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XXVI.—*On a Method of Measuring the Pressure of Light by Means of Thin Metal Foil. Part II.* By GILBERT D. WEST, B.Sc.

RECEIVED MAY 12, 1916.

IN an earlier Paper to the Physical Society* I have described the measurement of the pressure of light by a method requiring few of the elaborate precautions generally necessary in such experiments. The essential feature of the apparatus was a strip of gold leaf suspended in the middle of a test tube containing air or hydrogen at reduced pressure. Radiation from a 32 c.p. carbon filament lamp, impinging directly on one side of the strip, was sufficient to cause a microscopically measurable deflection of the end.

The pressure of normally incident radiation on a perfectly reflecting surface has been shown† to be numerically equal to twice the energy content of the radiation per unit volume, and hence if this quantity be measured in the way described below, a check on the original observations can be made. A mean of the results of several successive experiments with the deflected strips, gave a value for the pressure of radiation which only differed from that calculated from the energy density by a small per cent. The accuracy and constancy of the final results seemed to preclude their being seriously affected by gas action, but as gas action had to be taken into consideration, the present research was undertaken with a view to its fuller investigation, and if possible to its complete elimination.

As it is convenient to know in advance the value of the true pressure of the radiation employed, the measurements and calculations required for this purpose will be dealt with first.

Measurement of the Energy Density.

The method used was similar to that described in the previous Paper. The initial rate of rise of temperature of a blackened copper plate enclosed in the tube, was measured by means of an attached copper eureka thermo-junction. Due allowance was made for cooling corrections, and the lamp black was again

* "Proc. Phys. Soc.," Vol. XXV., 1913, p. 324.

† Maxwell, "Electricity and Magnetism," Vol. II. Larmor, "Encycl. Brit.," Radiation." See also Callendar, "Nature," Jan. 1, 1914.

assumed to absorb 95 per cent. of the incident radiation. The cold junction was immersed in oil contained in a vacuum flask, and during an experiment a delicate indicating thermometer in the oil, only showed negligible variations. The calibration of the thermo-junction was carried out in the usual way, and a number of minor matters received fuller consideration than was previously given.

When, from the measurements thus taken, the energy reaching 1 sq. cm. in one second is known, the energy per l c.c. can be calculated from a knowledge of the velocity of light.

The 32 c.p. lamp was enclosed in a metal box whose front face had been replaced by a glass screen covered with a few thin wires. Inasmuch as it is required that the radiation should be normally incident, the lamp was not brought too close to the tube—a calculation of the limiting approach having been previously made. The current passing through the lamp was kept at the same value throughout all the experiments.

The results obtained are indicated in the course of the ensuing work. Owing to extraneous thermo-electric effects, especially at brass contact screws*, the accuracy was not quite as great as had been hoped. Nevertheless on drawing a curve evenly between the points representing the energy density at various distances from the source, it was found that none of the readings diverged by more than about 3 per cent. This accuracy is above what is required.

Reflecting and Transmitting Powers of the Foils Used.

By coating the front surface of the copper plate of the apparatus described in the previous Paper, with the foil to be used instead of with lamp black, it was possible to obtain measurements of the fraction of the incident radiation that was absorbed. More satisfactory results, however, were obtained with an apparatus somewhat similar to that originally used by Lebedew.† The bulb of a sensitive thermometer was fitted into a hole in a small block of copper. Thermal contact was secured by means of a little mercury, and the whole was placed in the tube in which subsequent measurements were carried out. The front face of the block was first coated with lamp black and afterwards with the foil under observation, whilst

* A. G. Warren and F. Murphy, "Electrician," Jan. 31, 1908.

† Lebedew, "Ann. der Physik," VI., p. 433, 1901.

the rates of rise of temperature on exposure to radiation, were, in each case, measured by means of a magnifying cathetometer telescope.

