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XXIX. A magneto-electric phenomenon

C.V. Boys A.R.S.M.

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seems that the calculated values for oxygen and nitrogen are not very far wrong; but hydrogen is clearly incorrect. The explanation of this anomaly is probably to be found in the fact that the calculated molecular volume of hydrogen is wrong, and that instead of being unity on our scale it ought to be 3.5 like oxygen and nitrogen. In fact, the chemist would infer that, as the difference in the complexity of the molecular structure of hydrochloric acid, water, ammonia, and marsh-gas does not affect the molecular volume under the conditions we are discussing, in all probability the value for hydrogen would be identical with that of the above-mentioned bodies. If we adopt this view and change the value of the $T_c + P_c$ to 3.5, then the density of the fluid would become 0.034, which is in accordance with the experimental number of Cailletet and Hautefeuille. An accurate determination of the critical temperature and pressure of hydrogen, for which, judging from the success of the experiments of M. Olzewski, chemists will not have to wait long, will thus be of great interest.

XXIX. *A Magneto-electric Phenomenon.* By C. V. BOYS, A.R.S.M., *Demonstrator of Physics at the Science Schools, South Kensington**.

EVERY one is familiar with the effect produced when a copper disk is set to spin in a powerful magnetic field: the currents induced by the motion of the disk act in such a direction as to oppose the motion, which therefore speedily ceases. Faraday observed that if, instead of being set to spin, a disk is merely suspended between the poles of an electromagnet, it will in general be disturbed whenever the current in the coils of the electromagnet is made or broken. If it lie with its plane parallel or at right angles to the lines of force, no disturbance will be apparent if the lines of force where they are included by the disk are parallel. But if the plane of the disk makes an angle α with the parallel lines of force, then on making the current in the electromagnet an impulse is given tending to diminish the angle α , while breaking the current gives an impulse tending to increase the angle α .

Again, if the angle α be 90° , so as to eliminate this twisting effect, no movement will be visible at the making or the breaking in a parallel field; but if the disk be placed in a field with diverging lines of force, in which, of course, the strength diminishes as the lines separate, and if it be placed symmetrically so as to include the greatest number (*i. e.* with its

* Communicated by the Physical Society. Read June 28, 1884.

plane at right angles to those lines passing through its centre), then, on making the current, it will receive an impulse causing it to move parallel to itself along the lines of force towards the weaker part of the field, and at the breaking it will receive an impulse more evident in the opposite direction. If this radiating field is produced between a pointed and a flat pole, the disk will, on making the current, appear to be repelled from, and, on breaking, to be attracted by, the pointed pole. So powerful is this effect that a piece of impure copper, which is strongly magnetic, is repelled from the pointed pole on making, and attracted on breaking, the current, thus appearing at first sight strongly diamagnetic.

Though these impulses must have been observed by most experimentalists, their amount has not been, so far as I am aware, determined in absolute units, nor have they been turned to account for making any measurements. As they seem to afford one of the most convenient methods of determining conductivity and field-intensity, perhaps a short paper on the subject, even though it be incomplete, may be of interest to this Society.

The explanation of the motions described will be obvious, but it may be well to give it at length for the sake of arriving at quantitative results. In the first place, let the lines of force be parallel, so that the field is of uniform strength. Let a ring of (small) section s , of specific resistance ρ , and of radius r , be placed in the field, with its plane making an angle α with the lines of force. Let the strength of the field be H units. Then during a small increment of field-intensity dH , in the time dt , a current will be induced in the ring of the strength

$$\frac{rs \sin \alpha}{2\rho} \frac{dH}{dt}.$$

This current in the field H will produce a twisting tendency to increase α with a diminishing, or to diminish α with an increasing field, represented by the couple

$$- \frac{\pi r^3 s H \sin 2\alpha}{4\rho} \frac{dH}{dt}.$$

From this it is clear that the couple varies inversely as the time dt occupied in making any small change of field-intensity dH , but it lasts for the time dt ; therefore the momentum acquired by the suspended disk, if free to move, will be independent of the rate at which any small change in the magnetic field may be made, but will depend only on its amount, provided that the time is not sufficient for the angle α to have perceptibly altered during the change. Since this is true of any element, it is true of all; so the momentum acquired by

the ring is a direct measure of any total change in the strength of the field in which it lies, no matter by what law it changes in strength. If at the end of any rapid change the field remains of any strength, the motion of the ring will be rapidly stopped by the well-known damping action, of which I shall have more to say later. If, however, the field sinks to zero, or nearly so, the momentum acquired can be measured and the original intensity determined.

The current induced in the ring will of course react on the field and bend the lines of force in such a manner as to hinder their passing through its edge, that is to delay the change of included field-intensity; but the impulse is independent of the time or the manner in which the field changes, so it cannot be effected to any extent by this cause.

