On Attraction and Repulsion accompanying Radiation

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1874 Proc. Phys. Soc. London 1 35

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body thus arranged, and illuminating the crystal on the stage with convergent light by means of a condenser, the rings and brushes could be perfectly seen. The whole double series of rings in a biaxial crystal of carbonate of lead was thus shown.

The condenser used was a "kettle-drum" of two plano-convex lenses. The objective on the nozzle of the microscope was a $\frac{2}{3}$ of Ross; that within the draw-tube a 3-inch objective of the same maker.

June 20, 1874.

X. On Attraction and Repulsion accompanying Radiation.

By WILLIAM CROOKES, F.R.S. &c.

[With a Plate.]

BEFORE describing the apparatus and experiments which illustrate the attraction and repulsion accompanying radiation, it will perhaps be best to draw attention to the modification of the Sprengel pump which has so materially assisted me in this investigation.

Fig. 1 (Plate II.) shows the pump as now in use. Working so much with this instrument, I have endeavoured to avoid the inconveniences attending the usual mode of raising mercury from the lower to the upper reservoir. The mercury is contained in a closed glass reservoir A, perforated with a fine hole at the top. This reservoir is attached to a block capable of free movement in a vertical line and running in grooves, and connected with the lower reservoir by a flexible tube *g*. This tubing is specially made to stand a considerable pressure of mercury. It consists of a double thickness of india-rubber tubing enclosing a canvas tube in the centre, the whole being vulcanized together.

When the whole of the mercury has run through the pump, the reservoir and slide can be lowered by liberating a detent, T, and letting it descend to the block L. H is a glass reservoir which receives the mercury after flowing through the pump. When the reservoir A is emptied and has been lowered to the block L, the mercury from H is admitted into A by opening

the tap I. At *f* is another tap, of platinum, to regulate the flow of mercury through the pump. *c, c, c'* are mercury joints, it being inconvenient to have the apparatus in one piece of tubing, and not always possible to seal the different portions together by fusion. *ee* is a barometer dipping into the same vessel as the gauge-barometer P, the two thus forming a differential system by which the rarity of the atmosphere in the apparatus undergoing exhaustion can be easily estimated. *dd* is a millimetre-scale with pointed end, attached to the gauge and capable of being raised or lowered so as to make the point just touch the surface of the mercury. *b* is a reservoir of strong sulphuric acid, exposing as much surface as possible, but allowing the air to pass across it without resistance. The mercury joint *c'* may either be closed with a piece of glass rod ground in, or it may have either of the two pieces of apparatus *i* and *k* fitted to it. *k* is a mercurial siphon gauge, which is useful for measuring very high rarefactions in experiments where difference of pressure equal to a tenth of a millimetre of mercury is important. *i* is for still higher rarefactions; it is simply a small tube having platinum wires sealed in, and intended to be attached to an induction-coil. At exhaustions beyond the capabilities of the mercurial gauge I can still get valuable indications of the nearness to a perfect vacuum by the resistance of this tube. I have frequently carried exhaustion to such a point that an induction-spark will not strike across the small distance ($\frac{1}{4}$ inch) separating the wires of the vacuum-tube. *h* is the mercury-tap usually employed for letting air into the apparatus, and also for moistening the interior of the pump with oil of vitriol. *l* is a spiral of glass for attaching the various pieces of apparatus requiring exhaustion. As blown or fused joints are indispensable, this form of connecting piece is adopted to ensure the necessary flexibility. *m* is a trap to catch any air which might leak in through the platinum tap *f*, or the various joints in the lower part of the tubing *g*.

The reservoir A being filled with mercury, the tap I is turned off and the reservoir is raised to the top of the slide where it is supported by the detent T. On opening the tap *f* the mercury rises in the tube *fh*, and, falling through the chamber N, carries with it the air contained in the tube R, and in the apparatus attached to the tube *l*, as in the ordinary Sprengel pump. At N

the tubing is enlarged in order that the mercury may not be forced up the tube R, as otherwise frequently happens if the tubes or the mercury gets soiled.