By interposing a screen made of gold or aluminium foil, between the source and the blackened block, it was possible to show that neither kind of foil transmitted an appreciable fraction of the incident radiation. The only correction therefore in calculating the reflecting power of the foil, is the re-reflection* from the glass of the tube. This amounts to about 7 per cent. Re-reflections after the first need not be considered.

As a mean of several observations, it was found that both gold and aluminium foil reflected 90 per cent. of the incident radiation.

It was also found that light was reflected from a sheet of foil, in a direction sufficiently close to the normal for the purposes of the experiment.

Calculation of the Deflection of the Strip.

Since the foil reflects 90 per cent. of the incident radiation, and since 7 per cent. is re-reflected from the glass of the tube, the total pressure of the radiation is given by

$$E(1+0.07 \times 0.9)(1+0.9) \text{ or } 2.04E$$

where E is the energy density of the incident beam.

A certain amount of radiation, however, strikes the back of the glass tube, and some of this is reflected to the back of the strip. For a strip three-quarters the width of the tube, it is estimated that the normal component of this radiation is about 1 per cent. of all that is incident on the strip. It is therefore necessary to substitute $2.02E$ for $2.04E$.

It can be shown that a uniform flexible strip when deflected by a small uniform pressure, still remains straight. To a close degree of approximation, therefore, we may calculate the deflection of a strip such as that represented in Fig. 1, by taking moments about the axis of rotation.

It was considered preferable in this research to find, by means of a Bunge balance, the mass of 1 sq. cm. of the sheet of foil from which the strip was cut, rather than to weigh the strip itself, and we may modify the original formula accordingly.

* Re-reflection was not considered in the original Paper. I have to thank the late Prof. Poynting and Dr. Barlow for the suggestion.

If we write h the distance of the centre of gravity of the strip below the axis of rotation AB as $\frac{l^2 + f^2}{2(l+f)}$, where f is the length of the folded part AC , Fig. 1. We may write the deflection of the end of the strip of length l as

$$d = \frac{2.02El}{\left(1 + \frac{f^2}{l^2}\right)\rho g}$$

where ρ is the mass of 1 sq. cm. of the foil.

FIG. 1.

The Apparatus.

There are a few modifications of the original apparatus that need explanation. The top of the tube was closed by the hollow stopper H . In order to obtain a clear image of the end of the strip a small piece of cover glass was cemented to the inside of the tube at E by means of solid Canada Balsam. Another piece of cover glass was attached to the outside of the

FIG. 2.

tube with a viscous solution of Canada Balsam in Xylol. By this means it was found possible to get improved definition of the image given by the microscope. When it was required to obtain very high vacua, a tube was attached similar to *F*, containing charcoal that had been prepared by very slowly calcining elder pith.* In the ordinary course of events, however, the tube *G* was connected directly to a motor-driven Gaede pump and a McLeod gauge.

The general arrangement of the apparatus is shown in Fig. 2. Air may be admitted to the pump at *A*, but by a turn of the cock, electrolytically generated hydrogen from the reservoir *B* may be admitted instead. Before entering the pump, the gas

FIG. 3.

is forced to pass, first through strong sulphuric acid and then through a tube *C* containing phosphorous pentoxide. *D* is a barometric seal which prevents any small leakage to the tube *E* when the pump has ceased action. *F* is a McLeod gauge, *G* is directly connected to the Gaede mercury pump, and *H* is connected to a rotary pump exhausting to about 1 cm. mercury.

The apparatus for taking observations is represented in Fig. 3. The tube is mounted on a stand *A*, specially made by Messrs. Griffin & Co., and the lamp *B* can easily be swung round from side to side. Behind the tube is a small mirror *C* to illuminate the field of vision of the microscope *D*. *E* is a variable resistance, and *F* is a switch.

* In this connection I have to thank Dr. S. W. J. Smith for valuable suggestions.

