Summary.

Series.			Mgms.	Greatest deviation from mean in milligrammes.	
1	(B+X)−(A+Y)	=	·0718	·0099	A=B+·0446 mgm.
2	(A+X)−(B+Y)	=	·1610	·0067	
3	(A+X)−(B+Y)	=	·1732	·0057	A=B+·0116 mgm.
4	(B+X)−(A+Y)	=	·1500	·0122	
5	(B+Y)−(A+X)	=	·0065	·0057	B=A+·1989 mgm.
6	(B+X)−(A+Y)	=	·4043	·0078	
7	(B+Y)−(A+X)	=	·1283	·0089	B=A+·1418 mgm.
8	(B+X)−(A+Y)	=	·4119	·0037	

The greatest error—that is the greatest deviation of any one value from the mean of its series—in the first four series is $\frac{1}{20000000}$th of a pound. The greatest error in the four series Nos. 5—8 is $\frac{1}{50000000}$th of a pound.

II. "On Repulsion resulting from Radiation." Part VI. By William Crookes, F.R.S., V.P.C.S.

(Abstract.)

In this part, with which the research closes, the author first examines the action of thin mica screens fixed on the fly of an ordinary radiometer, in modifying the movements. It is found that when a disk of thin clear mica is attached 1 millim. in front of the blacked side of the vanes of an ordinary radiometer, the fly moves negatively, the black side approaching instead of retreating from the light. When a thin mica disk is fixed on each side of the vanes of a radiometer, the result is an almost total loss of sensitiveness.

In order to examine the action of screens still further an instrument is described having the screens movable, and working on a pivot independent of the one carrying the fly, so that the screens can move freely and come close either to the black or to the white surfaces of the disks. By gentle tapping the screens can be brought within 2 millims. of the black surfaces. A candle is now brought near, shaded so that the light has to pass through one of the clear disks and fall on the black surface. The black side immediately retreats, the clear disk remaining stationary for a moment and then approaching the light. If the candle is allowed to shine on the plain side of the black disk, no immediate movement takes place. Very soon, however, both disks move in the same direction away from the candle, the speed of the clear disk gradually increasing over that of the blacked disk.

Instead of allowing the clear screens to freely move on a pivot, an instrument was made in which the screens could be fixed beforehand in any desired position in respect to the blacked disks. It was then found that with the screens close to the blacked sides of the vanes the fly rotates very slowly in the negative direction, stopping altogether when the candle is moved five or six inches off. With the screens 1 millim. from the black surface the direction is negative and the speed at its maximum. When the screens and disks are 7 millims. apart a position of neutrality is attained, no movement taking place. When the distance is further increased, positive rotation commences, which gets stronger as the screens approach the bright sides of the disks, where the positive rotation is at its maximum. The author adduces reasons for considering that the negative rotations here observed are caused by the warming up of the black surface by radiation falling direct on it, through the clear mica screen, and the deflection backwards of the lines of molecular pressure thereby generated.

The action of these radiometers being complicated, owing to the surfaces of the vanes being different in absorptive power, another instrument was made in which the vanes were of polished aluminium, perfectly flat and symmetrical with the bulb. The screens were of clear mica movable in respect to the vanes, and at right angles to their surface. When exposed to the light of a candle it was found that with the screens brought up close to the disks, the rotation was as if the unscreened side were repelled; at an intermediate position there was neutrality. Explanations are given of these movements, but without the illustrative cuts they would be unintelligible.

Experiments on radiometers having movable screens interposed between the vanes and the bulb are next given, and these are followed by a long series of experiments on the influence of movable screens on radiometers with cup-shaped metallic vanes, the screens being varied in shape, and position in respect to the plane of rotation, as well as in respect to the distance from the vanes.

A similar series is given with metallic cylinders as vanes, and from the behaviour of the latter kind of radiometer, an explanation is given of the various movements previously obtained. It is found that when the screen touches the convex surface of the vanes the rotation under the influence of light is always positive. It commences at a low exhaustion, increases in speed till the rarefaction is so high that an ordinary radiometer would begin to lose sensitiveness, and afterwards remains at about the same speed up to the highest rarefaction yet obtained. At any rarefaction after 87 M (millionths of an atmosphere) there is a neutral position for the screen. When it is on the concave side of this neutral position the direction of rotation is positive, and when on the convex side of the neutral position it is

negative; the speed of rotation is greater as the vanes are further removed from this neutral position on either side. The position of this neutral point varies with the degree of exhaustion; thus at 12 M, the screens must be 3 millims. from the convex side; at ·18 M they must be 13 millims. from the convex side. The higher the exhaustion the greater the distance which must separate the convex side of the hemi-cylinders and the screens.