J, J are iron brackets supporting the apparatus. S is a large inverted glass receiver, to collect the small portions of mercury which are unavoidably and constantly being spilled; it should contain a little weak alkaline solution.

The part of the tubing *g, f, h, N* forms a barometric siphon arrangement, which effectually prevents air getting into the pump from the reservoir A when the mercury has completely run out. In this case no harm whatever is done to the operation: the vacuum is not injured; and the exhaustion proceeds immediately on retransferring the mercury from the reservoir H to the reservoir A, and raising A again into its place. The apparatus, as thus arranged, is readily manageable with certainty of obtaining a barometric vacuum.

The mercury fall-tube of a pump in constant use frequently wants cleaning. I find the most effectual means of doing this is to put oil of vitriol into the funnel *h*, and then, by slightly loosening the glass stopper, allow a little of the strong acid to be carried down the tube with the mercury. With care this can be effected without interfering with the progress of exhaustion. The residual acid adhering to the walls of the chamber N does good rather than harm. When sufficient sulphuric acid has run into the fall-tube, the funnel-stopper can be perfectly closed by pressing it in with a slight twist and then filling up with mercury.

Many physicists have worked on the subject of attraction and repulsion by heat. In 1792 the Rev. A. Bennet recorded the fact that a light substance delicately suspended in air was attracted by warm bodies; this he ascribed to air-currents. When, by means of a lens, light was focused on one end of a delicately suspended arm, either in air or in an exhausted receiver, no motion could be perceived distinguishable from the effects of heat. After Mr. Bennet the subject has been more or less noticed by Laplace, Libri, Fresnel, Saigey, Forbes, Baden Powell, and Faye; but the results have been unsatisfactory and contradictory.

My first experiments were performed with apparatus made on the principle of the balance. An exceedingly fine and light arm is delicately suspended in a glass tube by a double-pointed

needle; and at the ends are affixed balls of various materials. Amongst the substances thus experimented on I may mention pith, glass, charcoal, wood, ivory, cork, selenium, platinum, silver, aluminium, magnesium, and various other metals. The beam is usually either of glass or straw.

The apparatus, consisting of a straw beam and pith-ball ends, being fitted up as here shown attached to the pump, and the whole being full of air to begin with, I pass a spirit-lamp across the upper part of the tube just over one of the pith-balls. The ball rises. The same effect is produced when a bulb of hot water or even the warm finger is placed over the pith-ball.

On working the pump and repeating the experiment, the attraction to the hot body gets less and less, until it becomes *nil*, and after a certain barometric pressure is passed, the attraction gives place to repulsion, which gets stronger and stronger as the vacuum approaches perfection.

In order to illustrate more strikingly the influence exerted by a trace of residual air, an apparatus (fig. 2) is here shown in which the source of heat (a platinum spiral, *a*, rendered incandescent by electricity) is inside the glass tube instead of outside it as before. A mass of magnesium, *b*, turned conical, is suspended in a glass tube, *cde*, by a fine platinum wire of such a length as to vibrate seconds. The upper end of the platinum wire is sealed into the glass at *e*, and passes through to the outside for the purpose of electrical experiments. The platinum spiral is arranged so that when the pendulum hangs free the magnesium mass is about $\frac{1}{4}$ inch from it. In air the red-hot spiral produces decided attraction on the magnesium; and by properly timing the contacts with the battery, a considerable swing can be accumulated. On perfectly exhausting the apparatus, however, the incandescent spiral is found to energetically repel, and a very few contacts and breaks properly timed are sufficient to get up the full swing the pendulum is capable of.

A simpler form of the apparatus for exhibiting the phenomena of attraction in air and repulsion in a vacuum consists of a long glass tube *ab* (fig. 3) with a globe *c* at one end. A light index of glass with pith-balls at the ends *d, e* is suspended in this globe by means of a cocoon fibre. When the apparatus is full of air at ordinary pressure, a ray of heat or light falling on one of the pith-balls gives a movement indicating attraction.