A No. 3 Leitz objective coupled with a X20 eyepiece was used in the observing microscope. The slight chromatic aberration was reduced by means of a yellow screen placed in front of the eyepiece.* Before exhausting the tube, the stopper was sealed down with a mixture of wax and resin. The pump was probably capable of evacuating to pressures considerably below the vapour pressure of mercury,† but as no special precautions were taken, this was not generally attempted. For very low vacua, reliance was placed on liquid air and charcoal.

RESULTS.

Expansion of the Strips, due to Rise of Temperature.

Much light is thrown on the main issues, by a subsidiary phenomenon which escaped notice in the original Paper, owing probably to the bad definition of the image in the microscope, caused by the glass of the test tube.

The phenomenon referred to is the expansion of the strip under the influence of the radiation. To observe the expansions it was necessary to attach pieces of copper foil to the ends of the strips, as otherwise the movements under the influence of radiation prevented accurate observation. The expansion takes place rapidly, and is small and constant for gas pressures down to 1.5 cm. Below this it shows a slight increase, and then remains constant until a pressure of about 0.002 cm. is reached. On lowering the pressure still more it increases, until with the lowest vacua obtainable, it is nearly 20 times the original value. A series of results is given below.

ALUMINIUM STRIP.

Length=7.43 cm. Distance of lamp=10.5 cm. Energy density of radiation= 1.95×10^{-5} ergs./cc.

Pressure.	Expansion of strip in air.
74.3 cm. of mercury (atmosphere)	0.5×10^{-3} cm.
41.3 cm.	0.5 " "
24.3 cm.	0.5 " "
5.0 cm.	0.5 " "
1.5 cm.	0.5 " "
0.35 cm.	0.6 " "
0.027 cm.	0.6 " "
0.0025 cm.	0.8 " "
0.0005 cm.	1.6 " "
0.0001 cm.	2.4 " "
Liquid air vacuum.	8.7 " "

* I am indebted to Dr. Salisbury, of East London College, for this suggestion.

† "Gaede Sci. Abs.," p. 471, 1915; also "Ann. der Physik," 46, p. 357, 1915..

When the apparatus was filled with hydrogen (whose thermal conductivity is six times that of air), the expansions for pressures down to 0.005 cm. were scarcely observable, being about 0.1×10^{-3} cm. They increased after that point however.

The rises of temperature that the expansions of the strips imply, are shown in the table below. The values assumed for the co-efficients of expansion of aluminium and gold are 25.5×10^{-6} , and 13.9×10^{-6} , respectively.*

Pressures.	Rise of temperature (Degrees Centigrade).			
	Aluminium strip.		Gold strip.	
	In air.	In hydrogen.	In air.	In hydrogen.
74.3 cm.	2.5	Hardly observ- able, about 0.5	1.8	Too small to be observed
Liquid air vacuum	46.0	...	44.5	...

The estimated difference of temperature of the two sides of the aluminium and gold strips respectively, was $6 \times 10^{-7}^{\circ}\text{C.}$, and $9 \times 10^{-8}^{\circ}\text{C.}$ No effects attributable to these small differences of temperature have yet been observed.

The results are almost self explanatory. Convection, conduction and radiation each play a part in determining the temperature of the strip at pressures down to about 1 cm. Conduction is independent of pressure unless this is very low, and, together with radiation, is the important factor until the very lowest pressures are reached, at which radiation alone is important. Thus at high pressures the rise of temperature is small, but at very low pressures it is considerable. The results obtained are in general agreement with those of Kundt and Warburg,† and they are in close agreement with the more precise results of Sir William Crookes.‡

The accepted view that convection is unimportant at pressures below 1 cm. is confirmed, and in the work shortly to be described, it will be found that satisfactory explanations of phenomena can be given by neglecting convection, at low pressures, altogether.

The Thermo-Kinetic Reaction.

The motion of the strip under the influence of radiation was considered in the previous Paper down to a pressure of about

* Voigt, 1893.

† "Pogg. Ann.," CLVI., p. 177, 1875; also "Phil. Mag.," July, 1875.

