V. On the measurement of electromagnetic radiation

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such a length of time that we thought it would be interesting to analyse the resulting substance.

The residue from the action of the pure acid on the lead consisted of 82 per cent. of sulphate of lead and 18 per cent. of metallic lead, while that from the action of acid mixed with sulphate of soda consisted of 89 per cent. of lead sulphate and 11 per cent. of metallic lead.

Although the action of the acid on the lead was initially diminished by the presence of sodium sulphate, the final result in this instance was rather the other way. No doubt the whole of the spongy lead would have been converted into sulphate if it had not been for the large amount of insoluble salt which protected the remaining particles.

This result throws light on the reason why a lead plate deteriorates during a long rest.

V. *On the Measurement of Electromagnetic Radiation.* By C. V. BOYS, A.R.S.M., F.R.S., Assistant Professor of Physics at the Royal College of Science, London, A. E. BRISCOE, A.R.C.S., and W. WATSON, A.R.C.S., B.Sc.*

[Plate V.]

AT the time that Mr. Gregory described and exhibited his "Electric Radiation Meter"†, which indicated and measured electromagnetic radiation by the increase in length of a fine platinum wire stretched in a glass tube in consequence of the heat developed by the induced currents within it, one of us expressed the view that it would be interesting to confirm by some independent method the conclusion that the wire was lengthened by heat, as it was not absolutely certain, though exceedingly probable, that the increase in length might not be apparent only and not real.

The following is an account of experiments made by two independent methods, with the view of finding whether the expansion observed by Mr. Gregory was such as might be expected from the induced currents.

First Method.

Imagine two straight wires parallel and near together, but not touching one another or any conductor. Let them be placed parallel to and at a convenient distance from a cylindrical rod of the same length as either of the wires. Then, if electrical oscillations are started in this rod by any well-

* Communicated by the Physical Society; read June 20, 1890.

† Phil. Mag. Jan. 1890.

known method, the two wires will act as resonators, and induced oscillations will occur in them, not necessarily in absolutely the opposite phase to the oscillations in the primary, but at any rate in the same phase in the two wires, so that the electricity in each will surge up and down at the same time. If, then, the ordinary theories of electrodynamic and electrostatic action apply in the present case, which may be true or may not, then the currents going up together and down together will attract one another, while the charges resting chiefly at the two ends, being at one moment + above and - below, and at the next moment reversed, will repel one another. Owing to the harmonic distributions of the current and the charges, the electrodynamic attraction will be mainly in the middle parts, while the electrostatic repulsion will be mainly at the two ends. Further, both these distributions vary harmonically with the time, and are a quarter-period removed from one another; but the integral effect of each is equivalent to a steady force, and the quarter-period difference of phase has no influence as far as forces are concerned.

In order to realize what these forces are, and what are the relations between them, it will be necessary to consider them separately.

(1) *Electrodynamic Attraction*.—Let the wires be supposed to be very close together, so that the force felt by any element is almost entirely due to those elements of the other wire which are so close to it that the variation of the current strength in those elements along the wire is inconsiderable. Now, if the distance apart is d , if c is the strength of the current at any moment (measured electrodynamically), and if l is the length of the element, the force exerted by the other wire on this element will be $2 \frac{c^2 l}{d}$ dynes. But as the current at any point varies harmonically with the time, the average force will be necessarily half the maximum force; therefore the average force on the centre elements will be $\frac{c^2 l}{d}$, if c is the maximum current at the centre.

Since, also, the current varies harmonically along the wire, the average force per unit length over the whole wire will be half that at the centre; so that the attraction between the wires will be $\frac{c^2 L}{2d}$, where L is the whole length of the wire.

(2) *Electrostatic Repulsion*.—In the same way, if q is the quantity of electricity (measured electrostatically) on

unit length at any part of the wire, the force of repulsion upon an element at any moment will be $2 \frac{q^2 l}{d}$, the average force on this element will be $\frac{q^2 l}{d}$, and the total repulsion between the wires will be $\frac{q^2 L}{2d}$.

Now to find the relation between these it is necessary to remember that the wires are resonators; that is, the oscillations follow the natural period and are not forced. Also that the total quantity of electricity on one half of the wire is the integral of the current that has passed the middle point. Although there is no difficulty in finding the relation between the attraction and repulsion, the following graphic method may be worth giving. In order to simplify matters, the resonator will at first be supposed of such a length that the oscillations occur at the rate of one a second, *i. e.* it will be supposed to be $\frac{1}{2}$ of 3×10^{10} centim. long; also the maximum current at the centre will be supposed unity. Now let the vertical line in C (fig. 1) represent the wire, and the distance of the harmonic curve from it at any point the strength of the current at that point when it is at a maximum.

Fig. 1.

In the same way, let the distance of the harmonic curve in Q from the wire at any point represent the charge at that point a quarter-period later, at which time it is at a maximum; then the total quantity on one end, represented by the shaded area, is the integral of the current which has passed the middle point *p*. Now this current varies harmonically with the time, as shown in the time-diagram T. This is divided into four equal parts. Thus the first represents (say) an upward current rising from zero to its maximum; this just neutralizes the previously charged wire. Then, in the second period, the continuation of the current produces an equal and opposite charge, which is a maximum when the current has become zero. In the third period, the current in the opposite

direction has again neutralized the charges by the time that it is a maximum ; and in the fourth period, it charges the upper end negatively and has ceased to flow when the negative charge is a maximum.

