near that actually observed—namely, 21·8 revolutions a minute.

The candle was brought nearer, and the experiments repeated. The velocities were :—

In position A, 49·2 revolutions a minute.
„ B, 25·2 „ „
„ C, 26·7 „ „

310. The apparent attraction observed in position C, at first offered some difficulty in its explanation. Before attempting to theorise I tried further experiments. Thinking over the problem its solution appeared less difficult, and it seemed likely that a few experiments would give me a simple explanation. In the next experiment I varied the material of which the cones were made, and instead of choosing a good conductor of heat like aluminium, I took a bad conductor like mica.

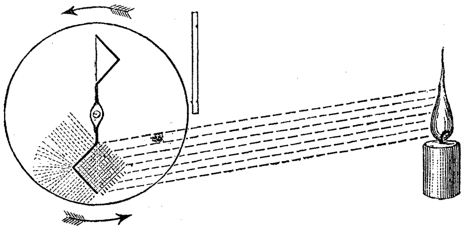
Cones made of clear mica were attached to arms and mounted like a two-vaned radiometer. With a candle there was no rotation, both sides being equally repelled, and the arm always setting at right angles to the line joining the candle and axis of rotation.

311. Cones were next made of silver flake mica, and similar experiments were tried with these as with the aluminium cones. With no screen in front, as in fig. 20, A, there was moderate rotation in the direction of the arrows, but there was great hesitation in passing the candle. In position B, the concave side being screened off, rotation continued at about the same speed as when the screen was absent, or if anything a little faster. In position C, the convex side screened from the light, there was no movement.

312. The explanation of the apparent attraction is now clear. The effect of bend-

ing the plates, or of making cones of them, is to produce a more favourable presentation to the inner surface of the glass bulb. Radiation falls from the candle on the aluminium ; some is reflected and is lost, but a portion is absorbed to be converted into thermometric heat or heat of temperature (171, 195, 278). Aluminium being a good conductor of heat, and the thickness of metal being insignificant, it becomes equally warm throughout, and a layer of molecular disturbance is formed on each surface of the metal. At a low exhaustion the thickness of this layer is not sufficient to reach from the metal cone to the side of the glass bulb ; as the exhaustion increases, this layer extends further from the generating surface, until at a sufficiently high exhaustion the space between the side of the glass bulb and the adjacent portion of the metallic cone is bridged over, and pressure is exerted between the two surfaces. A reference to the diagram (fig. 21) shows how this pressure will act. The direction of pressure is indicated by dotted lines issuing from the metal cone ; it is assumed that the exhaustion is such as to allow the layer of molecular disturbance under the influence of the candle to extend for 5 millims. from the surface of the metal, and I have considered that the pressure acts in a direction normal to the surface (really it will act in all directions, but for the sake of illustration I confine myself to the direction in which it acts with greatest force). The rays from the candle fall on the concave surface of the cone ; the substance being a good conductor of heat, molecular pressure is induced in the direction and to the distance shown by the dotted lines (fig. 21), the pressure being greater the nearer the layer is to the metal.

Fig. 21.



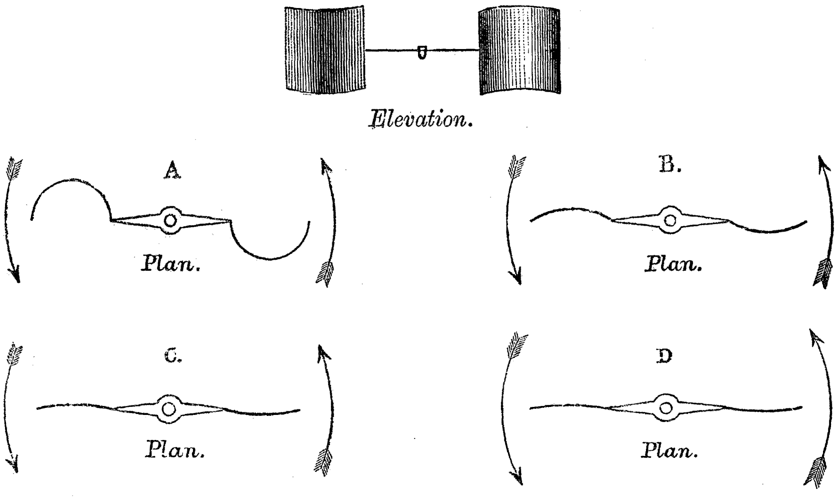
The pressure from the inside of the cone, and from the outside away from the side of the glass, is dissipated without acting, but the pressure between the glass bulb and the side of the cone nearest to it is active ; the cones, therefore, are pressed round in the direction of the arrows, and the motion has the appearance of *attraction*.

313. When cones of clear mica are used, very little radiation is arrested by them (276, 277). Mica being almost perfectly transparent both to light and radiant heat, enough radiation is not absorbed to raise the temperature to the point required to produce molecular pressure on the surface of the mica. The cause of the set of the two cones equi-distant from the candle is that the portion of the bulb nearest the candle gets warm, and this warm piece of glass does not act by radiation but is itself the repelling surface, through the intervention of the molecules rebounding from it with a greater velocity than that with which they strike it (219).

When silver-flake mica is used to make the cones, the action is different. Here some of the light and heat are arrested, with a consequent rise of temperature. But silver-flake mica being a very bad conductor of heat, most of the molecular pressure is exerted from the surface on which the light falls, and very little is generated on the other side. In position C, fig. 20, when the light shines only on the concave surface no motion is produced, as no pressure is generated on the surface away from the light; whilst in positions A and B, where the light shines on the concave surface, the movement is nearly equal in velocity. No effect being produced by the light shining on the concave surface, no retardation is caused when the light is screened from it.

314. The influence which a variation of shape of the moving fly has on the direction and amount of its repulsion depends on favourable presentation to the surrounding bulb. A very little alteration in angle of presentation has more effect than a great difference of colour. It remains to be seen, however, what angle or inclination of the vanes to the glass bulb is the most favourable. Cones being inconvenient in shape, I employed portions of cylinders wherewith to shape the vanes. Four sets of cylindrical aluminium vanes were mounted on arms, and pivoted on needle points, in four bulbs. They were made at the same time and were alike in all respects, except in the radii of curvature of the cylinders on which the vanes were curved. The vanes were of thin aluminium, and the bulbs were exhausted simultaneously by being sealed on to four arms of a five-tube mercury pump, so as to ensure the exhaustion being identical in the four bulbs. Fig. 22, A, B, C, D, shows the four sets of vanes drawn

Fig. 22.



the full size. The radius of curvature of A is 5 millims., of B 10 millims., of C 20 millims., and of D 30 millims. Each vane is 10 millims. high and 10 millims. across the chord of the arc; consequently there is more metal in the vanes of deeper than in those of shallower curvature. This was thought to afford a fairer means of

comparison than if the same area of metal had been present in each vane, for in that case each alteration of curvature would have altered the distance between the glass and the edge of the vane.

315. These four radiometers were exhausted and tested with a standard candle 3 inches from the centre of rotation. As the exhaustion approached the point of greatest sensitiveness, the fly A was the first to move, and it was in good rotation in the direction of the arrows before the others would rotate at all; soon after A and B were rotating, C commenced to rotate, but it required the exhaustion to be carried to a higher point before I could get rotation in D.

At the exhaustion corresponding to maximum sensitiveness, the rates of rotation were as follows:—

A	made	21·4	revolutions	a minute.
B	„	15·0	„	„
C	„	10·3	„	„
D	„	4·6	„	„

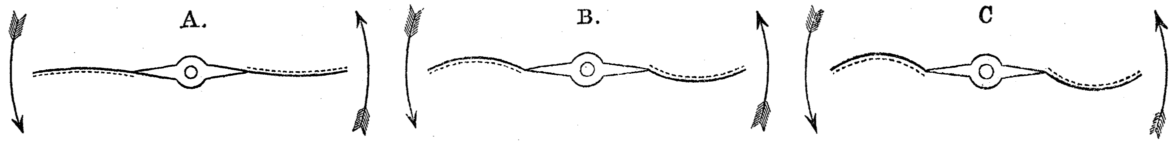
These figures show that the deeper the curvature, up to half a circle, the greater the repulsion.

316. The action of dark heat was now tried, as in the experiments with the radiometers, with "favourably presented" flat vanes. Dipped into hot water they behaved like the aluminium instruments (285, 286), rotating *negatively* whilst getting hot, then coming to rest, and rotating *positively* on cooling.

317. Experiments were now tried with hot rings applied at the poles and at the equator of the bulbs, as in experiments 298, 299, 301. The results fully confirmed those then obtained, and afford an additional proof that the explanation given in pars. 302, 303 is correct. When the hot ring was applied above, *negative* rotation took place, and when the heat was applied only to the equator of the bulb, *positive* rotation took place. In all cases, on cooling, the movement was in the positive direction.