When the apparatus is exhausted until the barometric gauge shows a depression of 12 millims. below the barometer, neither attraction nor repulsion results when radiant light or heat falls on the pith. When the vacuum is as good as the pump will produce, strong repulsion is shown when radiation is allowed to fall on one end of the index. The heat of the hand, or even of the body several feet off, is quite sufficient. The action is in proportion to the surface acted on rather than to the mass.

The barometric position of the neutral point dividing attraction from repulsion varies with the density of the mass on which radiation falls, on the ratio of its mass to its surface, and in a less degree on the intensity of radiation. In the case of pith it is seen to lie at about 12 millims. below a barometric vacuum, whilst with a heavy metal it is within a tenth of a millim. of a vacuum. Experiments to try to determine the law governing the position of the neutral point are now in progress.

Ice, or a cold substance, produces the opposite effects to heat. Thus a bar of pith suspended in a vacuum is energetically repelled by the warm hand, whilst it is as strongly attracted by a piece of ice. Cold being simply negative heat, it is not easy at first sight to understand how it can produce attraction. The law of exchanges, however, explains this perfectly. The pith index and the whole of the surrounding bodies are incessantly exchanging heat-rays; and under ordinary circumstances the income and expenditure of heat are in equilibrium. A piece of ice brought near one end of the index cuts off the influx of heat to it from that side, and therefore allows an excess of heat to fall upon it from the opposite side. Attraction by a cold body is thus seen to be only repulsion by the radiation from the opposite side of the room.

Instruments of the kind just described are perhaps the best for exhibiting large and striking movements of attraction or repulsion. Two glass globes 4 inches in diameter, fitted up with bars of pith $3\frac{1}{2} \times \frac{1}{2}$ inch, are now before you. One is full of air at ordinary pressure, whilst the other is completely exhausted. A touch with a finger on a part of the globe near one extremity of the pith will drive the bar round over 90° , in the vacuum. In air the attraction is not quite so strong.

If I place a lighted candle an inch or two from the vacuous globe, the pith bar commences to oscillate. The swing gradu-

ally increases in amplitude until one or two complete revolutions are made. The torsion of the suspending fibre here interferes, and the vibrations proceed in the opposite direction. The movement continues as long as the candle burns. This continued movement ceases if the source of radiation is removed some distance off; the pith index then sets equatorially. The cause of the continued vibration when the radiant body is at a particular distance from the pith is easy to understand on the supposition that the movement is due to the direct impact of waves on the suspended body.

For more accurate experiments I prefer making the apparatus differently. Fig. 4 represents the best form. ab is a glass tube, to which is fused at right angles another, narrower tube, cd ; the vertical tube is slightly contracted at e so as to prevent the solid stopper d , which just fits the bore of the tube, from falling down. The lower end of the stopper de is drawn out to a point; and to this is cemented a fine glass thread about 0.001 inch diameter, or less, according to the torsion required.

At the lower end of the glass thread an aluminium stirrup and a concave glass mirror are cemented, the stirrup being so arranged that it will hold a beam fg having masses of any desired material at the extremities. At c in the horizontal tube is a plate-glass window cemented on to the tube. At b is also a piece of plate glass cemented on. Exhaustion is effected through a branch tube h projecting from the side of the upright tube. This is sealed by fusion to the spiral tube of the pump. The stopper de , and the glass plates c and b , are well fastened with a cement of resin 8 parts and bee's-wax 3 parts*.

* This is the best cement I have used for standing a vacuum: for a few hours it is perfect. But at the highest exhaustions it seems to leak in the course of a day or two. India-rubber joints are of no use in these experiments, as, when the vacuum is near upon perfect, they allow oxygenized air to pass through as readily as the pump will remove it. Whenever possible the glass tubes should be united by fusion; and where this is impracticable mercury joints should be used. The best way to make these is to have a well-made perforated conical stopper, cut from plain india-rubber, fitting into the wide funnel-tube of the joint and carrying the narrow tube. Before fitting the tubes in the india-rubber this is heated in a spirit-lamp until its surface is decomposed and very sticky; it is then fitted into its place; mercury is poured over, and oil of vitriol on the top of that. When well made, this joint seems perfect.