The author gives explanations of these phenomena, based on the following already ascertained facts:—When thin aluminium vanes are exposed to light the metal rises in temperature and becomes equally warm throughout, and a layer of molecular pressure is generated on its surface. The thickness of this layer of pressure, or the length of the lines of force of repulsion, varies with the degree of exhaustion, being longer as the exhaustion increases. The lines of force appear to radiate from the metal in a direction normal to its surface. The force of repulsion is also greater the closer the repelled body is to the generating or driving surface, and the force diminishes rapidly as the distance increases, according to a law which does not appear to be that of "inverse squares." Diagrams are given illustrating the author's explanation, based on the above data.

An apparatus is next described not differing in principle from the last, but having, in addition to the aluminium hemi-cylinder and movable mica screen, a small rotating fly made of clear mica, mounted in such a way that it could be fixed by means of an exterior magnet in any desired position inside the bulb. The screen was also capable of adjustment by means of another magnet; the aluminium hemi-cylinder in this apparatus being fixed immovable. The adjustible indicator being very small in diameter in comparison to the other parts of the apparatus, and, being easily placed in any part of the bulb, was expected to afford information as to the intensity and direction of the lines of pressure when a candle was brought near the bulb. Experiments have been tried, *a*, with the screen in different positions in respect to the hemi-cylinder; *b*, with the indicator in different parts of the bulb; *c*, with the candle at different distances from the hemi-cylinder on one side or the other; *d*, with the degree of exhaustion varying between wide limits. It would be impossible to give an intelligible abstract of the results obtained with this apparatus without numerous diagrams. It may, however, be briefly stated that they entirely corroborate the theories formed from a study of the behaviour of the instruments previously described.

The next part of the paper treats of the action of heat employed inside the radiometer. In a previous paper, the author showed that phenomena feeble and contradictory when caused by radiation external to the bulb, became vigorous and uniform when the radiation was applied internally by the agency of an electrically-heated wire. It

was hoped that some of the more obscure phenomena shown by the deep cups with movable screens in front (referred to above) might be intensified if set in action by a hot wire. Several kinds of apparatus and experiments with them are described, but the results are too complicated to be given in abstract. One experiment proves that the direction of pressure is not wholly normal to the surface on which it is generated, but that some of it is tangential.

The author then describes the turbine radiometer, early specimens of which were exhibited before the Royal Society on April 5, 1876. In the ordinary form of radiometer the number of disks constituting the fly is limited to six or eight, a greater number causing interference one with the other and obstruction of the incident light. In the turbine form of fly there is no such difficulty, the number of vanes may be considerably increased without overcrowding, and with corresponding advantage. In the earlier turbine radiometers the flies were made of mica blacked on both sides, and inclined at an angle like the sails of a windmill, instead of being in a vertical plane. This form of instrument is not sensitive to horizontal radiation, but moves readily in one or other direction to a candle held above or below. A vertical light falling on the fly gives the strongest action, but rotation takes place, whatever be the incident angle, provided the light is caught by one surface more than by the other. Ether dropped on the top of the bulb to chill it causes rapid negative rotation. If the turbine radiometer is floated in a vessel of ice-cold water, and the upper portion exposed to the air of a warm room, it rotates rapidly in the positive direction, acting as a heat engine, and continuing so to act until the rotating fly has equalised the temperature of the upper and lower portions of the bulb. By reversing the circle of operations—by floating the turbine radiometer in hot water and cooling the upper portion of the bulb—the fly instantly rotates in the negative direction.

After describing experiments in which the same fly was made to rotate first in a large bulb and then in a small one at the same degree of exhaustion, the author proceeds to discuss the influence exerted by the inner side of the glass case of the radiometer as a reacting surface. A flat metal band was put equatorially inside a radiometer, and lamp-blacked, so that the molecular pressure generated under the influence of light should react between the fly and the black band, instead of between the fly and the glass side of the bulb. It was found that the maximum speed with the band present was 40 revolutions a minute, against $8\frac{1}{4}$ revolutions when the band was absent.

The rotation of the case of a radiometer, the fly being held immovable by magnetism, is next described. A preliminary note on this subject having already appeared in the "Proceedings,"* it need not be again

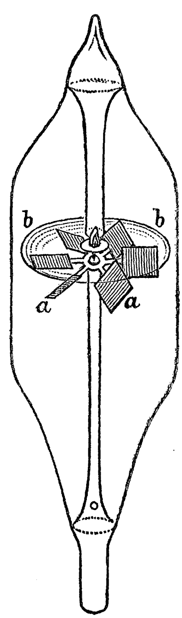
* "Proc. Roy. Soc.," No. 168, March 30, 1876.

described in detail. Many different forms of instrument for effecting this rotation are described, and their mode of action explained.

The reacting inner surface of the envelope being thus proved to be essential to the rotation of the fly, other instruments were made in which this necessary reaction is obtained in a more direct manner. In one, the radiometer is furnished with a fly carrying four flat aluminium vanes, polished on both sides. Three vertical partitions of thin clear mica are fixed in the bulb, with their planes not passing through the axis of rotation, but inclined to it, thus throwing the obliquity off the fly on to the case, and giving three fixed planes for the reaction to take place against. Candles arranged symmetrically round the bulb make the fly rotate rapidly against the edges of the inclined planes. Breathing gently on the bulb gives negative rotation. A hot glass shade inverted over the instrument causes strong negative rotation, changing to positive on cooling. When the fly is furnished with clear mica or with silver flake mica vanes, the same results are obtained as when aluminium vanes are employed. The principal action is produced by dark heat warming the bulb, screens, and vanes.