318. The shape of the vanes was now again altered. It was found that cups were more easily affected by radiation than portions of cylinders, and that they were also more

Fig. 23.



easily fashioned into shape. Spherical moulds were prepared with radii of curvature respectively of 35, 14, and 10 millims. By means of these moulds, disks of gold foil, 14·5 millims. diameter, were bent in the form of shallow cups, brightly polished on both sides. They were mounted in pairs in the experimental bulb, fig. 4 (244), and

blacked on the concave surfaces, as shown in fig. 23, A, B, and C. On exposure to the standard candle, 3 inches off, the shallowest cups, A, rotated with a speed of 16·6 revolutions a minute, the intermediate cups, B, made 54 revolutions a minute, and the deepest cups, C, made 60 revolutions a minute.

These experiments corroborate those tried with the aluminium cylinders (313), and prove conclusively that the deeper the curvature the stronger the repulsion.

319. It will be observed that the cups are blacked on the concave side, and bright on the other. Had the vanes been flat disks, the candle would have strongly repelled the black side. The very slight curvature of the shallowest disks, A, is, however, sufficient to overcome the repelling action of radiation on the black surface, and to leave a considerable balance in favour of the polished side.

It now became of interest to know what would be the effect of light on cups blacked on different sides. The following experiments were therefore tried with the pair of gold cups of intermediate curvature, B, fig. 23, and also, for the sake of comparison, on similar pairs of thin aluminium cups. For convenience of comparison I put the results in a tabular form.

	Standard candle 3 inches off.		Hot shade.	Cooling.
	Speed of rotation.	Direction of rotation.	Direction of rotation.	Direction of rotation.
Gold Cups.				
Both sides bright	18 revs. a minute	→ (	← (	→ (
Concave blacked	54 " "	→ (	← (	→ (
Convex blacked	60 " "	→ (	← (	→ (
Both sides blacked	67 " "	→ (	← (	→ (
Aluminium Cups.				
Both sides bright	26 " "	→ (	← (	→ (
Concave blacked	54 " "	→ (	← (	→ (
Convex blacked	75 " "	→ (	← (	→ (
Both sides blacked	86 " "	→ (	← (	→ (

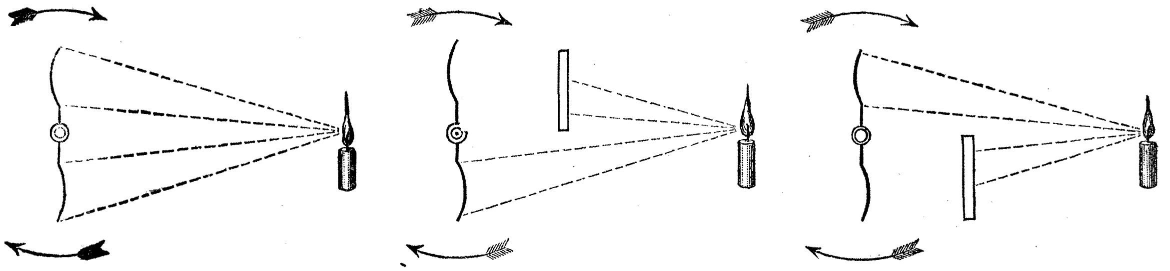
320. These four sets of aluminium cups were permanently mounted in bulbs, and were exhausted together as described at par. 314. They were sealed off at the point of maximum sensitiveness, and tested with a standard candle 3·5 inches off, the whole being enclosed in a space lined with black velvet. To avoid lengthened description, I give the results in the form of diagrams. Three experiments were tried with each radiometer :—*a*, when the light shone on both cups simultaneously ; *b*, when the concave side was screened off ; and *c*, when the convex side was screened off. They were then tested with a hot ring at the top, and another at the equator ; and finally the direction of motion on cooling was observed.

321. To save repetition, I will here state that in all four cases, the hot ring applied to the upper part of the bulb gave *negative* rotation, and equatorially applied gave *positive* rotation. The direction of movement during cooling was in each case *positive* (301). With the cups blacked on both sides, the revolutions. both

under the influence of heat and during cooling, came rapidly to a maximum, and then soon stopped.

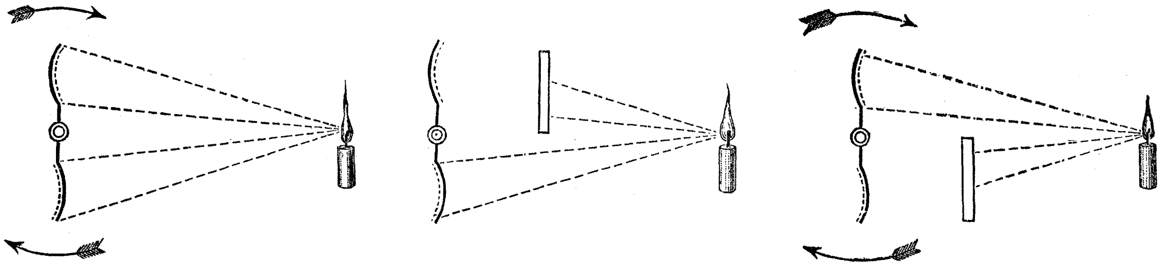
322. SERIES I.—Aluminium Cups, bright on both sides.

Fig. 24.



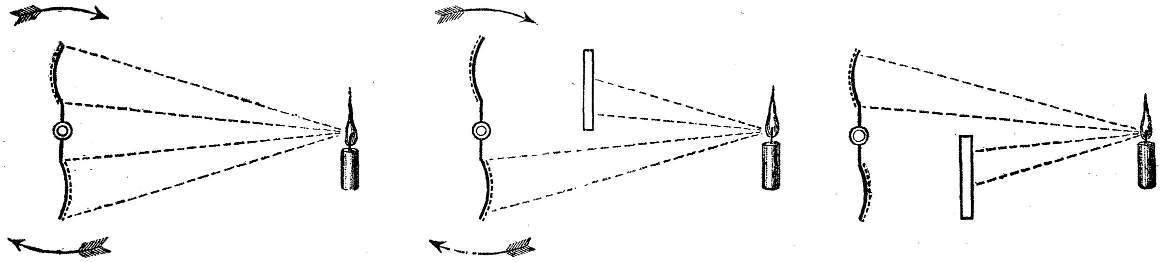
323. SERIES II.—Aluminium Cups, blacked on the concave side.

Fig. 25.



324. SERIES III.—Aluminium Cups, blacked on the convex side.

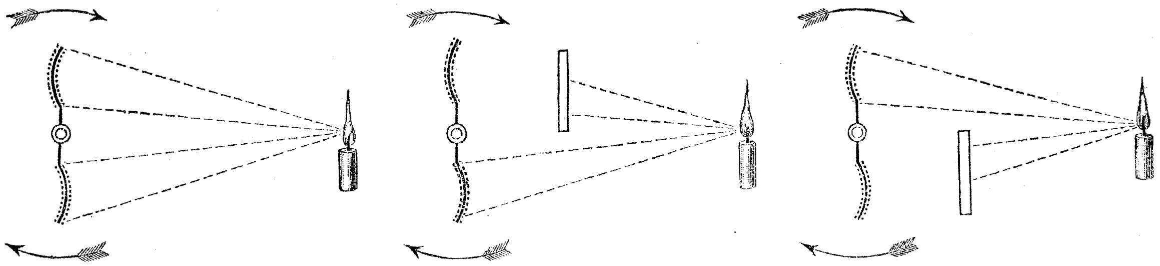
Fig. 26.



325. SERIES IV.—Aluminium Cups, blacked on both sides.

Fig. 27.

Experiment *a*. *No screen interposed.* — Experiment *b*. *Concave screened off.* — Experiment *c*. *Convex screened off.*



33 *revolutions a minute.* — 12 *revolutions a minute.* — 8 *revolutions a minute; apparent attraction.*

326. It will be observed that in Series I., experiment *c*, Series II., experiment *c*, and Series IV., experiment *c*, I get the same apparent attraction as with the bright aluminium cones (309, 310). The explanation given in par. 312 covers all these cases, and also accounts for the absence of rotation in Series II., experiment *b*, and Series III., experiment *c*. As the different behaviour of the blacked and plain cups affords a further proof of the correctness of the theory there advanced, it will be useful to consider these cases seriatim.