Now divide the second period of the time-diagram of current, T , into n ($=\frac{1}{4}$ of 3×10^{10}) elements, and the upper half of the wire in the quantity-diagram, Q , into the same number of equal parts, which will therefore each be one centimetre long. Now, since the total quantity of electricity represented by the shaded part in Q is equal to the time-integral of the current which is represented by the shaded part in diagram T ; and since also each of these is bounded by a quarter-period of a sine curve, and is divided into an equal number of elements, it is clear that each space-element in Q , 1, 2, 3, . . . n , must equal the corresponding time-element in T ; or, in words, though the quantity of electricity that has passed the point p in the first element of time is spread over the upper half of the wire in Q , and so on, yet at the n th element we may consider that that which passed during the first element of time is stored on the element 1, that which passed during the second element of time is stored on the element 2, and so on. Now, since the current-strength in the first element of time is 1, and since this element of time has been made equal to $1/(\frac{1}{3} \times 10^{10})$ second, the quantity of electricity on the end centimetre of wire is $1/(\frac{1}{3} \times 10^{10})$ electrodynamic unit, or 1 electrostatic unit. This will be repelled by the wire opposite with the same force as that with which the current in the centre element of one wire will be attracted by that in the other wire, both when each is at a maximum and through all the harmonic variations. In the same way, the next element near the end in Q will correspond to the next element near the middle in C , and so on over the whole length of each ; and so, since the electrodynamic attraction over every element in time and space is equal to the electrostatic repulsion in the corresponding element, removed both in time and space by a quarter period, the total force due to one is equal to the total force due to the other. If any other length of wire is taken, and of course its corresponding period, since the number or length of the elements in both T and Q must vary together, the same result will follow ; and if any other strength of maximum current is taken, the attractions and repulsions will be changed to an equal extent, and therefore, if two straight wires are placed so close together that the distance between them is very small compared to their length, they will, when their natural electrical oscillations are induced in them, on the whole neither attract nor repel one another.

It follows from this that, if the oscillations be forced and made too slow, the accumulation of charge on the ends will be greater for a given maximum current than it would be if the period were natural, and therefore the repulsion should overpower the attraction. In the same way, with too rapid vibrations the attraction should overbalance the repulsion. Also since, if the wires are not close together, the electrostatic repulsion will have fallen away in a higher ratio than the electrodynamic attraction, it would appear that resonators which balance when close should attract one another when at a distance, or that resonators subject to forced oscillations which repel when near might attract when at a distance.

Prof. Fitzgerald, when the above theory of the mutual action of resonators was put to him, at once suggested that if the molecules of a body were subject to electrical oscillations it would be possible to imagine a physical cause for their supposed attraction when far, and repulsion when close.

In order to test the matter experimentally, the wires were made of a cranked form, as shown in fig. 2, so that the ends were on one side of a vertical axis (dotted), and the middle part on the other side. Then, if one is held close to the other, and if the second one is free to turn about the vertical axis, the attraction of the centre and the repulsion of the ends should conspire to produce rotation in the same direction*.

The first experiment was made with a pair of copper wires each one foot long, bent so that the end parts were each $2\frac{1}{2}$ inches, the middle part 5 inches, and the horizontal part 1 inch. This was suspended in a glass jar by a quartz fibre, so that the vertical axis of rotation was halfway between the ends and the middle portion. An ordinary galvanometer-

Fig. 2.
 $\frac{1}{4}$ full size.

* It may be worth mentioning that the invention of this method was made in a particularly vivid dream, in which I found myself at the black-board in the physical lecture-room, explaining that if the two wires were close together, the currents in each would be going up and down together, and so would attract one another, and that in order to make this attraction evident, the wire should be suspended near the axis of rotation, for the reason that where quartz-fibres can be employed there is a greater gain owing to the reduction of moment of inertia than loss by reduction of statical moment. I did not in the dream see that the charges should repel, or the necessity for the cranked form of wire. I may say that this was after Mr. Gregory had described his instrument, but the idea of looking for mutual attraction between a pair of resonators had not before occurred to me.—C. V. B.

mirror was attached to the rigid glass hook from which the wire was suspended, and this could be seen through a plate-glass window in a torsion-box above the jar. The oscillator consisted of two pieces of brass tube half an inch in diameter with hemispherical ends, each 6 inches long in all. This was placed in a vertical position two or three feet away from the wires, and in the plane of the suspended wire, so that it should not act directly upon it. The two parts of the oscillator were connected by very fine wires with the terminals of a Voss machine. Then it was found that when the halves of the oscillator were separated too far for a spark to pass, there was no deflexion, while when they were gradually made to approach one another, no motion was visible on the scale until sparks passed, and then the motion was evident enough, the light even going in favourable cases off the scale in the right direction.