The advantage of a glass-thread suspension is that the beam always comes back to its original position. Before you is an instrument of this description, perfectly exhausted and fitted up with pith plates at each extremity. A ray of light from the electric lamp is thrown on to the mirror *c*, and thence reflected on to the opposite wall. The approach of a finger to either extremity of the beam causes the luminous index to travel several feet, showing repulsion. A piece of ice brought near causes the spot of light to travel as much in the opposite direction.

Here is another form of the apparatus (fig. 5). The letters and description are the same as in fig. 4, the apparatus, however, being double. The pieces *f*, *g* on the end of one beam consist of platinum-foil exposing a square centimetre of surface, whilst the extremities *f'*, *g'* on the other beam consist of pith plates of the same size. It has already been explained that the neutral point of rarefaction for platinum is much higher than for pith; consequently at a pressure intermediate between these two neutral points, radiation ought to cause the platinum to be attracted and the pith to be repelled. This is seen to be the case. A wide beam of radiant heat thrown in the centre of the tube on to the plates *g*, *g'* causes *g* to be attracted and *f'* to be repelled, as shown by the light reflected from the mirrors *c*, *c'*. The atmospheric pressure in the apparatus is equal to about 40 millims. of mercury.

The position of the neutral point not only depends on the density of the body acted on by radiation, as in the above case, but also on the relation of surface to mass. Thus a square centimetre of thin platinum-foil on the extremity of the beam requires a lower exhaustion for neutrality than a thicker piece exposing the same surface. Also a flat disk of platinum has a lower neutral point than the same weight of platinum in the form of a sphere.

Intensity of radiation likewise affects the neutral point. With pith extremities a point of rarefaction can be obtained at which the warm fingers repel and incandescent platinum attracts.

During the course of this lecture I have spoken frequently of repulsion by *heat*, and have used a spirit-lamp as a source of heat to illustrate the facts described. I now wish to show that these results are not confined to the heating rays of the spectrum, but that any ray, from the ultra-red to the ultra-violet, will produce repulsion in a vacuum.

In my own laboratory I have used sunlight, and have experimented with a very pure spectrum, taking precautions to avoid any overlapping or diffusion of one part of the spectrum with another. Here I can only use the electric light, and, in order to get results visible at a distance, the spectrum cannot be very long.

The spectrum is formed with one disulphide-of-carbon prism, and is projected on to the screen by a lens. Immediately behind the screen is an exhausted bulb, having a movable index with pith terminals suspended with a cocoon fibre (fig. 3). This is delicate enough to swing over 90° with a touch of the finger, and it will even move under the influence of a ray of moonlight. I first of all arrange the spectrum so that the extreme red would fall on one pith disk were it not for the screen. On removing the screen the index immediately retreats, making nearly half a revolution.

I now replace the screen, and arrange the spectrum so that the invisible ultra-violet rays are in a position to fall on the pith disk. On removing the screen the index at once behaves as it did under the influence of the red rays, and is driven away twenty or thirty degrees. The action is not so powerful as when the other end of the spectrum is used; but this may partly, if not wholly, be accounted for by the much greater concentration of energy at the red end of the spectrum, and expansion at the violet end, when using glass or disulphide-of-carbon prisms.

I now, without disturbing the position of the spectrum, interpose in the path of the rays a cell containing a solution of iodine in disulphide of carbon, which is opaque to the luminous and ultra-violet rays, but transparent to the invisible heat-rays. Not a trace of repulsion is produced. The iodine solution is now removed and the ultra-violet rays again fall on the pith, producing strong repulsion. A thick screen of clear alum cut from one of Mr. Spence's gigantic crystals is now interposed; but no effect whatever is produced by it, the ultra-violet rays acting with unabated energy. As alum cuts off all the dark heat-rays, this experiment and the one before it prove the sufficient purity of my spectrum.

The spectrum is again turned until the dark ultra-red heating rays fall on the pith. The movement of repulsion is energetic. The iodine solution, interposed, cuts off apparently none of the

action. The alum plate cuts off a considerable amount, but by no means all. On uniting the alum and the iodine solution the whole of the spectrum is obliterated, and no action is produced, whatever be the ray which would, were it not for this double sifting, fall on the pith.