327. The case of the cups bright on both sides (Series I., par. 322) is covered by that of the bright aluminium cones already discussed (309 to 312). In Series II. (323), the lampblack is applied to the concave side of the cups; the absorption of light on that side is consequently increased, and the temperature of the cups rises more rapidly than when both sides are bright. Lampblack is not only a good absorber of light and heat, but it rapidly gives up its heat to the gaseous molecules, and is thereby a most powerful generator of molecular pressure, whilst the bright side, giving up heat less easily, produces less molecular pressure. An excess of molecular pressure is therefore generated on the concave side by virtue of its black surface, and a less amount of pressure produced on the bright convex side. Were the presentation of these two sides to the glass bulb equally favourable, the excess of pressure on the black side would overcome the other, and the black would retreat; but as shown in fig. 21 (312), most of the molecular disturbance from the concave surface is dissipated before it gets to the glass, whilst a great part of that from the convex surface is active. It follows that the active pressure from the black is not sufficient to overcome that from the convex surface, and the excess determines the direction of rotation. The influence of the black is apparent in diminishing the speed from 18 to 11 revolutions a minute.

328. In Series II., experiment *b*, in which the concave black is screened off and the light shines only on the bright convex side, there is no rotation but only slight

repulsion. The light falls on a polished metallic surface, and about half is reflected without absorption (278). That which is absorbed acts as in the last case, but the forces on each side being more nearly equal, the balance in favour of the convex side is not enough to cause rotation and can only produce slight repulsion.

329. When the light is screened from the bright convex side and allowed to fall on the black concave side, as in Series II., experiment *c*, the same action takes place as in the two previous cases. The light falls on the black side, and the absorption and consequent generation of molecular pressure are greater than in experiment *b*. The balance in favour of the convex side is now enough to drive it round. No light, however, falling on the vane presenting the convex side, the slight additional impetus which would have been given by this vane is absent, and the rotation is not so rapid as when both vanes were illuminated.

330. In the next series (324) the black is applied to the convex side of the cups. The pressure arising from the black surface, conspiring with that due to favourable presentation, drives the fly round with a greater speed than in any of the other experiments—viz., at a rate of 46 revolutions a minute. It is easy to understand that cutting off the light from the convex cup, as in experiment *b*, will diminish the speed, but it is not immediately apparent why the rotation stops when the light is screened from the bright concave cup. A little consideration, however, shows that it must be so. The light here shines on a polished metallic surface, and as in experiment *b* of Series II., not more than half is absorbed. The molecular pressure generated is therefore insufficient to leave enough balance in favour of the convex side to drive it round.

331. The apparent attraction in Series IV., experiment *c*, is easy to understand. The light falling on the black surface is almost entirely absorbed and converted into heat of temperature. The metal being very thin and a good conductor, this heat is equally apparent on the convex and concave sides, both being black. The molecular pressure on each face is therefore equal, and the more favourable presentation of the convex side determines the excess of active pressure in its favour.

332. In testing the action of dark heat on these metallic radiometers by immersing them in hot water, I noticed that the negative rotation which generally resulted (304) took much longer to sink to rest when all bright cups were used than would appear necessary for the whole instrument to acquire the temperature of the water. The communication of heat from the glass bulb to the metallic cups is effected not by conduction or convection (in addition to radiation), but by the molecules travelling to and fro between the glass and the metal; and each molecule depositing or handing on towards the metal the extra force it has received from the glass, it is conceivable that the process of equalisation may be slower than under ordinary circumstances. This is a point which can be settled by experiment, and I intend to return to the subject.

333. When a radiometer immersed in hot water has come to rest, the approach

of a lighted candle causes rotation in the positive direction. But the action is not so strong as when the radiometer is cold or no water intervenes.

334. A four-armed cup-shaped aluminium radiometer, the cups being 10 millims. in diameter and the radius of curvature being 6 millims., was sealed on to the mercury pump. During exhaustion accurate observations were taken of the number of revolutions per minute caused by one or more standard candles 3 inches from the centre of the bulb. At the same time observations of pressure were taken and the exhaustion was carried to a very high point. The results are shown in the following Table :—

Pressure in millionths of an atmosphere.	Number of candles used.	Number of revolutions per minute.	
		Revolutions.	Reduced to 1 candle.
577·0	1	1·0	1·0
400·0	1	3·1	3·1
309·0	1	4·8	4·8
219·0	1	7·0	7·0
159·0	1	10·0	10·0
102·0	1	16·6	16·6
69·0	1	22·2	22·2
41·5	1	26·8	26·8
27·8	1	25·6	25·6
24·0	1	25·0	25·0
19·5	1	23·8	23·8
14·7	1	21·4	21·4
9·5	1	16·4	16·4
8·6	1	15·0	15·0
6·5	1	12·5	12·5
3·8	1	7·1	7·1
2·5	2	9·4	4·7
1·5	3	6·6	2·2
0·9	4	8·0	2·0
0·23	5	4·5	0·9
0·2	5	0·0	0·0 stopped.

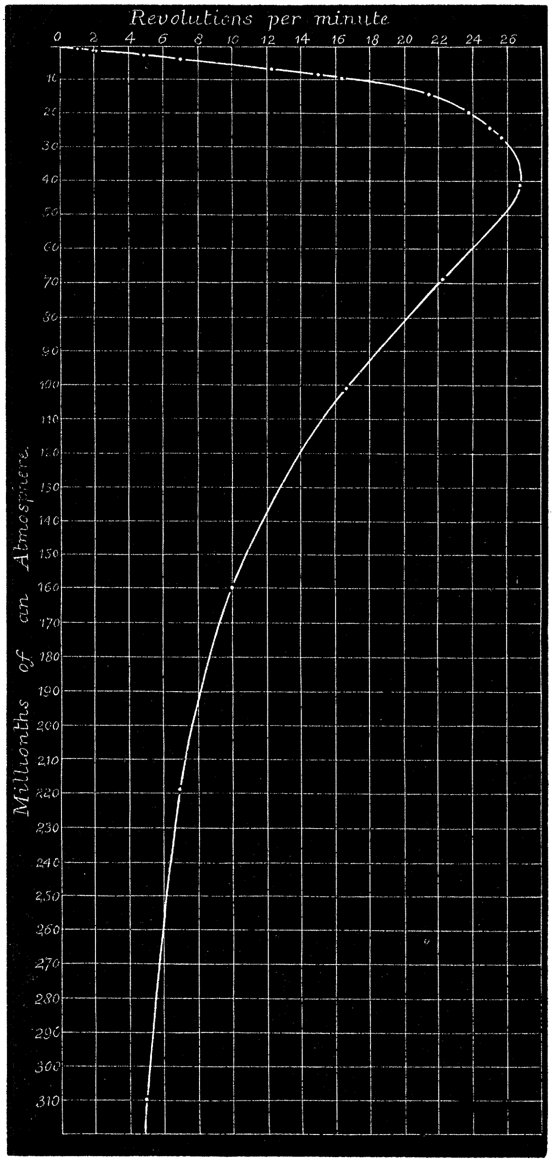
The first column gives the millionths of an atmosphere* at which the experiment was tried. The second column gives the number of candles, 3 inches off, used to produce rotation. Up to 3·8 millionths of an atmosphere one candle was sufficient, beyond that rarefaction a greater number was required. At 0·2 millionth five candles ceased to cause rotation. The third column gives the actual number of revolutions obtained with one or more candles, each recorded observation being the mean of several. The last column gives the revolutions per minute, calculated from the third column on the assumption that the number of revolutions per minute is in

* 0·2 millionth = 0·00015 millim.
1·0 millionth = 0·00076 „
4·0 millionths = 0·00304 „
577·0 millionths = 0·43825 „
One atmosphere = 760·00000 „

direct proportion to the number of candles (149). This law is somewhat interfered with at close quarters by the heating of the bulb and fly when extra candles are brought near ; but for such an experiment, in which great accuracy cannot be expected, and which is only of illustrative interest, the figures given are near enough.

Fig. 28 shows the curve plotted from these observations, using the first and fourth

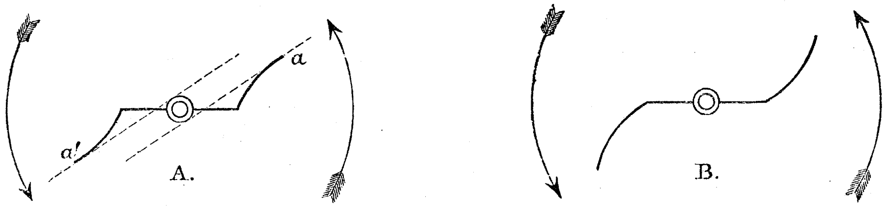
Fig. 28.



columns, and omitting the observations at 577 and 400 millionths of an atmosphere, so as not unduly to extend the diagram. The curve traced through the dots representing observations, illustrates the gradual increase of sensitiveness up to a certain point of rarefaction, and the sudden drop after that point is reached.

335. To further test the theory that the direction of rotation of the curved vanes depends not on any special effect of curvature as such but on favourable presentation, Professor STOKES suggested that I should make a radiometer having the curved vanes sloping, as shown in fig. 29, A, so that the tangent at the extremity a would

Fig. 29.



fall below the centre, and the same at a', or at most pass through the centre. Such a fly ought to move in the direction of the arrows, or in the same direction as a fly made like B (fig. 29), under the same circumstances, although the curvatures lie in opposite directions.