However, this was only a preliminary experiment made with materials at hand. It was clear that the material which was most suitable was that which had the highest conductivity for its density, namely, aluminium, and that only the outer surface of the wire could be efficacious, since the oscillations were at the rate of about 500,000,000 a second. Accordingly, thick aluminium wire was rolled into thin ribbon, which was then drawn through successive holes in a draw-plate until a perfect tube, cracked down one side of course, was formed.

We used resonators made of this material in the next experiments, which were made with the view of seeing whether the couple observed was due equally to the repulsion of the ends and attraction of the centre, or if one preponderated over the other. The fixed cranked resonator was then replaced by a straight one, which was held at first close and opposite to the ends of the suspended cranked resonator, when a strong repulsion was observed, as expected. It was then held in the corresponding position opposite the centre part, when, instead of the expected attraction, feeble repulsion was observed; and finally, on being placed equidistant from the two, the ends were repelled away.

Since this appeared to show that the electrostatic repulsion was much greater than the electrodynamic attraction, we tried the following experiment, in which the electrostatic action was reduced to practically nothing. A pair of resonators were made of the form shown in fig. 3, and one was weighted with a non-conductor and sus-

Fig. 3.

pended so that the straight part was in the axis of rotation. The other was then held with the curl close and parallel to the curl of the other, and so that at first the current in each should go round the same way, and then in opposite ways. No action was observed in either case. When also cranked or straight resonators were entirely immersed in water, no effect at all was observed.

We have given a short account of the early experiments because at first they were so completely in accord with the result of the theory put forward, though the action was more powerful than had been expected, that for a time we were deceived as to the real cause, and we wish to guard others from falling into what is after all a very obvious error. The later experiments showed either that the theory was only true as regards electrostatical repulsion, the electrodynamic attraction of the momentary currents being *nil*, or else that the results already obtained were spurious.

We have stated that the two resonators were suspended in a glass jar, outside which the primary oscillator was placed, and that while no repulsion was observed during the gradual charging of the oscillator-ends to a higher potential than that employed with the sparks, yet the moment the sparks passed when the ends were nearer together, the suspended resonator was observed to move in the expected direction. Now if the glass jar were a conductor, the oscillator-ends might be charged to any extent and no action would be felt inside; if, on the other hand, it were a perfect insulator, then during the charging of the oscillator-ends before the spark the resonators would have induced charges in their ends which would make them repel one another. The glass jar exposed to the moisture of the air was a sufficiently good conductor, on its outer surface at any rate, to be able to screen the statical action of the charges on the oscillator-ends which were by the arrangement only slowly made to vary, and so the repulsion which might have been looked for was not observed; but the moment a spark passed in the primary, the conditions were changed. The fall of potential was instantaneous, but the screening charge on the glass surface, which the previous moment produced within the jar an effect equal and opposite to that of the charges on the oscillator-ends, was unable instantly to disappear owing to the imperfectly conducting surface of the damp glass, and thus at this moment the resonators were in the condition that they would have been in had there been suddenly developed on the oscillator-ends equal and opposite charges, but with no glass jar between. This then was the cause of the repulsive impulse which was observed at each spark when they followed one another at

intervals. When, however, a torrent of sparks was produced, the glass surface would take up a screening charge equivalent to the mean charge on the oscillator-ends; then, when the oscillator-ends had charges either above or below the mean charge, the statical action on the resonators would be the same as that due to the excess or defect on the oscillator, so that the steady repulsion observed was due to induction alone, and had nothing whatever to do with electrical oscillations proper.

In order to perfectly screen off this induction effect, and yet leave the action of the true electrical oscillations, it was necessary to so increase the conductivity of the surface of the glass jar that it would have time to acquire a screening charge which should follow variations of potential accompanying the sparks at the rate of, say, 10 or 20 a second, and yet leave it so imperfect as to be practically an insulator to oscillations at the rate of 500,000,000 a second, which corresponded to the apparatus in use.

Prof. J. J. Thomson has shown* that the conductivity of liquids may be determined by finding what thickness of a sheet of liquid is just sufficient to prevent oscillations of a known rate from exciting a resonator on the other side, and that the thickness must be proportional to the specific resistance. For instance, he found that a layer of dilute sulphuric acid three or four millimetres thick was just opaque to oscillations at the rate of 100,000,000 a second. It would therefore require a greater thickness to be opaque to oscillations of 500,000,000 a second, and a very much greater thickness for water to be opaque to oscillations of this rate. A duster, therefore, soaked in water, though it might reflect some fraction of this radiation, should be practically transparent to it. Nevertheless a wet duster would be amply sufficient to screen the action of true harmonic variation of potential of the frequency of the sparks, *i.e.* 10 or 20 a second. As a matter of fact, these variations of potential are not simply harmonic, but since by Fourier's principle the non-harmonic periodic change is equivalent to a series of true harmonic changes at successively higher rates all superposed, the wet duster should completely screen all the lower of these components up to a certain point, and probably far enough. On wrapping up the jar with a wet duster all effect was found to cease, and the spurious character of the deflexions was demonstrated. It is possible that these are not the only experiments with electrical oscillations in which a wet duster or its equivalent might be found of service.