The *otheoscope* is the next subject treated on in the paper. This has already been given in abstract,* and need not be again referred to. Many different varieties of otheoscope are figured and described.

FIG. 1.



* "Proc. Roy. Soc.," No. 180, April 26, 1877.

It was suggested by Professor Stokes that a disk might be made to revolve on its axis, and the author describes an instrument in which this suggestion is carried out. The disk is horizontal, mounted like the fly of a radiometer, and for lightness' sake is of mica, blacked above. Fixed to the bulb above the disk are four flat pieces of clear mica; each extends from the side of the bulb to near the centre, and ends below in a straight horizontal edge, leaving just space enough for the disk to revolve without risk of scraping. The edge is in a radial direction, and the plane of the plates is inclined about 45° to the horizon, in the same direction for them all. Exposed to the light of a candle, the rotation is against the edge. By slightly modifying this form, the instrument becomes much more sensitive. Fig. 1 shows the complete instrument; *a*, *a*, are six vanes of copper foil, oxidised by heating to redness in the air; they are attached to arms, and are inclined at an angle of 45° to the horizon. They are firmly fixed to the support. Through the centre passes a needle-point, on which is balanced a glass cup, carrying a thin clear disk of mica, *b*, *b*, freely rotating about 1 millim. above the top edges of the copper vanes. When exposed to light, the mica disk rotates with great speed against the edges. The pressure which drives the movable fly round reacts equally on the driving surface: by suspending both vanes and disk independently on needle-points the effect of light causes them to rotate in opposite directions.

Whilst experimenting with the otheoscope it was found that, for a given exhaustion, the nearer the reacting surfaces were together the greater was the speed obtained. In the "Proceedings of the Royal Society" for November, 1876,* the author described an apparatus by which he was able to measure the thickness of the layer of molecular pressure generated when radiation impinged on a blackened surface enclosed in an atmosphere the rarefaction of which could be varied at will.

It was found that in this apparatus repulsion could be obtained at ordinary atmospheric pressures. Observations are given at normal pressure and at various degrees of rarefaction, with the driving and moving surfaces separated 1, 2, 3, 4, 6, 8, and 12 millims.; and diagrams of the resulting curves are shown when the atmospheric tension and the force of repulsion are used as abscissæ and ordinates. The tables and curves show that the law of increase of the force with the diminution of the distance between the disks does not remain uniform at all rarefactions. At the lowest exhaustions the mean path of the molecules of the attenuated gas is less than 1 millim., as rendered evident by the force of repulsion diminishing rapidly as the distance increases. At exhaustions higher than 9 millims. this condition alters, and as the

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

gauge approaches barometric height, the molecular pressure tends to become uniform through considerable distances, the mean path of the molecules now being comparable with the greatest distance separating the surfaces between which they act.

A similar apparatus to the one in which the last experiments were tried was used to measure the action at pressures at and approaching atmospheric. At pressures between atmospheric and 210 millims., the first action is very faint repulsion, immediately followed by strong attraction. The attraction then begins to decline, until at 15 millims. pressure it disappears. At the same time the repulsion, which begins to be apparent at 250 millims., increases as the attraction diminishes. The author considers that the attraction is the result of air-currents, caused by the permanent heating of the surface in front of the moveable disk.

The paper concludes with experiments undertaken to measure the amount of repulsion, using a horizontal torsion balance,* on the principle of Ritchie's, in which the force of repulsion is balanced by the torsion of a fine glass fibre. The *pan* of the balance is a clear mica disk, and a similar disk is fastened to the tube in which the beam oscillates. This fixed disk is lampblacked on the upper side, and beneath is a spiral of platinum wire, connected with terminals sealed through the side of the tube. When the spiral is ignited by a constant electric current, the blacked mica disk fixed above it becomes heated, and the molecular pressure thereby generated between it and the mica pan causes the latter to rise. The glass thread attached to the beam is thus twisted, and by means of a graduated circle the number of degrees through which the thread has to be turned in order to bring the beam back to equilibrium is noted. This gives a measurement of the pressure exerted, in torsional degrees, and these are converted into grains by ascertaining how many torsional degrees correspond to a known weight. A ray of light reflected from a mirror in the centre of the beam is used as an index, being brought back to zero at each experiment. The author gives in a table, and also shows in the form of a curve, the results obtained with this apparatus, giving the force of molecular pressure in grains weight at exhaustions varying between 2,237 and 0·7 millionths of an atmosphere.

* For a description of this form of torsion balance, see the author's paper, "Phil. Trans.," 1876, vol. clxvi, p. 371.