Since the impulse given to the disk during any element of time is

$$-\frac{\pi r^3 s H \sin 2\alpha}{4\rho} \frac{dH}{dt},$$

the total impulse while H changes between 0 and H will be

$$-\frac{\pi r^3 s H^2 \sin 2\alpha}{8\rho}.$$

If the moment of inertia of the disk be M , and the torsional value of the supporting wire be T , the angular velocity ω generated will be

$$\omega = -\frac{\pi r^3 s H^2 \sin 2\alpha}{8\rho M},$$

and the throw of the ring θ will be

$$\theta = -\frac{\pi r^3 s H^2 \sin 2\alpha}{8\rho \sqrt{MT}}.$$

The action on a disk may be considered as the sum of the actions on the several elementary rings of which it is composed, for there cannot be any tendency for any part of the currents to cross over the elementary circles. The impulse therefore on a disk of radius r and thickness s will be

$$-\frac{\pi r^4 s H^2 \sin 2\alpha}{32\rho};$$

and the impulse on a disk of radius r_2 with a concentric hole of radius r_1 will be

$$-\frac{\pi s H^2 \sin 2\alpha}{32\rho} (r_2^4 - r_1^4).$$

Since the moment of inertia of a disk is also proportional to the fourth power and to the thickness, so long as the thickness is small, it will appear that the velocity imparted to a disk of any size or thickness, or to a ring, during a change in a magnetic field will be the same. To what extent a correction should be applied to these results for self-induction between different parts of the disk I am not prepared to say; their calculation would give trouble.

For comparing one field with another, disks or rings of metal may be used; but for absolute measurements, as it would be impossible to measure the exact conductivity of a disk, a coil is preferable. By employing disks of different metals their conductivities can be compared without the trouble of drawing into wire or cutting into long strips.

It will be found that a coil of area A and resistance R will, under a torsion T , experience a throw

$$\theta = - \frac{A^2 H^2 \sin 2\alpha}{4R\sqrt{MT}}.$$

If, instead of a disk, a sphere be used, no twisting should be experienced if the conductivity in different directions is the same. If, however, there is a plane of greatest or least conductivity, it should be possible to discover it. Crystallization or mechanical treatment might give rise to such planes in metals; no definite results could be expected in any thing else.

I have referred to the apparent repulsion and attraction of a disk of metal by a pointed pole at the making and breaking of the magnetizing current. As the lines from such a pole radiate outwards, they are not normal to the metal except in the middle. On their passage inwards or outwards they give rise to circular currents tending to move each part of the disk normally to the lines of force. There is therefore a longitudinal component away from the point of radiation during an increase in the field, and towards it during a diminution of the field. A closed coil of wire is subject to the same forces. If a coil be made of uncovered copper wire in the form of a double helix with the ends joined together, and if the convolutions are separate so as nowhere to touch one another, the growth of the magnetic field can be watched by placing the coil nearly over one pole. On making the current the field begins to grow, at first quickly and afterwards more slowly. The coil will receive a push and will extend itself. As the push diminishes in amount, owing to the diminishing rate of growth of the magnetic field, the coil will gradually regain its former shape. It might be thought that the slow recoil is simply due to the damping action of the field; but this is not sufficient

to account for it, as when the field is fully grown the coil will, on being forcibly drawn out, recover its shape much more quickly. On breaking the magnetizing current, the impulse in the opposite direction, being the same as before but lasting for so much shorter a time, is far more evident.

My first experiments were made with a view to determine whether the impulse was proportional to $\sin 2\alpha$ when other things remained the same. I therefore cemented a disk of metal (a half-crown) to an ebonite rod carrying a glass index and hung by a torsion-wire of platinum. The glass index travelled over a card divided into degrees; and the wire to which the upper end of the torsion-wire was soldered also carried a pointer, the position of which could, if desired, be read on a divided card. The disk was suspended between two parallel polar faces of iron. The upper index was turned until, on making and breaking the current, the lower index showed no sign of motion. It could thus be placed within a small fraction of a degree, so that α was either 90° or 0° . The lower card was then adjusted, and the upper index turned so that the lower rested successively at 5° , 10° , 15° , &c. up to 90° . The negative impulse on making, and the positive impulse on breaking, the current were observed by the throw of the lower index. These are given in the second and third columns of the following Table. In the fourth column is a series of numbers in the proportion of $\sin 2\alpha$, the largest number being made to agree with the observed positive throw.

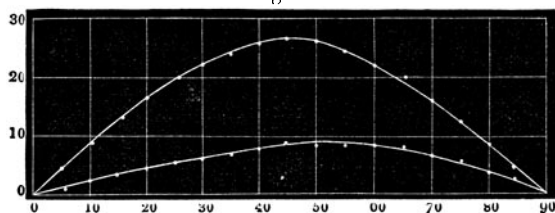
TABLE I.