‡ "Proc. Royal Soc.," Vol. XXXI., p. 239, 1880-81.

1 cm. At that pressure, only very small gas action effects make their appearance, but as the pressure is lowered to, say, 0.002 cm., the movements of the strip may become a hundred times as large as before.

The strip may move initially either towards or from the source, and the first movement is followed by a much slower movement which is always away from the source. The first movement is strongest when the tube is inclined to the vertical—that is to say, when the end of the strip is nearer to one side of the tube than to the other. A typical series of readings for various pressures is given below in the table and in the diagrams on following page. It will be noted that in spite of the inclination of the tube, reasonable values for the pressure of light are obtained both at 1.5 cm. and 0.9 cm. of mercury.

ALUMINIUM STRIP.

Length=7.43 cm. Distance of lamp=10.5 cm. Energy density of radiation= 1.95×10^{-5} ergs./c.c. Tube inclined so that end of strip was nearer to right side of tube. Observations taken at the end of the first movement.

Pressure.	Deflections.		Mean deflection from lamp.	Deflection calculated from energy density.
	Lamp on left side.	Lamp on right side.		
1.5 cm. Hg.	0.3×10^{-3} cm. towards lamp	6.6×10^{-3} cm. from lamp	3.1×10^{-3} cm.	2.6×10^{-3} cm.
0.9 cm. Hg.	1.6	7.9	3.1	2.6

When the tube was inclined in the opposite way, so that the end of the strip was nearer to the left side than to the right, a similar series of curves, as given on following page, was obtained, but the initial deflections were to the right instead of to the left. When the tube was filled with hydrogen, and when the aluminium leaf was exchanged for one of gold, similar curves were again obtained. The material of the strip and the nature of the gas seemed to have little influence on the results.

As shown by the curves the slow progressive movement that occurs when the first movement is over, is always away from the source, and it is therefore natural to attribute this motion to the gradual warming up of the surface of the tube. Further, it is possible to reduce greatly the ratio of the rate of this motion to the deflection, by the interposition of a thick glass plate in the path of the radiation. At low pressures, when the mean free path is a few centimetres, we may consider the strip

to be bombarded by molecules returning from the heated glass surface. The strip is therefore deflected in the way observed. As the surface of the glass still remains hot when the lamp is switched off, and as the bombardment therefore continues, the strip does not return to zero for some time.

As was observed in the expansion experiments, the heating of the strip takes place rapidly, and it is this heating of the strip that accounts for the first part of the curves.

FIG. 4.

Molecules that strike the strip are sent back with increased velocities, and, at very low pressures, a given molecule strikes the side of the strip nearest the glass more frequently than does the corresponding molecule on the other side. A greater change of momentum per second implies a greater pressure, and hence motion of the strip. As the pressure rises and the mean free path is reduced, molecular collisions complicate the problem, and the simple theory needs the same elaborate

modification that was given by Prof. Osborne-Reynolds* in connection with the theory of the Crookes Radiometer.

The deflections of the strips due to the heated glass rendered the apparatus unsuitable for the observation of the pressure at which the gas action effect described above reached a maximum, and recourse was therefore had to the weighted gold and aluminium strips used in the expansion experiments. It was found that throughout the region of pressures 0.01 cm. — 0.0005 cm. there were no great variations. The maximum in hydrogen was much the same as in air. To be certain of any difference, more precise experiments would be required. The results are similar to those of Sir William Crookes,† although the conditions are somewhat different. A comparison is given in the table below.

GOLD STRIP.

Pressure.	Deflections obtained.	Magnitude of radiometer effect calculated from Crookes' results.
0.16 cm. mercury	0.1 eyepiece divisions	1.0
0.02 "	0.4 " "	3.9
0.002 "	0.55 " "	8.3
0.0005 "	0.50 " "	4.1
0.0001 "	0.40 " "	2.0
0.00005(?) "	0.35 " "	1.7

To confirm the above theory a strip was mounted in a small rectangular glass cell in such a way that by tapping the cell the strip could be moved from side to side. The apparatus is represented in Fig. 5. The radiation may be allowed to fall normally on either side of the strip, but the deflection is always away from the closest glass surface, and is easily visible to the naked eye when the strip is placed so as to be nearly in contact with the glass. When the strip is in the middle of the containing vessel no movements are apparent.