The apparatus was then remade with the view of obtaining

* Proc. Roy. Soc. vol. xlv. p. 269.

very great delicacy. To make the resonators aluminium wire was rolled into ribbon of $\cdot 2 \times \cdot 001$ centim., so that each centimetre in length weighed only half a milligram. Two pieces 30 centim. long were fastened in the cranked form previously described on very light frames made by cementing to almost capillary thin glass tubes cross bars cut from microscope cover-glass, so that the ends of these cross bars held the corners of the cranked pieces of aluminium ribbon. One of these was suspended in the same apparatus by a fine quartz fibre, and all was arranged with the view of obtaining a delicacy comparable with that employed by one of us in the Cavendish experiment. It was now impossible to keep the spot of light at rest, owing mainly to air-currents in the jar set up by differences in temperature of the sides of the jar which could not be avoided in the schools, and also to the perpetual tremor. In the winter, however, the elementary laboratory on the other side of the Exhibition Road was not being used, and so everything was transferred to a small room there, where a fair degree of quiet and uniformity of temperature could be obtained. The Voss machine was replaced by a large induction-coil, which gave a greater torrent of sparks. Then, to get more energy in each spark, the primary oscillator, made of 12 millim. tube, was replaced by a pair of spheres 100 millim. in diameter, with small spheres on short sliding rods, between which the sparks passed. The scale was placed at a distance of 281 centim. from the mirror. Then, when the wet duster was placed round the jar and the sparks made to pass, deflexions of 5 to 10 millim. were observed. Fearing, however, that even the wet duster failed to completely screen the induction-effects due to the rise and fall of potential of the primary or rather some of the higher harmonics already alluded to, we soaked it in dilute sulphuric acid instead of water, so that no doubt should exist as to its sufficient conductivity to quench the sham effect while it still remained unable to stop more than a small proportion of the waves of 500,000,000 a second. With this precaution all definite movement of the spot of light ceased. It was seldom that air-currents did not cause a gentle hovering of the index a few millimetres either way, which, however, had no relation to the starting or stopping of the sparks; on one or two frosty days, however, when the temperature was very uniform, there being no fire, the spot of light was so steady that a movement of even $\frac{1}{10}$ millim. on the scale would have been observed, but we have based our calculation on the certainty that the deflexion was not $\frac{1}{2}$ millim.

In order to make sure that this was a true negative result the duster was removed, when at once the index was driven

violently off the scale, and then a Hertz resonator tuned to the oscillations of the primary was placed in the jar and surrounded by the same acid duster when the sparks in the gap were evident, showing that the proper electromagnetic waves did penetrate into the jar as supposed.

The turning moment corresponding to a deflexion of $\frac{1}{2}$ millim. may be found from the following particulars :—

Period of oscillation of mirror and stem (oscillator removed), $\cdot 947$ second.

Period of oscillation with wire ring hung on, $4\cdot 13$ second.

(Wire ring $1\cdot 6$ centim. diameter outside, made of wire $\cdot 122$ centim. in diameter; mass $\cdot 4635$ gramme.) Hence

Couple = $1\cdot 1 \times 10^{-5}$ C.G.S. units, and

Average value of couple = $3\cdot 7 \times 10^{-7}$ C.G.S. units
per centim. of wire of resonator,

which corresponds to a force of about 3×10^{-7} dynes, since the distance from the axis is $1\frac{1}{4}$ centim. This is less than a two-hundred-millionth of the weight of a grain, or a three-thousand-millionth of the weight of a gramme.

Since the wires were only $\cdot 2$ centimetre apart, this shows that, if the currents in the wires, instead of being oscillating, had been simply ordinary steady currents, those currents could not have reached the value of $\cdot 00017$ C.G.S. electromagnetic unit or $\cdot 0017$ ampere.

Now the moment, if the theory advanced is correct, is due partly to electrostatic repulsion and to electrodynamic attraction which are equal to one another, but owing to the harmonic distribution of both, both in time and in position, and owing to the fact that the weaker part of each of these forces is tending to counteract the stronger part, the total average resultant force is by no means double or even equal to that due to a steady current alone of a strength equal to the actual maximum.

To find the relation it is necessary to first consider the effect of the harmonic distribution of either, say the current, along the wire. The square of this at any point is a measure of the force at that point, so that the force varies from zero at the ends to its full value in the middle, having passed its half value at the points where the wire crosses the axis of rotation.

Thus, in fig. 4, the ordinates of the upper curve $a b c$, which is half a sine curve, represent current strength, those of the lower curve $a d b e c$, which is a complete sine curve on half the scale, but shifted vertically by the amount of its own maximum ordinate, since

$$\sin^2 \alpha = \frac{1 - \cos 2\alpha}{2},$$

represent the force due to the current at each point. The rectangular area $f g c a$, equal to 2π , measures the total force

due to a uniform current of the maximum value. The areas $a d h$ and $c k e$ are the forces due to the ends of the wires in the wrong direction, and these together

$$= \frac{\pi}{2} - \int_0^{\pi/2} \sin \theta d\theta = \frac{\pi}{2} - 1.$$

The area $h d b e k$ is the force due to the middle half of the wire in the right direction, and this

$$= \frac{\pi}{2} + \int_0^{\pi/2} \sin \theta d\theta = \frac{\pi}{2} + 1.$$

The difference of these, which is the area $d b e l$, is the balance in the right direction, and this $= 2$. But the force due to a current of the maximum strength over the whole length of the wire is 2π , so the force in the cranked conductor due to the harmonically distributed current and the opposite effect of the ends is $\frac{1}{\pi} \times$ that due to uniform maximum current over

the whole wire. The current is not steady, but varies harmonically with the time, so on this account the value must be halved again, but this halving is exactly balanced by the doubling which results from the fact that the electrostatic exactly equals the electrodynamic effect.