On trying the experiment with the fly A, I found that when exhausted to the most sensitive point a candle repelled each face with nearly equal force, and therefore no rotation took place, although the tendency was in the direction of the arrows. When heated with a hot ring round the equator of the bulb, strong rotation took place in the direction of the arrows ; there was no reverse movement on cooling.

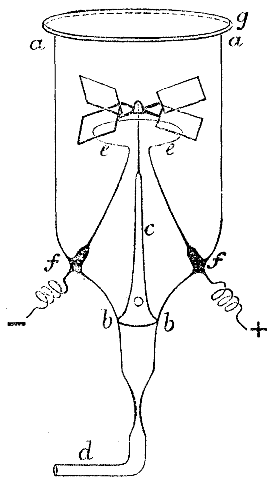
A radiometer fitted with a fly like. B revolved very well in the direction of the arrows.

EXPERIMENTS WITH DARK AND LUMINOUS HEAT APPLIED INTERNALLY.

336. The experiments on the action of dark heat on radiometers with "favourably presented" vanes, tried with hot rings applied above, equatorially, and below (298, 299, 301), could not give results of very great accuracy, as radiation heated a considerable portion of the bulb on each side of the hot ring. In some of the observations the results scarcely accorded with theory, and although I could explain most of the anomalies, there were irregularities which seemed to point to another influence which might cause me to modify the theory of the action of dark heat on the vanes. For strict investigation of this it was necessary to contrive a very intense source of heat always ready to be applied in the same place ; the heat should not pass through glass, and it should be completely under control as to intensity and time of action. The vanes also should be turned in the most favourable position for rotating under the influence of the molecular pressure, and the apparatus should be capable of having the exhaustion carried to a very high point and measured when an observation was taken. These advantages are all secured in an apparatus represented in fig. 30.

This apparatus consists of a wide glass tube, *a a*, *b b*, drawn off narrow at the end *b b*, and a stem, *c*, sealed in to hold a needle point. To the narrow end a fine tube, *d*, is attached to connect the apparatus to the mercury pump. Round the needle is placed a ring of fine platinum wire, *e e*, the ends of which are joined to thicker

Fig. 30.



platinum wires passing through the glass at *f f*. A current of electricity from two Grove's cells, turned on or off by a contact key, gives the power of making the wire ring, *e e*, red hot when desired. The top of the wide tube is ground and polished quite flat, and is covered by a piece of plate glass, *g*, which can be cemented on so as to form a perfectly tight joint, and may be removed by warming so as to admit of any experimental fly being supported on the needle point.

The fly used in these experiments consists of four square vanes of thin clear mica, supported on light aluminium arms, and having in the centre a small glass cap, which rests on the needle point. The vanes are inclined at an angle of 45° to the horizontal plane. They are in such a position that when rotating the centres of the vanes pass along the platinum ring and keep about 5 millims. distant from it.

337. In describing the direction of rotation of this fly, I shall consider the observer's eye to be on a level with the plane in which the fly rotates, and the direction recorded will be that taken by each vane as it passes in front. Assuming that the fly shown in fig. 30 is rotating in the same direction as the hands of a watch, were the watch laid face upwards on the top of the plate glass cover, each vane will be fore-shortened, and passing the observer will have the appearance of /. The direction of rotation in this case will be expressed by $\underleftarrow{/}$, and will be considered as *positive* rotation —*i.e.*, as the direction which would be followed by the fly were molecular pressure to proceed from the platinum wire.

338. The apparatus was exhausted till the gauge showed a pressure of 8 millionths of an atmosphere. Contact was made with the battery, the platinum ring became hot,

and the vanes rotated rapidly in the *positive* direction, as if driven round by molecular pressure coming from the hot wire. The rotation kept up with great rapidity as long as the wire was kept hot, and did not show any signs of diminution of speed.

When the apparatus was again cold, and the vanes quiet, I put a finger on the top plate of glass so as to cause molecular pressure to strike the vanes from above downwards. The vanes now moved in the *negative* direction, or normally to the source of pressure.

The lower part of the apparatus was now grasped in the hand to warm it, when positive rotation commenced, showing that pressure came from beneath.

339. Air was now admitted into the apparatus until the gauge was depressed 12 millims. Battery contact was made, and very slow *negative* rotation immediately took place, at the rate of one revolution in 168 seconds. The exhaustion was continued, followed by a gradual increase in the speed up to about 400 millionths, at which point the rate was 10 revolutions a minute, still in the negative direction. A little beyond this degree of exhaustion, the vanes refused to move when the platinum wire was heated. At a higher rarefaction, *positive* rotation, took place. At a rarefaction of 34 millionths of an atmosphere (about the point of maximum sensitiveness for a radiometer), the speed of the vanes was 200 revolutions a minute. At 3 millionths of an atmosphere the speed was 300 revolutions a minute; and at 1 millionth of an atmosphere the speed continued about the same. Owing to the cement joint I was unable to get a greater amount of rarefaction with this apparatus.

340. These results are of interest in many respects. When using a candle as the source of radiation, I have always found very little repulsion until the gauge has risen to within about 5 millims. of a vacuum; from this point the repulsion increases steadily up to a rarefaction of about 35 millionths of an atmosphere, when it rapidly sinks, until at 0·1 millionth it is less than one-tenth of its maximum.* Below 5 millims. attraction or repulsion takes place according to circumstances which are not clearly explained; but above that point, when repulsion has fairly commenced, I have never observed a change of sign. In the experiments just described, the radiation from an ignited platinum wire is used; there are only about 5 millims. space between the wire and the fly, and no glass intervenes. The results, therefore, are likely to be much more definite than with the usual radiometer-kind of apparatus, and the actions should commence at a lower pressure.

341. In previous experiments with candles, the abnormal movement at low exhaustions was faint and irregular; here they occur with a sharpness which gives one hope of getting at a law. The *negative* rotation of the fly is evidently the analogue of the *attraction* observed in my early experiments at low exhaustions, both being abnormal

* Proc. Roy. Soc., Nov. 16, 1876, No. 175, p. 305.

on the supposition that the movement is due to a push away from the source of radiation.

In an experiment tried in 1875* I used a pendulum with a magnesium weight at the end (99), exposed in vacuo to the radiation from a platinum coil ignited by electricity. The distance from the pendulum bob and the spiral was 7 millims., and two series of observations were given in tabular form (100), showing the direction and amplitude of the swing of the pendulum at different barometric heights when the wire was ignited. The hot wire gave *attraction* in air of ordinary density; this kept pretty constant up to a pressure of about 20 millims., when the attraction began to increase. At about 1 millim. the attraction was at its maximum. Above this exhaustion the attraction suddenly dropped and changed to repulsion, which kept on increasing up to the highest exhaustion I was then able to get.†

In the present experiments the parallel is sufficiently close to show that the same causes are at work. Negative rotation is apparent 12 millims. below a vacuum, and a negative movement would be detected at much lower exhaustions. This negative movement rises to a maximum, suddenly sinks to zero as the exhaustion proceeds, and gives place to a positive rotation which keeps up at nearly a maximum speed and at an exhaustion which would almost stop an aluminium radiometer (334)

342. Were the rotation in moderately rarefied air due to air currents rising from the hot wire, it is difficult to understand why it should be *negative*. To eliminate as far as possible the action of air currents, the apparatus was modified by raising the platinum wire ring so that it was about 5 millims. above the sloping mica vanes, instead of under them, everything else remaining the same.

At low exhaustions, when the wire was ignited, the fly rotated slowly in this direction . The hot wire being above, this is a *negative* movement, as it is opposite to what would be caused by pressure from the wire acting in the vanes, and is therefore quite in keeping with the results obtained with the hot wire beneath.

When the rarefaction reached 0·5 millim. the negative rotation ceased. The fly oscillated to one side and the other without rotating. At higher exhaustions the fly moved *positively* , and this movement increased in strength as the rarefaction increased.

343. When the exhaustion was good, and the vanes were still, a piece of wet blotting-paper was put on the top plate of glass to cool it slightly. Rapid negative rotation took place . Making battery-contact immediately reversed this movement. Touching the top plate of glass with the finger caused positive rotation.

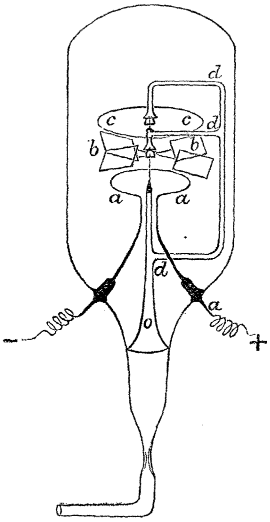
344. These movements are of the same kind as those given by the apparatus in which the wire was beneath the vanes. It is difficult to prevent the action of

* Phil. Trans., Vol. 165, pt. 2, pp. 528–532, March 20, 1875.