The excess of pressure above the normal gas pressure that a heated surface experiences has been termed the thermo-kinetic reaction.

In the Crookes Radiometer the motion of the vane is caused by the difference of the thermo-kinetic reactions, due to the difference of the temperatures of the two sides of the vane.

In the Radiometer described above the initial motion of the strip is caused by the difference of the thermo-kinetic

* "Phil. Trans.," II., 1879, p. 768.

† "Phil. Trans.," I., 1879, p. 133.

reactions on the two sides of the strip, arising from their different distances from the walls of the containing vessel.

Under certain conditions, more complicated movements of the strip may occur. As it is proposed, however, to deal more fully with the subject in a subsequent Paper, further space will not be devoted to it here.

FIG. 5.

The Pressure of Radiation.

Under the new conditions, it is evident that to obtain trustworthy values of the pressure of radiation :—

- (i.) The strip should be as central as possible.
- (ii.) The vacuum should be very high.

The latter object was attained by the use of liquid air and charcoal. Further, only short exposures of about one second, were given, and the source of radiation was placed first on one side and then on the other. Any small deflection due to the difference of thermo-kinetic reaction on the two sides of the strip would therefore be eliminated by taking half the sum of the two readings.

The viscosity of a gas remains constant over wide ranges of pressure, but at very low pressures it is much reduced.* As a result, it was noticed that with liquid air vacua the strip was

* Crookes, "Phil. Trans.," 172, Part II., p. 378.

kept constantly vibrating like a pendulum by accidental tremors. The period of vibration was 0.45 sec., a value which agrees with the period of vibration of a flexible chain of the same length. A great advantage of the original apparatus, namely, its comparative insensitiveness to vibration, was thus lost at very low pressures. By mounting the apparatus, however, on the concrete floor of a basement, and by waiting for quiet intervals, some reasonably good results were obtained for the pressure of radiation. A series of results taken in succession is given below.

GOLD STRIP.

Liquid air vacuum. Energy density of radiation when lamp 10.5 cm. distant = 1.95×10^{-5} ergs./c.c. Length of strip = 7.10 cm. Length of folded part AC = 1.02 Mass of 1 sq. cm. of gold leaf = 1.82×10^{-4} gm.

Distance of source.	Deflections from lamp.			Deflections calculated from energy density.
	Lamp on left side.	Lamp on right side.	Mean.	
10.5 cm.	2.5×10^{-3} cm.	3.2×10^{-3} cm.	2.8×10^{-3} cm.	1.6×10^{-3} cm.
11.5 cm.	1.9	2.7	2.3	1.4
12.5 cm.	1.7	2.2	2.0	1.2

The reason why all the preceding results are too high has not been explained, and it is proposed to undertake further investigations on the matter. Other results obtained with the gold strip were also too high, but better results were obtained with the aluminium strip. They are recorded below.

ALUMINIUM STRIP.

Liquid air vacuum. Energy density of radiation when lamp is 10.5 cm. distant = 1.95×10^{-5} ergs./c.c. Length of strip = 7.43 cm. Length of folded part AC = 0.83 cm. Mass of 1 sq. cm. of aluminium foil = 1.16×10^{-4} gm.

Distance of source.	Deflections from lamp.			Deflections calculated from energy density.
	Lamp on left side.	Lamp on right side.	Mean.	
10.5 cm.	2.4×10^{-3} cm.	2.5×10^{-3} cm.	2.5×10^{-3} cm.	2.6×10^{-3} cm.
11.5 cm.	2.0	2.1	2.0	2.3
12.5 cm.	1.6	1.3	1.5	2.0

Other results obtained with the aluminium strip were similar to those above.