We have seen that the force was not so great as that due to a steady uniform current of $\cdot 0017$ ampere; therefore the maximum current in the centre could not, if the oscillations continued uninterruptedly, have reached the value of $\sqrt{\pi} \times \cdot 0017$ or $\cdot 003$ ampere. Since in the most violent torrent of sparks that can be produced the time during which the oscillations

last is very small compared to the interval between two sparks, it is quite possible, and even probable, that the actual current during the earlier part of each spark greatly exceeded this, but this is a superior limit to the value of the square root of the mean square of the strength of the current in the particular case.

It should be noted that two errors, each of which is numerically insignificant, have, for convenience, been made. One is the supposition that the forces on the elements near the ends of the resonators are the same as though they were continued together with the stationary wave. As a matter of fact, it is only the last few millimetres for which there is a falling off. The second error is made by supposing that the middle half of the wire is all at one distance from the axis on one side, and the two end quarters at an equal distance from the axis on the other side. As a matter of fact, the wire has to cross over, but as the two forces almost exactly balance on the small part which crosses the axis, it was not worth while to complicate the simple statement of conditions illustrated by fig. 4 for the sake of an imaginary degree of accuracy which the nature of the observations would not justify.

Second Method.

As the first method, carried out with all the delicacy which under the conditions we could make use of, gave no promise, we determined to find by some direct process whether the heat which Mr. Gregory had inferred from the expansion of the wire was real. For this purpose we made use of one of the most delicate heat-measuring instruments that exist, which is specially suitable for detecting very small quantities of heat diffused over a great length of wire, namely the convection air-thermometer of the late Dr. Joule*. With this instrument he was able to detect the direct heating-effect of the moon's rays unconcentrated by lens or mirror.

His instrument consisted of a tube about 2 feet long and 4 inches in diameter, divided longitudinally by a blackened pasteboard diaphragm, leaving spaces at the top and bottom. In the top space a piece of magnetized sewing-needle, furnished with a glass index, was suspended by a single silk fibre. Any excess of temperature on one side of the partition caused an air-current, which at the top passed from the hot to the cold side and deflected the needle.

* Proc. Manchester Phil. Soc. vol. iii. p. 73.

We have made use of Joule's instrument, not exactly in the original form, but with two classes of index, and with an essential improvement which makes it extraordinarily sensitive without greatly affecting its simplicity. The first class of index depends for its working on the fact that when a small piece of phosphorus is placed in air it gradually oxidizes, and the oxide formed slowly falls, if the air is still, in a well-defined column, appearing like smoke. If there is any very small motion of the surrounding air, this column of phosphorous oxide will be deflected. It thus forms an excessively delicate and light index for detecting movements in the air.

To overcome the difficulty of keeping the index at rest, owing to radiation from neighbouring bodies or to draughts of varying temperature, we have surrounded the divided tube by another, which was kept rotating continuously by clock-work. If any part of this guard-tube becomes slightly heated, it is carried round and made to heat the instrument equally all round, and so it produces no effect.

As the determination on theoretical grounds of the most suitable dimensions presents considerable difficulties, we decided to make a series of tubes of different sizes and compare their sensibility. The object of the instrument being to measure the heat developed by the electromagnetic radiation in a wire within the instrument, it was necessary to make both the tube and guard-tube of some insulating material, such as glass.

The tube to be used was cleaned, and a roll of brown paper about 1 inch long was pasted round one end. This fitted tightly into a mahogany ring, D (Plate V. fig. 5). The tube was divided longitudinally by a partition of cardboard (F), which was made to fit tightly into the tube. This partition extended from the bottom to within about an inch of the top, which end was closed by a cork.

The projecting end of the mahogany ring (D) fitted into a corresponding hole in a piece of wood (E), which was itself supported on two blocks (A and B). The tube (represented by the dotted circles in the plan, fig. 6) came directly over this space between A and B, the partition being parallel to their adjacent faces.

Between A B, and immediately beneath the tube, two glass semi-cylinders were placed, with their convex surfaces facing each other. They are shown in plan in fig. 6 (MN), and one is shown in perspective in fig. 7. At 2 centim. from the top of one of these semi-cylinders a small paper scale (fig. 5), divided in half-millimetres, was attached. When a current

Figs. 5 to 10.
Scale $\frac{1}{2}$.

Fig. 9.

Fig. 5.

Fig. 11.

Fig. 10.

Fig. 7.

Fig. 8.

Fig. 6.

of air passes from one side of the tube to the other, it has to pass through the narrow space between these cylinders.