Throughout the course of these investigations, which have occupied much of my spare time for some years, I have endeavoured to keep in my mind the possible explanations which may be given of the actions observed; and I have always tried, by selecting some circumstances and excluding others, to put each hypothesis to the test of experiment.

The most obvious explanation is, that the movements are due to the currents formed in the residual gas which theoretically must be present to some extent even in those vacua which are most nearly absolute.

Another explanation is, that the movements are due to electricity developed on the moving body or on the glass apparatus by the incident radiation.

A third explanation has been put forward by Professor Osborne Reynolds, in a paper which was read before the Royal Society on June 18th last. He considers the results to be due to evaporation and condensation.

I will discuss these explanations in order.

First, the air-current theory. However strong may be the reasons in favour of this explanation, they are, I think, answered irrefragably by the phenomena themselves. It is most difficult to believe that the residual air in a Sprengel vacuum, when the gauge and barometer are level, can exert, when gently warmed by the finger, an upward force capable of instantly overcoming the inertia of a mass of matter weighing 20 or 30 grains. It must be remembered that the upward current supposed to do this is simply due to the diminished weight of a portion of the gas caused by its increase in volume by the heat applied.

An air-current produced by heat may possibly cause the beam of a balance to rise, may drive a suspended index sideways, and by a liberal assumption of eddies and reflections, may perhaps be imagined to cause these movements to take place sometimes in the opposite directions; but as rarefaction proceeds these actions must certainly get less, and they will

cease to be appreciable some time before a vacuum is attained : a point of no action or neutrality will be reached. But this neutral point should certainly be nearer to a vacuum when a light body like pith, exposing much surface, is under experiment, than when the mass acted on is heavy like brass ; whereas in practice the contrary obtains. Pith ceases to move under the influence of radiation at a rarefaction of about 7 to 12 millims., whilst brass only ceases to be affected when the gauge and barometer are appreciably level.

But even could the phenomena up to the neutral point be explained by air-currents, these are manifestly powerless to act after this critical point is passed. If a current of air within 7 millims. of a vacuum cannot move a piece of pith, certainly the residual air in a Sprengel vacuum should not have more power ; and *à fortiori* the residual gas in a perfect chemical vacuum cannot possibly move a mass of platinum.

It is, however, abundantly demonstrated that, in all cases after this critical point is reached, the repulsion by radiation is most apparent ; it increases in energy as the vacuum approaches perfection, and attains its maximum when there is no air whatever present, or at all events not sufficient to permit the passage of an induction-spark.

I will now refer to the electrical explanation. Very early in my investigation, phenomena were noticed which caused me to think that electricity played a chief part in causing the movements. When a hot glass rod is held motionless against the side of an exhausted tube containing a pith index, repulsion takes place in a perfectly regular manner ; but if the glass rod has been passed once or twice through the fingers, or is rubbed a few times sideways against the exhausted bulb, the index immediately moves about in a very irregular manner, sometimes being repelled from, and at others attracted to, the side of the glass, where it adheres until the electrical excitement subsides. Friction with the finger produces the same results ; and a small spirit-flame causes similar, but much fainter, electrical effects. I soon ascertained, however, that, although electricity is capable of producing many movements similar to those caused by radiation, they are never so alike as to be mistaken. Electricity frequently interferes with, disturbs, or neutralizes the true action of radiation ; but it acts in such a manner as to show that it is not

the primary cause of the movement. At the highest rarefactions, and when special precautions have been taken to avoid the presence of aqueous vapour, slight friction with the finger against the bulb, or a touch with the flame of a spirit-lamp, excites so much electrical disturbance in the pith and other indexes that accurate observations become impossible with them for several hours. I have tried many means of neutralizing the electrical disturbance ; but they are only partially successful, and at the highest rarefactions interference through electrification is very troublesome.

I may draw attention to the following experiments, which are devised with the object of showing that the attractions and repulsions are not due to electricity.