† In my first paper on this subject (Phil. Trans., Vol. 164, pt. 2, pp. 513–518, pars. 37–46, August 12, 1873) I also described analogous results with an ignited spiral acting on a balanced brass ball.

air currents: as the sloping vanes are eminently favourable for their detection, I therefore endeavoured to devise an instrument which should rotate without being unduly influenced by air currents, and with which I can get some insight into the direction of the lines of molecular pressure after passing and acting on the moving fly.

Fig. 31.



345. Fig. 31 represents the apparatus. Instead of being open and closed with a plate cemented on, the cylinder is now sealed at the top, so as to enable me to proceed to the highest exhaustion, which cannot be reached unless all the joints and connections are fused together. The platinum wire ring is shown at *a*, *a*, *a*, the sloping mica vanes are shown at *b b*. Above the vanes is a flat disk of clear mica, *c c*, having a glass cap in its centre, and easily rotating on a needle point. The vanes and the mica disk are supported independently of each other on separate needle points which are held in glass rods, *d*, *d*, *d*.

346. In air of the ordinary pressure (Bar. = 761 millims.) on igniting the platinum ring to redness by a current from two Grove's cells, both the vanes and disk rotate in this direction ; that is, the vanes go in the *positive* direction, supposing they are driven round either by molecular pressure from the wire or by air currents. The speed of the vanes is 13·3 revolutions a minute, and that of the disk 1 a minute.

347. I continued the exhaustion. At a pressure of 220 millims. on igniting the wire the rotations are the same as in air, but the speed of the vanes has diminished to 7·5 revolutions a minute, and the disk scarcely rotates at all.

Pressure 80 *millims.*—The disk will not rotate, but oscillates a little to and fro. The vanes still rotate *positively* at a speed of 1·5 revolutions a minute.

Pressure 34 *millims.*—The disk has ceased to move. The vanes move very slightly in the *positive* direction when the apparatus is tapped.

Pressure 19 *millims.*—No movement whatever. The disk and vanes are as still when the wire is ignited as when it is cold.

348. *Pressure* 14 *millims.*—The disk is still stationary: The vanes move very slowly in the *negative* direction .

Pressure 1 *millim.*—The disk has commenced to rotate in the same direction as the vanes, at a speed of 3 revolutions a minute. The vanes have been gradually increasing in speed as the exhaustion has progressed until they now rotate at a speed of 43 revolutions a minute in the negative direction .

349. These results are sufficient to show that the negative movement met at moderately low exhaustions (339, 342) is not caused by air currents. As shown in par. 342, the effect of a current of hot air rising from the platinum ring should be the same as that of molecular pressure coming from the ring. If the molecular wind may be supposed to blow the vanes round in a *positive* direction a molar wind should certainly act in the same manner. The present apparatus shows that this supposition is correct. In air at normal density the action of air currents is strong, blowing the vanes round *positively*. As the density diminishes, the strength of the air currents lessens likewise, until at a pressure of 19 millims. the ascending current of hot air has not strength enough to blow the vanes round positively, in opposition to the friction of the needle point, and possibly in opposition to the tendency to a negative movement which at a little less pressure begins to be apparent.

350. *Pressure* 706 *millionths of an atmosphere.**—The disk and the vanes both rotate in the same direction; the disk making 10 revolutions and the vanes 40 revolutions a minute *negatively* .

Pressure 400 *millionths of an atmosphere.*—Movements and direction as at 706 millionths. The disk making 12 and the vanes 25 revolutions a minute *negatively.*

Pressure 294 *millionths of an atmosphere.*—At this pressure the speed of the disk and of the vanes is exactly alike. They rotate together in the same direction as when last observed, as if they were fixed to the same axis, at a speed of 12·5 revolutions a minute .

351. *Pressure* 141 *millionths of an atmosphere.*—Up to this observation the vanes have been gradually diminishing whilst the disk has been increasing in speed. At this pressure, under the influence of the ignited wire, the disk rotates at a speed of 26 revolutions a minute. The vanes, however, do not rotate at all, but oscillate a little as if under the influence of two opposing forces.

352. *Pressure* 129 *millionths of an atmosphere.*—Between this experiment and the last a sudden change has occurred. The vanes which then were still now rotate rapidly in the *positive* direction with a speed of 100 revolutions a minute. The disk continues to rotate in the same direction as before, but with slightly diminished speed (18·5 revolutions a minute) . It is probable that some of the speed of the disk is

* At low exhaustions I speak of millimetres of pressure, but at high exhaustions I prefer to count in millionths of an atmosphere. The inconvenience of using two units of measure is less than that of employing one system for both ends of the scale.

quenched by the rapid movement of the vanes in the opposite direction. As is already shown,* the viscosity of air at a rarefaction of 129 millionths of an atmosphere is only a little less than its viscosity at the normal density; hence the vanes, at a speed of 100 revolutions a minute, must exert a considerable drag on the opposite rotation of the disk.

353. *Pressure* 82·5 *millionths of an atmosphere.* The disk has again increased in speed, now revolving at the rate of 24 turns a minute. The speed of the vanes is too great to count; a rough estimate shows that the rate is about 600 revolutions a minute. The direction of the vanes is positive, whilst the disk rotates in the opposite direction .

The increased speed of the disk, in spite of the greater rapidity of the vanes tending to drag it round in the opposite direction, shows that the viscosity of the residual gas is diminished. On referring to my preliminary note,† it will be seen that the viscosity of air has commenced to diminish rapidly at 82 millionths of an atmosphere, and after that the fall is very quick. To carry these experiments to a much higher exhaustion, some modification in the apparatus is needed; the heat must be less concentrated, so as to diminish the speed, since it is useless to continue observations when the rate of rotation cannot be estimated. The following apparatus was accordingly fitted up, to enable me to get the observation of speed, together with the viscosity of the internal air.

As the results obtained with this new apparatus are more numerous than with the previous apparatus, I will for the present defer comments on the different motions of the disk and vanes.

354. The apparatus is the most complicated I have yet used, and in order to make clear the relative bearing of the different observations I will describe it in detail, and give a drawing of it (fig. 32). This will serve a double purpose; it will enable my description to be clearly understood, and it will illustrate, better than is possible by mere words, the great complexity of apparatus frequently requisite to obtain, in a physical investigation, results which can be expressed in a few short paragraphs.

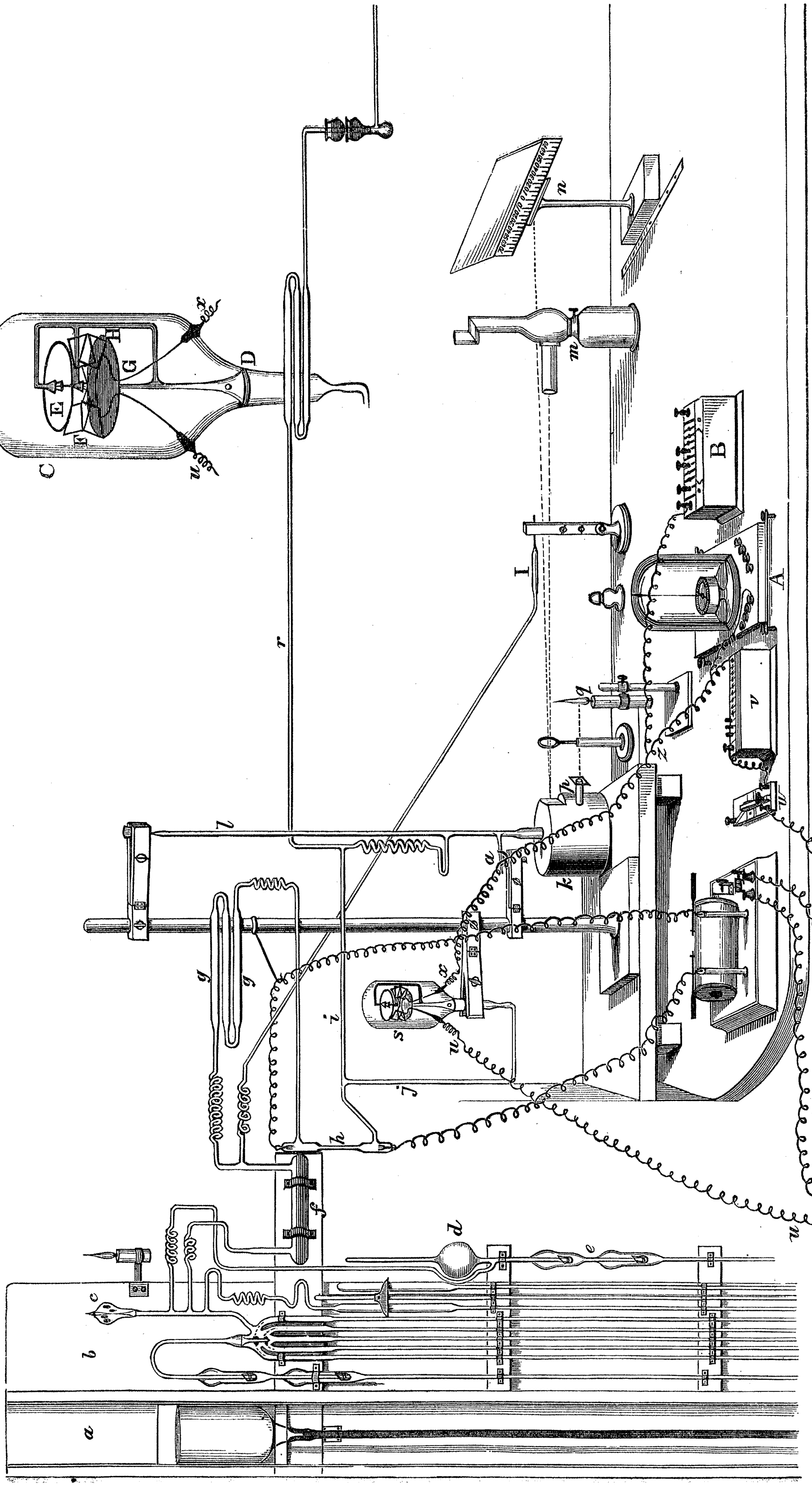
355. The pump is shown at *a b*, the upper part only being represented. It does not differ materially from the form of pump described by Mr. C. H. GIMINGHAM in the 'Proceedings of the Royal Society,' No. 176, 1876. It has, however, five fall tubes instead of three, and is fitted with a small radiometer, *c*, and a McLeod measuring apparatus, *d e*, to enable me to ascertain the degree of exhaustion in the apparatus. The facility of working has been considerably improved by the introduction of phosphoric anhydride‡ instead of sulphuric acid for absorbing aqueous vapour. The phosphoric anhydride dries gases better than sulphuric acid does, and evolves no vapour, whereas at the highest exhaustions sulphuric acid evolves a perceptible vapour.