By inclining the tube it was found possible to increase the difference of the thermo-kinetic reactions on the two sides of the strip, but this effect was always comparatively small.

The results are similar to those obtained in the previous research. Moreover the disturbing effects which were then attributed to convection, were really effects of the same kind as those described in this Paper.

Starting at atmospheric pressure, the thermo-kinetic reaction increases as the pressure is diminished, until a maximum is reached at a pressure of about 0.002 cm. of mercury. Experiments on the pressure of light may be advantageously carried out as far below the maximum as possible, or as far above the maximum as convection currents will permit. The latter alternative is the easier, and appears to give more consistent results.

In conclusion, I have pleasure in thanking Prof. Lees for valuable suggestions, and for affording me every facility for prosecuting this research.

ABSTRACT.

The pressure of the radiation emitted by a carbon filament lamp at a distance of a few centimetres, is sufficient to cause a microscopically measurable deflection of the end of a strip of gold or aluminium foil, suspended in a closed test tube. By this means the radiation pressure may be measured, and the results may be checked by a comparison with the energy density of the radiation, as deduced from the initial rate of rise of temperature of an exposed blackened copper plate.

In a previous Paper, experiments were carried out in atmospheres of air and hydrogen, and at pressures extending from 76 cm. to 1 cm. of mercury. Under certain conditions it was found possible to obtain satisfactory results. The present Paper deals with experiments at pressures from 1 cm. of mercury down to the highest exhaustions that could be reached.

As the pressure is lowered, certain gas-action effects make their appearance, but, inasmuch as there is no appreciable difference of temperature on the two sides of the strip, the effects are somewhat different from those that occur in the ordinary type of Crookes' radiometer.

When the surface of the strip is closer to one side of the containing vessel than to the opposite side, a deflection away from the closer side occurs, and the direction of this deflection is independent of the side of the strip on which the radiation falls. With a symmetrically-placed strip the deflection should be negligibly small. An explanation of these effects is suggested in the Paper, and a special type of radiometer is described.

The nature of the residual gas in the tube does not seem to be very important, but it is found that the repulsive force acting on the strip increases with decreasing pressure, until a maximum is reached at about 0.002 cm. of mercury. With further reduction of pressure a progressive decrease takes place.

By symmetrical suspension, and by the use of liquid air and charcoal, it is possible so to reduce the gas action effect that measurements of the pressure of light of reasonable accuracy are again possible.

Experiments on the pressure of light may thus be advantageously carried out at the highest vacua obtainable, or at pressures as far above 0.002 cm. of mercury as convection currents will permit. The latter alternative is the easier, and leads to more consistent results.

DISCUSSION.

Mr. D. OWEN (communicated remarks) thought the author was to be congratulated on his determined attempt to eliminate gas action at the lowest possible vacua. It appeared, from the tables at the end of the Paper, that even at the lowest pressures the deflection of the leaf differed according to the direction of the incident light. Such dissymmetry as is thus implied in the apparatus might also account for the different effects obtained with gold and aluminium. Observations with much larger vessels appeared to be desirable. The optical arrangements might perhaps be modified to avoid the contiguity of the leaf to the microscope objective. Such conditions might also be expected to enhance the undoubted advantage of the author's method, namely, rapid attainment of the final state; in some of Poynting & Barlow's experiments as much as an hour was found necessary. Had the author found it practicable to calculate the gas pressures, at the highest exhaustions, from the damping of the foil?

The AUTHOR, in reply, stated that he was in agreement with Mr. Owen as to the desirability of using larger containing vessels. It was felt, however, that before attempting more accurate measurements, a fuller investigation of the gas action was necessary. Owing to the disturbing effect of incessant tremors it had not yet been found possible to obtain an estimate of the pressures at the highest exhaustions, by observing the degree of damping. A modification of the method of mounting the strips might make such observations possible.