In describing the pendulum apparatus (fig. 2) which I set in motion at the early part of this lecture, I explained that the mass of magnesium forming the weight was in metallic contact with the platinum wire which supported it, and that the upper end of this platinum wire was fused into the glass tube and passed through to the outside. With this apparatus I have tried a great number of experiments. I have connected the projecting end of the platinum wire with "earth," with either pole of an induction-coil the other being insulated more or less, with either pole of a voltaic battery, with a delicate electroscope ; I have charged it with an electrophorus, and have submitted it to the most varied electrical conditions ; and still, on allowing radiation to fall upon the suspended mass, I invariably obtain attraction when air is present, and repulsion in a vacuum. The heat has been applied both from the outside, so as to pass through the glass, and also inside by means of the ignited platinum wire ; and the results have shown no difference in kind, but only in degree, under electrical excitement. I have obtained interference with the usual phenomena, but never of such a character as would lead me to imagine that the normal results were due to electricity.

It occurred to me that the repulsion might be due to a development of electricity on the inner surface of the glass bulb or tube under the influence of the radiation as it passed from the glass into the vacuum. This appears to be disproved by the fact that the results are exactly the same whether the radiation passes through the glass, or whether it is developed inside the apparatus as in the above instance.

I have produced exactly the same phenomena whether the exhausted apparatus has been standing insulated in the air, or whether it was completely immersed in water connected electrically with "earth," or surrounded with wet blotting-paper.

Here are two experiments which bear on this subject. A straw beam furnished with brass balls at each end is suspended on a double-pointed needle, and the brass balls and needle are placed in metallic connexion by means of fine platinum wire. The needle does not rest on the sides of the glass tube, but in steel cups, to which is soldered a platinum wire passing through the glass tube and connected with "earth." The tube is then exhausted, and the usual experiments are tried with hot and cold bodies, both with and without a wet blotting-paper cover. In all cases the moving beam behaves normally, being repelled by heat and attracted by cold.

An apparatus is prepared similar to that shown in fig. 4. The inside of the tube ab is lined with a cylinder of copper gauze, having holes cut in the centre for the passage of the supporting thread dc and the index ray of light falling on the mirror c , and holes at each end to admit of the plates f and g being experimented with. A wire attached to the copper gauze passes through a hole in the plate b , so as to give me electrical access to the copper gauze lining. Under the most diverse electrical conditions, whether insulated or connected with "earth," this apparatus behaves normally when exhausted.

A further reason why electricity is not the cause of the movements I have described is, that they are not only produced by heat, but also by ice and cold bodies. Moreover I shall presently show that any ray of the spectrum, besides those red and ultra-red rays which produce dilatation of mercury in a thermometer, excite an electric current between antimony and bismuth couples, and cause a sensation of warmth when falling on the skin, will produce the effect of repulsion in a vacuum. It is therefore to my mind abundantly proved that electricity, such as we at present know this force, is not a chief agent in these attractions and repulsions, however much it may sometimes interfere with and complicate the phenomena.

I will now discuss Professor Osborne Reynolds's theory, that the effects are the results of evaporation and condensation. In my exhausted tubes he assumes the presence of aqueous

vapour, and then argues as follows:—"When the radiated heat from the lamp falls on the pith, its temperature will rise, and any moisture on it will begin to evaporate and to drive the pith from the lamp. The evaporation will be greatest on that ball which is nearest to the lamp; therefore this ball will be driven away until the force on the other becomes equal, after which the balls will come to rest, unless momentum carries them further. On the other hand, when a piece of ice is brought near, the temperature of the pith will be reduced, and it will condense the vapour and be drawn towards the ice."

Professor Reynolds has tried an experiment with pith-balls attached to a light stem of glass and suspended by a silk thread in a glass flask. The exhaustion was obtained by boiling water in the flask and then corking it up and allowing it to cool. The gauge showed an exhaustion of from $\frac{1}{2}$ to $\frac{3}{4}$ of an inch. The pith-balls behaved exactly as I have already shown they do at that degree of exhaustion, heat repelling and ice attracting. He found that the neutral point varied according to whether air was present with the aqueous vapour, or whether the vapour was pure water-gas. Professor Reynolds states:—"From these last two facts it appears as though a certain amount of moisture on the balls was necessary to render them sensitive to the heat. . . . These experiments appear to show that evaporation from a surface is attended with a force tending to drive the surface back, and condensation with a force tending to draw the surface forward."