* Proc. Roy. Soc., Nov. 16, 1876, No. 175, p. 304.

† Do. Do. p. 305.

‡ Do. Do. p. 306.

Fig. 32.



This acid is discarded altogether from the pump, and the lubrication thought at first to be essential to the production of a good vacuum, is now found to be unnecessary, provided clean, pure mercury is used. The phosphoric anhydride is contained in the horizontal tube *f*. In order as far as possible to prevent the passage of mercury vapour, three long narrow tubes, *g g*, are introduced between the pump and the apparatus to be exhausted; the one nearest the pump is filled with precipitated sulphur, the centre tube contains metallic copper reduced from its oxide, and the third tube phosphoric anhydride. The sulphur absorbs mercury vapour, the copper keeps sulphur vapour from getting into the apparatus, and the phosphoric anhydride is a further precaution against the introduction of aqueous vapour, the presence of which, in even small traces, interferes with the results. At *h* is a vacuum tube, containing aluminium wires and having a capillary bore for examining the spectra of the residual gas. An induction coil and battery are connected with the tube by wires, as shown, and in this way useful information is given as to the progress of the exhaustion. From the tube *h* two tubes branch off; one of them, *i*, leads to the "viscosity" apparatus, and the other, *j*, goes to the apparatus to be exhausted.

356. The viscosity apparatus is contained in the case *k*; I do not propose to describe it fully now, as the researches on which it has been chiefly employed are not yet concluded, and detailed description will be more appropriate hereafter. I may however state that at the lower end of the long glass tube, *l*, is a bulb. In this bulb is suspended, by a fine torsion fibre of glass, an oblong plate of mica, lampblacked at one end. The connexion between the bulb-stem and the pump being made by a long, thin, glass spiral, an angular movement can be given to the bulb without difficulty. To the mica plate a mirror is attached, so that by means of a lamp, *m*, a spot of light is reflected to the scale, *n*, where its passage along the graduations gives an accurate representation of the movement of the mica plate inside *k*. A handle with a stop at each side, *o*, allows the whole vessel to be rotated on pivots at the top and bottom, through a small arc, and the observation consists in noting the successive amplitudes of vibration when the swing of the mica plate is started by this rotation. The amplitudes are observed by the passage of the index spot of light across the graduated scale, and they form a decreasing series with a regular logarithmic decrement. This logarithmic decrement is a constant, which may be taken as defining the viscosity of the gas in which the mica-plate swings. Measured in this way, the viscosity of air is represented by 0·126 at the normal pressure of the atmosphere; and at an exhaustion of 0·19 millims. of mercury, or 250 millionths of an atmosphere, it has only diminished to 0·112. After this it begins to fall off: at 200 millionths it is 0·110; at 100 millionths it is 0·096; at 50 millionths it is 0·078; at 20 millionths it is 0·052; at 10 millionths it is 0·035; and at 0·1 millionth it has sunk to about 0·01.

At present I will say no more of the results obtained with this portion of the apparatus, as the investigation of the decrease of viscosity in various gases and vapours

when subjected to high rarefaction is still in progress, and owing to the great expenditure of time required in getting accurate results it may be some time before the research is finished. I may, however, refer to the preliminary notice on this subject, given in the 'Proceedings of the Royal Society,' November 16, 1876, for an account of some of the viscosity results obtained at that time, with a diagram of the curves of diminution of the viscosity of air, oxygen, and hydrogen, as the rarefaction proceeded.

357. I have said that one-half of the mica plate swinging in the bulb of the viscosity apparatus is lampblacked. This lampblacked half is opposite a tube, *p*, furnished with a shutter, by means of which the light of a candle, *q*, can be thrown on the blacked plate. The repulsion thus produced is measured by the successive swings and final deflection of the index ray on the scale.

358. When other gases than air are experimented on they are introduced into the apparatus through the tube, *r*, which is connected with gas reservoirs and appropriate apparatus for purifying and drying the gas.

359. The apparatus, *s*, more especially under examination, is sealed to the tube, *j*. It is shown on a larger scale at C, D. The platinum ring in *s* is ignited by the battery *t*. As the power of this battery varies considerably during a series of experiments, to render it practically constant I adopted the following plan. One pole of the battery is connected with the wire, *u*, running direct to *s*; the other pole is connected with a box of resistance coils, *v*, through which the current passes; it then goes to the contact key, *w*, and thence to the other wire, *x*, up to *s*. By depressing the contact key, *w*, the current passes through the wire ring in *s*, and ignites it. The strength of the current passing through the ring can be regulated to a nicety by adding or subtracting resistance by means of the coils at *v*. At *y* and *z* wires shunt off a portion of the battery current and conduct it to the galvanometer A and the resistance coils B. The galvanometer is a very delicate one, and the resistance in B is so adjusted that the current flowing through the galvanometer shall deflect the needle 18°. This being adjusted once for all the resistance B is never altered. Any variation of battery power will now show itself on the galvanometer A, and the resistance of the coils, *v*, is immediately altered until the galvanometer needle is again brought to 18°. This method I have found sufficiently accurate for all purposes, and since its adoption I have been able to experiment day after day with the certainty of always having, practically, the same amount of battery power igniting the platinum ring.

360. The apparatus, *s*, containing the rotating disk and vanes is shown enlarged at C, D. The construction of glass bulb, the rotating mica plate, E, the sloping vanes, F, and the platinum ring, G, connected with the outer wires, *u*, *x*, do not differ from those in the apparatus shown in fig. 31, paragraph 344. On the top of the platinum ring rests a disk of mica, H, lampblacked on the upper surface; this cuts off direct radiation from the hot ring, and diffuses the heat somewhat over the surface of the

black mica. Instead, therefore, of the molecular pressure starting from the wire, as in previous experiments, the blacked mica now becomes the driving surface.

361. The whole of this complicated arrangement of apparatus is connected together by actual fusion of the glass tubes one to another; no joint whatever occurs in any part, and a certain point of exhaustion being once attained, I can leave the apparatus to itself with the certainty that no leakage from without can occur. The apparatus by which the gas is introduced has, it is true, a tap, but when it has effectually done its work this tap is disconnected from the rest of the apparatus by fusion.