A hole was bored through the top of B, through which a capillary glass tube could be passed. This tube was filled with phosphorus, and the glass broken away for about one millimetre, so as to expose a clean piece of phosphorus whenever the stream of oxide had to be observed. The tube was then passed through the hole (K), so that the exposed piece of phosphorus came just beneath the partition and between the glass cylinders. It is shown in place at H in fig. 5.

By this means the stream of phosphorous oxide was formed at the narrowest part of the air channel, and so was affected to the maximum extent by any passage of air from one side of the partition to the other. The resulting deflexion of the phosphorous-oxide stream could be read with an accuracy of about one-tenth millimetre. In this form, when the phosphorus index is deflected it is carried to a part where the channel is much wider, owing to the curvature of the glass half-cylinders. On this account the deflexion of the index is not any simple function of the rate at which the air is passing. With a view to do away with this want of proportionality, and also, if possible, to render the instrument more sensitive, the glass half-cylinders were replaced by a pair of narrow flat glass plates, near together, with a wide channel on each side communicating with the tube above. The instrument was, however, found to be less sensitive in this form than when the half-cylinders were used.

The sensitiveness of the instrument could, to a certain extent, be altered by moving M and N (fig. 6) further apart, so that the phosphorus stream fell in a wider channel.

The divided tube was surrounded by another glass tube (G, fig. 5), which was about 10 centimetres longer. This formed the guard-tube, and was suspended from one of the axles of a clock (K, fig. 11), which made one revolution in about eight seconds.

By means of three levelling-screws the guard-tube was made to hang free of the inside tube, so that it did not touch it at any part of its revolution. Thus no heat due to friction was developed near the divided tube.

The phosphorus could not be placed at the top of the tube, as the falling column of oxide was found to go on one side of the partition, and its weight was sufficient to keep up a down-current of air on this side and an up-current on the other side, and so make the instrument unstable.

Inside the divided tube, and on one side of the partition, two fine platinum wires were stretched, reaching from the top

to the bottom. They were connected together at the top, and at the bottom were brought out and connected to two binding-screws fixed on the ring D (fig. 5). By means of this wire, whose resistance was measured, a known amount of heat could be developed in the tube by passing a current of known intensity. The current was, in all the experiments, supplied by a single Daniell cell, which contained in its circuit, beside the wire of the instrument, a resistance-box and a key.

The clock was kept working for about half an hour before the commencement of an experiment, in order to equalize the temperature within the tube; and then a fresh piece of phosphorus was introduced. When the phosphorus index was quite steady, and approximately at the centre of the scale, the reading was taken (zero-reading), then resistance was unplugged in the box, and the current passed till the index had again come to rest. The current was then stopped, and another zero-reading taken.

In testing the different tubes the largest resistance which would give a readable deflexion was in each case ascertained. The resistance of the cell and the connecting-wires could be neglected in comparison with the external resistance.

In the different tubes the total heat developed was not the same when the same current was passed, as the wires were of different lengths. This, however, was not taken into account in comparing the tubes together, as for the measurement of the electromagnetic radiation it was necessary to get the greatest possible sensitiveness per centim. of the wire.

It is hardly necessary to give particulars of the different tubes experimented upon. It is sufficient to say that, while the length of the tube was of little consequence, it was found that a wide tube was much more sensitive than a narrow one. The results obtained in a particular case are given.

Tube No. 3 :—Length 82, diameter 5 centimetres. Resistance of wire 29 ohms; outside resistance 500 ohms. Deflexion 1 millimetre.

To calculate the amount of heat corresponding to this deflexion, we have, taking the E.M.F. of a Daniell cell as 1 volt,

$$\begin{aligned} \text{Heat developed per sec.} &= \frac{RC^2}{4 \cdot 2} \\ &= \frac{29}{529} \times \frac{1}{4 \cdot 2} = \cdot 000,024 \text{ calorie} \end{aligned}$$

over the whole length of the tube, or $\cdot 000,000,3$ calorie per centimetre of the tube.

While this very small degree of heating was within the range of experimental certainty so long as the clockwork was going, it was impossible to keep any index visible at all when the clock had stopped, even though several concentric screens were placed round the tube.

The apparatus in this form was subject to the great fault that the phosphorus refused to form the oxide at a temperature below 15°C. , which prevented the instrument being used on many days.

With the view of getting over this difficulty with the phosphorus index, and if possible of obtaining greater sensitiveness, a form of index was adopted which was a modification of Dr. Joule's arrangement.

The tube was closed at each end, the partition reaching right up to the cork at the top and leaving a space of about fifteen centimetres at the bottom. Twelve centimetres below the top of the partition a hole was punched in the card. Into this hole a short cylinder of paper was glued. This is shown at A in figs. 8 & 9. A plane mirror, M, fitted into this tube, allowing about 1 millimetre clearance all round. It was fastened to a cross bar, at the other end of which a counterpoise (W) was fixed.

The mirror and counterpoise were suspended by a fine quartz fibre from a pin (E, fig. 8), which passed through the cork used to close the tube. When the mirror is at rest it almost completely fills up the hole in the partition, and forms a very delicate means of detecting any differences of pressure in the air at the two sides of the partition.