It does not appear that Professor Reynolds has tried more than a few experiments; and he admits that they were in reality undertaken to verify the explanation above quoted. I have worked experimentally on this subject for some years; and the last experiment recorded in my notebook is numbered 584. From the abundant data at my disposal, I can find many facts which will, I think, convince you that this hypothesis has been arrived at on insufficient evidence.

In the first place, I will show that the presence of moisture or of a condensable vapour is not necessary. Besides pith, which from its texture and lightness might be supposed to absorb and condense considerable quantities of vapour, I have used glass, mica, and various metals; and with a proper amount of exhaustion they all act in the same manner. The fact that the neutral point for platinum is close upon a vacuum, whilst that for pith

is so much lower, tends to show that the repulsion is not due to any recoil caused by condensable vapour leaving the surface under the influence of heat. Were it so, it would certainly require more vapour to be present when platinum had to be driven backwards than when pith had to be moved; but the contrary obtains in all cases. The rule seems to be, the greater the density the higher the neutral point.

I have worked with all kinds of vacua; that is to say, I have started with the apparatus filled with various vapours and gases (air, carbonic acid, water, iodine, hydrogen, &c.); and at the proper rarefaction I find no difference in the results which can be traced to the residual vapour. A hydrogen vacuum seems neither more nor less favourable to the phenomena than does a water vacuum, or an iodine vacuum.

If moisture be present to begin with, I find it necessary to allow the vapour to be absorbed by the sulphuric acid of the pump, and to continue the exhaustion, with repeated heating of the apparatus, until the aqueous vapour is removed. Then and then only do I get the best results.

When pith is employed as the index, it is necessary to have it thoroughly dried over sulphuric acid before using it, and during the exhaustion to keep it constantly heated to a little below its charring-point, in order to get the greatest sensitiveness.

Professor Reynolds says, "In order that these results might be obtained, it was necessary that the vapour should be free from air." On the contrary, I find the results take place with the greatest sharpness and rapidity if the residual gas consists of nothing but air or hydrogen.

Professor Reynolds further says, "Mr. Crookes only obtained his results when his vacuum was nearly as perfect as the Sprengel pump would make it. Up to this point he had nothing but the inverse effects, viz. attraction with heat and repulsion with cold." In the abstract of my paper published in the Proceedings of the Royal Society, I describe an experiment with a pith-ball apparatus in which the neutral point is 7 millims. (about $\frac{1}{4}$ inch) below the vacuum, repulsion by heat taking place at higher exhaustions. At the Royal Society *Soirée*, April 22, 1874, I showed, and fully described in print, the apparatus now before you, consisting of a pith bar suspended by a cocoon fibre in a glass bulb, from which the air is exhausted until the baro-

metric gauge shows a depression of 12 millims. below the barometer. Neither attraction nor repulsion results when radiant light or heat falls on the pith. Exhaustions of 7 and 12 millims. are certainly very inferior vacua for a Sprengel pump.

As a matter of fact, however, I have obtained repulsion by radiation at far higher pressures than these. The true effect of radiation appears to be one of repulsion at any pressure, overbalanced when a gas is present by some cause—possibly air-currents, but probably not. I have already explained that the barometric height of this neutral point dividing attraction from repulsion varies with the density of the substance on which radiation falls, on the relation which the mass bears to the surface, and on the intensity of radiation. By modifying the conditions it is not difficult to get repulsion by radiation when the apparatus is full of air at nearly the normal pressure of the atmosphere.

Professor Reynolds again says, "The reason why Mr. Crookes did not obtain the same results with a less perfect vacuum was because he had then too large a proportion of air, or non-condensing gas, mixed with the vapour." On this I may remark that the writer, before he explained how it was I could *not* get certain results, should have made sure that what he assumed to be the case was really so. I have not the least difficulty in showing repulsion by heat in imperfect vacua when mixed vapours and gases are present.