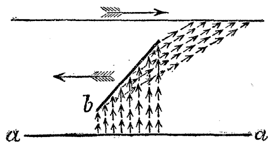
362. An observation with this apparatus is taken in the following way. Having arrived at a point when a depression of the contact key tells me, by the behaviour of the rotating disks, that a useful observation can be taken, the pressure is first measured in the McLeod apparatus. The viscosity of the gas is then observed, and next the repulsion exerted on the viscosity-plate by the candle. At a very high exhaustion the appearance of the induction spark in the tube, *h*, is also noted, together with the spectrum given by it. The strength of the current being first regulated by the resistances, *v*, the key, *w*, is pressed down, and the direction and speed of the vanes and disk in *s* are taken by a chronograph recording to tenths of a second. Frequently duplicate or triplicate observations are taken at each pressure, time being allowed to elapse between the observations for the apparatus to become cool.

363. In describing the direction of rotation of the vanes and disk, I shall call the direction they take at high exhaustions the *positive* direction, and the contrary the negative; thus, the positive rotation of the disk and vanes will be as follows:— 

364. At a pressure of 761 millims., when the wire is heated, positive rotation takes place both of the disk and vanes. As the exhaustion increases the positive rotation of the disk diminishes, then stops, and at 100 millims. pressure the disk commences to rotate *negatively*, or the same way as the vanes go, thus:  . The viscosity of the air is 0·124.

The probable explanation of these actions is as follows:—In air at the normal density the red hot ring causes air currents to rise; these strike the vanes and cause them to rotate positively. The sloping vanes also cause a deflection in the ascending current of hot air, and the disk, therefore, is struck at an angle by the air currents, causing it to rotate the opposite way to the vanes. The diagram (fig. 33) represents

Fig. 33.



this action. *a*, *a*, is the hot wire ring, the small arrows show the direction of the rising currents of hot air, which, striking against the vanes, are deflected in such a way as to cause the disk to rotate. The direction of rotation is shown by arrows.

At 100 millims. pressure the ascending current of hot air is not strong enough to turn the disk round, and it is therefore carried along with the vanes by the viscosity of the air, which is practically the same as at 760 millims.

At a pressure of 10 millims. the vanes become still, but the disk rotates very slowly *negatively*.

At 1 millim. pressure, the disk still rotates slowly negatively, whilst the vanes will not move.

365. *Pressure* 824 *millionths of an atmosphere.*—When the current is first turned on, the vanes give half a revolution in the negative direction, , they then stop. The disk continues to rotate in the *negative* direction, . An observation of viscosity at this pressure gives the figure 0·106. The repulsion produced by the candle on the viscosity plate shows a force of 4·8.

It will be observed that the first movements of the vanes at this pressure is in the *negative* direction, but this soon stops. On referring to par. 348, where I describe an experiment on a similar apparatus, but where the platinum wire is uncovered, and the heat therefore more intense, it will be seen that the negative tendency is strong enough to cause continuous rotation of the vanes. This negative rotation of the vanes begins to be apparent at 14 millims. pressure; it is very strong at 760 millionths of an atmosphere (350), and disappears at about 140 millionths of an atmosphere (351). Between a pressure of 294 millionths of an atmosphere and 129 millionths of an atmosphere, there is a great change in the movement of the vanes when under the influence of the hot, naked, platinum ring, the rotation changing from 12·5 revolutions a minute *negatively* at the former pressure, to 100 revolutions a minute *positively* at the latter pressure. How narrow are these limits may best be seen by converting them into decimals of a millimetre: the negative rotation is good at 0·2234 millim., whilst the positive rotation is very strong at 0·0978 millim. The negative rotation between the above-named limits is not so apparent in the apparatus where the platinum wire is covered with mica (345) as when the naked wire is used. This behaviour offers an anomaly which I shall endeavour to clear up at a future time. As I do not believe in *attraction*, and consider that all these movements are caused by a force having the action of a *push*, many experiments now in progress will be required to explain the difficulties of this negative action.

366. *Pressure* 530 *millionths of an atmosphere.*—A little negative rotation of the vanes takes place on first making contact, and they then become stationary. The disk rotates at a speed of one revolution a minute in the *negative* direction, . The viscosity of the air is 0·104, and the candle repulsion = 7·1.

367. *Pressure* 470 *millionths of an atmosphere.*—The vanes remain stationary. On first making contact the disk makes $1\frac{1}{2}$ revolution in the *positive* direction, and then rotates continuously in the *negative* direction, at the rate of one-third of a revolution a minute. Viscosity = ·102. Candle repulsion = 8·2.

368. *Pressure* 388 *millionths of an atmosphere.*—No movement of the vanes on making contact. Negative rotation of the disk, at a speed of 1·25 revolutions a minute. Viscosity = 0·103. Candle repulsion = 9·3.

369. *Pressure* 212 *millionths of an atmosphere.*—On first making contact the vanes and disk move in the same direction, the vanes going $\frac{1}{4}$ revolution *negatively*, and the disk $\frac{1}{2}$ revolution *positively*, thus . The vanes then remain still, but the disk rotates negatively, at a uniform speed of 1 revolution a minute. Viscosity = ·099. Candle repulsion = 12·7.

370. *Pressure* 118 *millionths of an atmosphere.*—The vanes now rotate continuously in the *positive* direction at the rate of 19 revolutions a minute. The disk first rotates *positively*—*i.e.*, in the opposite direction to the vanes—then stops and rotates very slowly the same way as the vanes. Viscosity = ·092. Candle repulsion = 24.

371. *Pressure* 94 *millionths of an atmosphere.*—On igniting the wire, the general action is as last described, but the disk continues the preliminary *positive* rotation for a longer time before it takes up its negative rotation . The vanes rotate *positively* at a rate of 30 revolutions a minute. Viscosity = ·089. Candle repulsion = 29.

372. *Pressure* 59 *millionths of an atmosphere.*—The positive rotation of the disk now continues, at a uniform speed of 2·5 revolutions a minute, without changing to negative, as in the last two cases. The vanes move *positively*, at a rate of 68 revolutions a minute . Viscosity = ·080. Candle repulsion = 35·5.

When the disk and vanes are moving *positively* at a uniform speed, if the battery current is turned off so as to let the platinum ring cool, the positive motion of the disk soon stops, the vanes continuing to rotate. The disk now changes its direction and rotates *negatively* the same way as the vanes; its velocity soon becomes equal to that of the vanes, and they then both rotate together as if fixed to the same axis.

This change of direction in the disk and its subsequent following the vanes are due to the viscosity of the air causing the rapidly moving vanes to drag the disk round with it.

373. *Pressure* 14 *millionths of an atmosphere.*—The positive rotations of both disk and vanes continue as in the last experiment, the speed increasing. The vanes rotate 150 times a minute, and the disk 10 times a minute . Viscosity = ·044. Candle repulsion = 27.

374. *Pressure* 11 *millionths of an atmosphere.*—The positive rotations are the same as before. The velocity of the vanes is about 600 revolutions a minute, but it is difficult to register accurately these high speeds. The disk rotates 12 times a minute. Viscosity = ·039. Candle repulsion = 23·5.

At this pressure, when the battery is turned off, and the wire allowed to cool, the disk continues its positive movement for a considerable time. The viscosity of the rarefied air is now only ·039, and the drag of the vanes on the disk takes longer to exert its influence than when the viscosity was ·08.

375. *Pressure* 6 *millionths of an atmosphere.*—The speed of the vanes is far too great to count, and their shape is scarcely distinguishable owing to the velocity. The disk rotates steadily at a rate of 22 turns a minute . Viscosity = ·029. Candle repulsion = 16.

376. *Pressure* 2 *millionths of an atmosphere.*—By reason of their great speed, the vanes are now invisible, except as a nebulous ring. The disk makes 30 revolutions a minute. Viscosity = ·020. Candle repulsion = 10.

377. *Pressure* 0·4 *millionth of an atmosphere.*—The vanes and disk rotate as at the last pressure. There is no apparent diminution in the speed of the vanes, and the disk is going at the rate of 31 revolutions a minute. Viscosity = ·016. Candle repulsion = 6.

378. I could not get a higher exhaustion in this experiment, so I filled the apparatus with pure hydrogen. This was effected, previous to the first experiment, by sealing on to the pump a tube, shown at I, containing palladium foil saturated electrolytically with hydrogen. This alloy is perfectly stable in the cold at the highest exhaustions (233), but when gently heated the hydrogen is given off in quantities which can be easily regulated by careful manipulation. The gas was allowed to depress the gauge about 50 millims. The pump was then worked till a high exhaustion was reached, and more hydrogen evolved. After two or three heatings and pumpings, the residual air was assumed to have been washed out, and the observations in hydrogen were commenced.

379. At a pressure of 5 millims., when the platinum ring is ignited, the vanes are still, but the disk rotates in the *negative* direction. At 1·25 millims. both vanes and disk are still. At ·8 millim. the vanes keep stationary as before, but the disk assumes a *positive* rotation.

At ·6 millim. positive rotation of the vanes commences, and that of the disk continues at a little greater speed than before .

At 47 millionths of an atmosphere the positive rotation of the vanes is too rapid to count. That of the disk is 10 revolutions a minute.