A small recess (B, fig. 9) was made in the partition for the counterpoise, and covered in so that it was not exposed to the current of air. The arrangement is shown in elevation in fig. 8, and in section through K L in fig. 9. Fig. 10 shows the mirror and counterpoise separately. A hole was ground in the tube immediately in front of the mirror, into which a lens of a metre focal length was cemented.

In this form of the instrument the guard-tube, if continuous, would have prevented the formation of a clear image. It was therefore necessary to divide it into two portions. Rings of mahogany (N, fig. 11) were cemented to the top of the lower portion and to the top and bottom of the upper. The two rings N_1 N_2 were connected together by three bolts, of such a length as to leave a space of about two centimetres between the rings. This break in the guard-tube came just on a level with the mirror, and thus allowed the beam of light to pass freely. The passage of the bolts before the mirror produced no inconvenient effect on the image formed on the

scale. The ends of the wire were brought out at the bottom of the tube, leaving about half an inch free. When using a continuous current, two brass clips (A, fig. 11) were placed on these ends so as to connect them to a pair of binding-screws. When using the oscillator these clips were turned down (as in the figure), so that the wire should not be connected with any body having capacity.

The following are the dimensions of this tube (No. 4):—

Length 126 centimetres, diameter 4·7 centimetres.

Length of wire 2×103 centimetres.

Resistance of wire 38 ohms.

Diameter of guard-tube 7 centimetres.

Diameter of mirror 1·2 centimetre.

Length of fibre 9 centimetres.

As shaking interfered with the working of the instrument, the experiments were performed in a vault, which, however, was by no means steady.

The following are the results obtained when testing the sensibility of the instrument (scale at 100 centimetres from mirror):—

Added Resistance.	Total Resistance.	Deflexion.
ohms. 500	ohms. 538	centimetres. 3·3
762	800	1·6

In the case of 800 ohms total resistance we have

$$\begin{aligned} \text{Heat developed in wire per sec.} &= \frac{1}{800^2} \times \frac{38}{4 \cdot 2} \\ &= \cdot 000,014 \text{ calorie.} \end{aligned}$$

This is equivalent to one calorie developed in 19 hrs. 42 min. Or we may say that one calorie per day developed by the whole wire could certainly be detected; that is, one calorie in 103 days per centimetre of tube.

The oscillator used to set up the electromagnetic radiation consisted of two hollow brass cylinders (D E, fig. 11), fixed to ebonite cross pieces (F, C), which could be placed at different heights in a wooden stand. Short brass cylinders, with well-rounded ends, fitted into the ends of D and E, and allowed the length and sparking-distance to be altered. These cylinders were connected by very fine wire with the terminals of the large Ruhmkorff's coil belonging to the Physical

Laboratory. The length of the oscillator was the same as that of either of the wires in the tube, and it was placed so as to be in the plane of the partition of the tube, at a distance of about 30 centimetres (fig. 11). The best length of spark was about half a centimetre.

At first, on separating the knobs of the oscillators, so that no spark passed, the instrument showed a large deflexion in the direction of cold. This was due to electrostatic attraction between the oscillator and the mirror. To prevent this action a piece of tin-foil (E F G H, fig. 8) was pasted round the tube at the level of the mirror, a hole being cut in it the size of the lens, which effectually put a stop to this action.

The instrument now indicated a considerable amount of heat developed in the wire whenever the coil was worked.

The effect of altering the capacity of the oscillator by adding pieces of tin-foil to the ends was tried, but with no beneficial result.

A wet duster was hung between the oscillator and the instrument for the purpose of seeing whether the radiation would pass through. The deflexion produced was only slightly less than when no duster was interposed.

In order to measure the heat developed by the induced currents in the wire, the deflexion produced when the coil was worked was noted; then a steady current was sent through the wire, and the resistance in the circuit altered till an equal deflexion was obtained. The readings obtained with the oscillator were somewhat varied, owing to small changes in the character of the sparks. Another difficulty was caused by the coil often refusing to work continuously for the time necessary to get a reading (about $1\frac{1}{2}$ minute), as the contact-breaker became burnt by the sparks.

The following are the deflexions obtained in centimetres :—

45 ; 44 ; 37 ; 36 ; 35·6 ; 36·9 ; 44·8 ;
45·5 ; 40·2 ; 40·2 ; 39.

Mean 40·4 centim.

One Daniell cell working through a total external resistance of 115 ohms gave the following deflexions :—

41·0 ; 40·0 ; 39·3 ; 40·0 ; 41·0.

Mean 40·3 centim.

We may therefore say that the heating-effect due to the oscillations (oscillator at 30 centim.) is equal to that pro-

duced by one Daniell cell when the external resistance is 115 ohms, and the working resistance 38 ohms.

Therefore the heat produced per sec.

$$= \frac{38}{115^2} \times \frac{1}{4 \cdot 2} \text{ calories,}$$

$$= \cdot 000685 \text{ calorie ;}$$

or it would take 24 minutes 20 sec. to produce one calorie.