In my arguments against the air-current theory, I have shown that the best results are obtained when the vacuum is so nearly perfect that an induction-spark will not pass through it. This is an equally good argument against the presence of a condensable vapour as it is against that of air.

From the construction of my Sprengel pump I am satisfied that the vapour of mercury is absent from the apparatus.

The following experiments have been specially tried with the object of testing this theory. A tolerably thick and strong bulb is blown at the end of a piece of combustion-tubing; and in it is supported a bar of aluminium at the end of a long platinum wire. The whole is attached to the Sprengel pump, and exhaustion is kept going on for about two days, until a spark will not pass through the vacuum. During this time the bulb and its contents are frequently raised to an incipient red heat. At

the end of that time the tube is sealed off, and the bar of aluminium is found to behave exactly as it would in a less perfectly exhausted apparatus; viz. it is repelled by heat. A similar experiment, attended with similar results, has been tried with a glass index. It is impossible to conceive that in these experiments sufficient condensable gas was present to produce the effects Professor Reynolds ascribes to it. After the repeated heatings to redness at the highest attainable exhaustion (the gauge and the barometer being level for nearly the whole of the 48 hours), it is impossible that sufficient vapour or gas should condense on the movable index to be instantly driven off, by the warmth of the finger, with recoil enough to drive backwards a heavy piece of metal.

My own impression is that the repulsion accompanying radiation is directly due to the impact of the waves upon the surface of the moving mass, and not secondarily through the intervention of air-currents, electricity, or evaporation and condensation. Whether the ætherial waves actually strike the substance moved, or whether at that mysterious boundary-surface separating solid from gaseous matter there are intermediary layers of condensed gas which, taking up the blow, pass it on to the layer beneath, are problems the solution of which must be left to further research.

In giving what I conceive to be reasonable arguments against the three theories which have been supposed to explain these repulsions, I do not wish to insist upon any theory of my own to take their place. The one I advance is to my mind the most reasonable, and as such is useful as a working hypothesis, if the mind must have a theory to rest upon. *Any* theory will account for *some* facts; but only the true explanation will satisfy *all* the conditions of the problem, and this cannot be said of either of the theories I have already discussed.

My object at present is to ascertain facts, varying the conditions of each experiment so as to find out what are the necessary and what the accidental accompaniments of the phenomena. By working steadily in this manner, letting each group of experiments point out the direction for the next group, and following up as closely as possible, not only the main line of research, but also the little bylanes which often lead to the most valuable results, after a time the facts will group themselves together

and tell their own tale. The conditions under which the phenomena invariably occur will give the laws; and the theory will follow without much difficulty. To use the eloquent language of Sir Humphry Davy, "When I consider the variety of theories which may be formed on the slender foundation of one or two facts, I am convinced that it is the business of the true philosopher to avoid them all together. It is more laborious to accumulate facts than to reason concerning them; but one good experiment is of more value than the ingenuity of a brain like Newton's."

XI. *Modification of the usual Trombone Apparatus for showing the Interference of Sound-bearing Waves.* By W. F. BARRETT, F.R.S.E. &c., Professor of Physics in the Royal College of Science, Dublin.

A SIMPLE apparatus for showing the interference of sound-bearing waves may be made by employing a circular arrangement of tubes, one sliding within the other. One tube, A, to which the mouthpiece M is fixed, is three fourths of a circle; the other tube, B, to which the nozzle N is attached, is half a circle, and of such diameter that it slides freely over the tube A.

When the nozzle is diametrically opposite the mouthpiece, the path of the sound-waves is of equal length, and hence the sound from any convenient source placed near to or within the mouthpiece is distinctly heard. By turning the nozzle towards N', in the direction shown by the dotted lines, one limb of the tube is lengthened whilst the other is correspondingly shortened; the path of the waves being now unequal, a point is soon reached where the sound is nearly obliterated.

Employing a suitable source of sound, and a sensitive flame or a resonant jar as a phonoscope, an audience can perceive at