380. *Pressure* 8 *millionths of an atmosphere.*—When the current is first turned on, the vanes commence to rotate rapidly in the positive direction, and the disk revolves more slowly in the positive direction. The speed of the vanes gradually increases up to a maximum of at least 1000 turns a minute; and during this increase of speed the disk revolves slower and slower, until, when the vanes rotate at the highest velocity, the disk is quite still. The reason of this peculiar behaviour is probably this: the enormous speed of the vanes, acting on the disk through the viscosity of the residual gas, causes a tendency to *negative* rotation—*i.e.*, in the same direction as the vanes; this tendency to negative rotation balances the rotation due to the tangential action of the molecular pressure, which, deflected from the sloping vanes, would turn the disk *positively*.

By gently tilting the apparatus, I can make the rotating vanes strike the support. They are thus stopped, and the disk immediately commences its *positive* rotation. The drag of viscosity being removed, molecular pressure prevails.

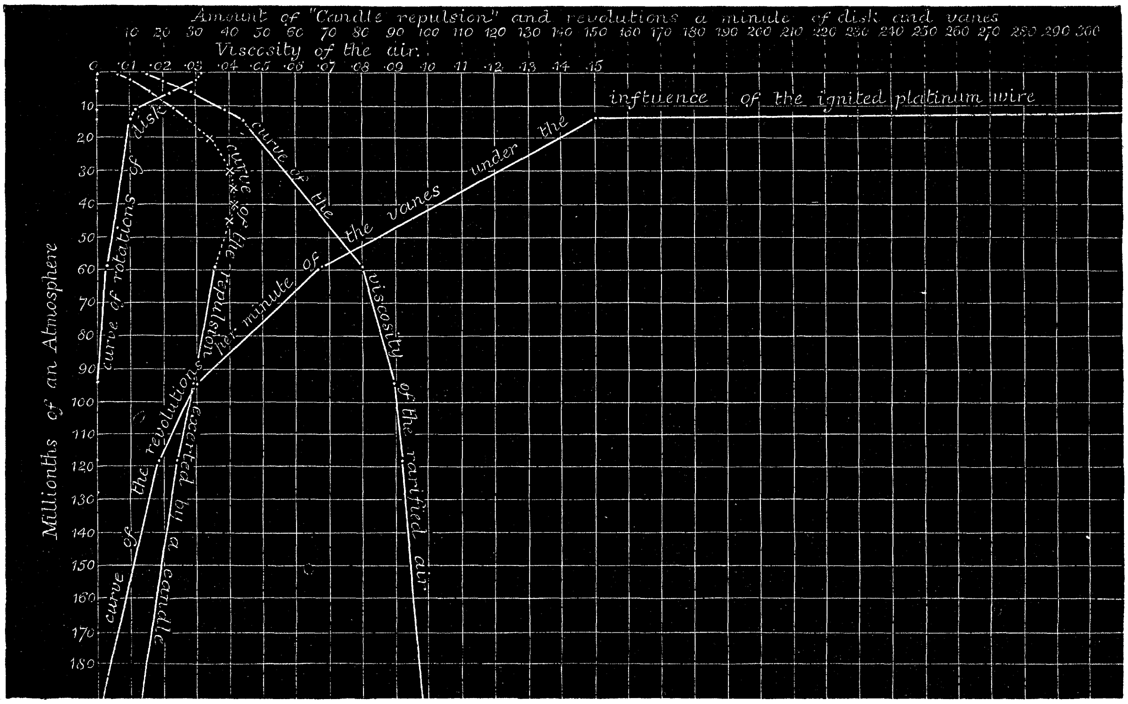
The deflection of the molecular pressure, by the vanes, on to the disk, turning the disk in the direction opposite to that of the vanes, may also be represented by fig. 33, par. 364, which shows the similar action of a current of hot air.

381. Whilst this action was going on, the disk stationary and the vanes in full rotation, I turned off the battery current. The vanes continued to move in the positive direction, and when their speed had sunk to about 100 revolutions a minute, the disk commenced to turn with the vanes, being dragged round by the viscosity, there now being no molecular pressure tending to give positive movement.

382. *Pressure* 1·4 *millionth of an atmosphere.*—On first turning on the battery, both the vanes and disk turn *positively*. As the speed of the vanes increases, that of the disk diminishes; but when the vanes are rotating at their uniform maximum speed, the disk does not quite stop but moves a little positively. The viscosity of the hydrogen at this rarefaction is only ·0168 (as against ·057 at the normal pressure), and it is therefore not enough to quite neutralise the action of the molecular pressure. On turning the battery off, the vanes nearly stop before they exert any drag on the disk.

At this pressure the spectrum of hydrogen in the vacuum tube only shows one line in the green (the F line), and that very faint.

Fig. 34.



383. In fig. 34 I have plotted down the observations taken in air vacua in this appa-

ratus from the data in paragraphs 369 to 377. They are connected together by lines forming curves; in the curve representing the "candle repulsion" I have interpolated a few observations from other experiments to fill up a gap between 59-millionths and 14-millionths, and to give a better idea of the direction the true curve would take.

The "candle repulsion" and the "viscosity" curves are similar to those already published in the 'Proceeedings of the Royal Society.'* In describing these curves in November, 1876, I said that the viscosity of the residual gas in an air vacuum was practically constant up to an exhaustion of 250 millionths of an atmosphere, having only diminished from 0·126 at the normal pressure of the atmosphere to 0·112. It now begins to fall off, and at 0·1 of a millionth of an atmosphere it has fallen to about 0·01. Simultaneously with this decrease in the viscosity, the force of repulsion exerted on a black surface by a standard light varies. It increases very slowly till the exhaustion has risen to about 70 millionths of an atmosphere; at about 40 millionths the force is at its maximum, and it then sinks very rapidly, till at 0·1 millionth of an atmosphere it is less than one-tenth of its maximum.

384. The diagram (fig. 34) entirely confirms the observations described last year. In order to keep the diagram within reasonable limits, I have omitted the observations at lower exhaustions than 118 millionths of an atmosphere, but from that point upwards the parallelism is close. The candle repulsion rises to a maximum somewhere between 59 and 14 millionths of an atmosphere, and then rapidly sinks up to the highest exhaustion obtained. Simultaneously the viscosity drops rapidly at the high exhaustions. From these observations I might be justified in assuming that it would be a general law that above 40 millionths of an atmosphere the repulsion resulting from radiation would fall off as the exhaustion got nearer absolute, and this idea would be greatly confirmed by the experiment with the radiometer described in paragraph 334, and graphically illustrated in the curve on fig. 28.

It now seems that this generalisation would be too hasty, and the utmost that can be said is that the statement is true for the particular instances described. When, instead of the feeble intensity of radiation which can penetrate glass from a candle some inches off, I substitute the intense energy of a red hot platinum wire a few millimetres off, the answer given to my interrogations is very different. There is now no maximum at 40 millionths, and subsequent rapid falling off, but a steady increase of speed from 67 revolutions a minute at 59 millionths, 150 revolutions at 14 millionths, 600 revolutions at 11 millionths, up to over 1000 revolutions at 6 millionths, and still increasing speeds at 2 millionths and at 0·4 millionth. At an exhaustion where the repulsion set up by the candle is least, that caused by the hot wire is greatest.

In air, at still higher exhaustions, I could detect no falling off of speed, but when the residual gas was hydrogen I thought that there was a diminution of velocity after 1 millionth of an atmosphere had been reached.

* No. 175, 1876, page 305.

385. The term "vacuum" has till recently been greatly misapplied. Formerly, an air-pump, which would diminish the volume of air in the receiver 1000 times, was said to produce a vacuum. Later, a perfect vacuum was said to be produced by chemical absorption and by the Sprengel-pump, the test being that electricity would not pass when the air is rarefied a few hundred thousand times.

386. It is generally taken for granted that when a number is divided by 10,000,000 the quotient must be necessarily small, whereas it may happen that the original number is so large that its division by 10,000,000 seems to make little impression on it. According to Mr. JOHNSTONE STONEY,* the number of molecules in a cubic centimetre of air at the ordinary pressure is probably something like 1000,000000,000000,000000. Now, when this number is multiplied by 0·0000004, or in other words divided by 2,500000, there are still 400,000000,000000 molecules in every cubic centimetre of gas at the highest exhaustion to which I carried the experiment illustrated in fig. 34—a rarefaction which would correspond to the density of the atmosphere about seventy-five miles above the earth's surface, assuming that its density decreases in geometrical progression, as its height increases in arithmetical progression (21 *note*, 74). Four hundred billion molecules in a cubic centimetre appear a sufficiently large number to justify the supposition that when set into vibration by a white hot wire, they may be capable of exerting an enormous mechanical effect.

* Phil. Mag., vol. xxxvi. p. 141.