The steady E.M.F. between the terminals of the wire which produces the same effect as the oscillations is $\cdot 33$ volt. Mr. Gregory gives $\cdot 5$ volt as the equivalent E.M.F. in his experiments. Though the conditions were not sufficiently similar to make the numerical results strictly comparable, nevertheless the fact that the figures obtained are of the same order goes to show that the expansion observed by Mr. Gregory was a true expansion due to heat, and that his results were real.

In calculating from the heat developed the mean square of the current produced in the wire by the electrical oscillations, it is necessary to take into account the fact that these rapidly alternating currents are not uniformly diffused throughout the cross section of the wire, but only pass through a thin stratum at the surface. On this account the resistance which the wire offers to these rapidly alternating currents is greater than that which it offers to steady currents.

Lord Rayleigh* gives a formula for calculating the effective resistance of a wire of round section to an alternating current of given frequency. It is

$$R' = \sqrt{\left(\frac{1}{2} p l \mu R\right)},$$

where R' is the effective resistance ; R the resistance to steady currents in C.G.S. units ; $p2\pi$ times the number of oscillations in one second ; l the length of the wire ; and μ the magnetic permeability of the substance of which the wire is composed.

In the following calculation one of the wires only is considered.

The length of the primary oscillator is 109 centimetres, and therefore the wave-length of the radiation given out is 218 centimetres. If n = number of oscillations per sec., then

$$n = \frac{v}{\lambda} = 1 \cdot 376 \times 10^8.$$

* Phil. Mag., May 1886, p. 388.

The length of the wire (l) is 103 centimetres, and its resistance 19 ohms = 19×10^9 C.G.S. units.

In the case of platinum μ may be taken as unity.

From this it follows that

$$R' = 29 \text{ ohms,}$$

and since H (half the heat developed in the two wires) = 0.000342 calorie per second

$$\begin{aligned} C^2 &= \frac{JH}{R'} \\ &= 0.00049. \end{aligned}$$

Owing to the harmonic distribution of the current along the wire, in order to produce a given amount of heat in the whole wire, the strength of the current at the centre must be $\sqrt{2}$ times as great as that which would be necessary if the current were of uniform strength in all parts of the wire.

$\therefore$ the square root of the mean square of the current at the centre = 0.1 ampere.

While it is impossible from the heat found to form any conclusion as to how fast heat was being generated during each spark, or what fraction of the whole time the oscillations lasted, yet here, as in the former case, the final result depends on the mean square of the current. We found by the first method that the square root of the mean square was certainly not 0.003 ampere, if the theory was correct; while by the heat we find the square root of the mean square to be 0.1 ampere. The arrangements in the two cases were not strictly comparable, for in the first the oscillator was only 30 centimetres long, while in the second it was 109 centimetres, and because the distance of the primary from the secondaries was relatively greater in the first than in the second case. We intended to have made a second set of measures in which the suspended cranked oscillator should itself be in the tube of the convection-thermometer together with the fixed cranked oscillator. In this way the force, if any, between them could be observed and measured at the same time that the deflexion of the mirror due to the heat was read; then, by making contacts with the ends of the fixed cranked oscillator alone, and passing a current through it so as to produce the same deflexion, all the data would be obtained to tell for certain whether the absence of force, or, if force was observed, if the actual force was that which the provisional theory set out at the beginning of this paper indicated. The discrepancy of 3:10 in the present instance

cannot be taken as proving that the theory is wrong, and that the forces ought not to be observed, but it does clearly show that they must be excessively minute, and that, if they exist, it is only by great refinement that they can be made evident. No doubt, as Prof. Fitzgerald suggested, the use of concentrating cylindrical mirrors of proper form would greatly increase the sensitiveness of the whole apparatus.

We have been prevented from completing this work because the elementary laboratory was required, and it is impossible to carry on any really delicate research requiring uniform conditions and steadiness in so unsuitable a building as the Science Schools. We have therefore published our results in their present imperfect condition, partly because we believe that the methods employed may be useful to others, but chiefly because we hope that some physicist who has the advantage of having a steady underground room may be induced to make the experiments under more perfect conditions, and so carry the matter to a successful issue.

VI. *The Measurement of the Time of the Fall of Magnetization in a Magnetized Iron Cylinder.* By FREDERICK J. SMITH, M.A., Millard Lecturer on Mechanics and Physics, Trinity College, Oxford*.

WHILE working at the construction of electromagnetic styli, as used in the Tram Chronograph, described at p. 377, Phil. Mag. xxix., I wished to determine the conditions for producing a stylus with a small "latency." One of the principal things to be determined was the time of the fall of magnetization in different iron bars. As the determination of this period of magnetic change appears to be a subject of interest apart from the way in which it affects the action of styli, I beg respectfully to send you a brief account of the method by which I have arrived at certain results respecting it.

If an iron bar be magnetized by a current of electricity and the current be broken, the bar after a short time loses some of its magnetism. The time varies with the kind of iron used and the magnetizing force.

If the terminals of the coil conducting the magnetizing current could be quickly shifted from the battery to the terminals of a galvanometer, then a deflexion would be expected if the pole changing took place before the magnetization of

* Communicated by the Author.