Position of rest.	Negative throw.	Positive throw.	Calculated positive throw.
5	1	4.5	4.6
10	2	9	9.1
15	3	13	13.2
20	4.5	17	17.1
25	5	20	20.3
30	6	22.5	23
35	7	24.5	25
40	7.8	26.2	26.2
45	8.8	26.5	26.5
50	8.5	26.2	26.2
55	8.2	24.5	25
60	7.8	22	23
65	7.5	20	20.3
70	6.5	16	17.1
75	5.5	12.5	13.2
80	3.5	9	9.1
85	2	4	4.6

The close agreement of the other numbers shows clearly

that, on breaking the circuit, the impulse is truly proportional to $\sin 2\alpha$. Examination shows that the negative impulses, though in reality equal to the others, are apparently much less in amount, that they are not even in proportion, and not only this, but that the corresponding values on either side of 45° are not the same. This want of symmetry is clearly shown by fig. 1. The discrepancy is due to the fact that the disk is brought to rest by the damping action of the field as well as by the torsion of the wire, and that the damping action is greater as the angle is less, being $\propto \cos^2 \alpha$.

Fig. 1.



I thought it would be interesting to determine to what angle the disk would be thrown if the torsion of the wire did not act. I therefore suspended, instead of the disk, the coil used in the absolute experiments by a silk thread, adjusted the lower card by the method of no throw, and brought the index to rest successively over 10° , 20° , 30° , &c. up to 90° . The index came to rest at the series of positions shown in column 2 of the following Table:—

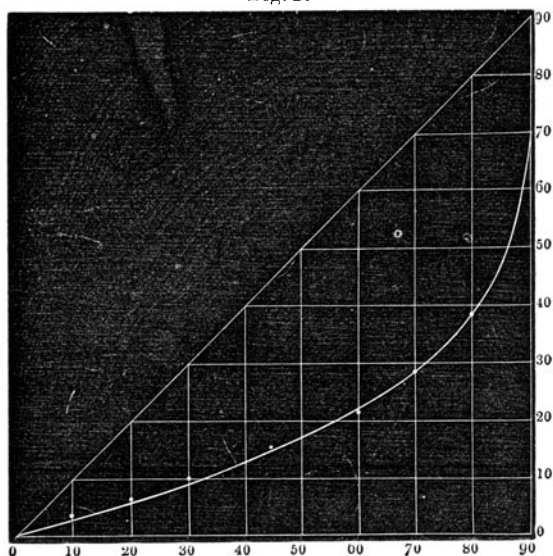
TABLE II.

Pointer fell	
From	To
10	3.6
20	6
30	10
40	13
45	16
50	18
60	22
70	29
80	39

The same results are shown graphically in fig. 2. It is

interesting to note that the curve shown is a natural curve depending on circular functions only. It is independent of the nature of material, such as conductivity, moment of inertia, or of the strength to which the field is made to grow from zero. It is subject to a small error, for I did not destroy the residual magnetism. That the effect of this is appreciable is evident, for in one series of experiments with a disk the throw on making was always from 45° to 33° ; but the first time that the direction of the magnetizing current was changed the throw was from 45° to 35° , after which it was from 45° to

Fig. 2.



33° , as before. This diminution at the first reversal was always the same. I found almost the same fall with the half-crown as with the coil, and with one cell as with ten cells. There were slight differences, but not more than draughts from which I did not shield the needle would have accounted for. The lower angle can be read with precision, but the higher angles become difficult to observe as the damping influence diminishes. The position $\alpha = 90^\circ$ is one of instability; for however slight a velocity is given to the disk, it will not be brought to rest for a considerable time, owing to the very minute nature of the squares of the cosines of angles nearly equal to 90° .

The last series of experiments was made with a view to determine whether the strength of field determined by observation of the throw of the disk at breaking agreed with the

strength determined by some recognized method. I therefore made a small coil of twelve turns of copper wire of 1·45 centim. radius and with a resistance of 0·085 ohm. The area of the coil was 79·4 square centim. The moment of inertia of coil and index was found by comparison with a cylinder to be 58·1 units, and the torsional value of the supporting wire to be 17,000 units. The plane of the coil was adjusted by the usual method to zero, and then set to 45°. The currents from 10, 9, 8, &c. to 1 Grove cells were sent in succession through the coils of the electromagnet and through a Siemens electro-dynamometer. The following Table shows the amounts of the positive and negative impulses, the strengths of the magnetizing currents in amperes, and the field-intensities calculated from the positive throws by the formula

$$H^2 = 9311000 \times \text{Throw measured in degrees.}$$

TABLE III.

Number of cells.	Magnetizing current, in amperes.	Negative throw.	Positive throw.	Calculated field, in absolute units.
10	11·85	10·5	27·5	16,000
9	11·2	9	26	15,600
8	10·44	8·2	24·5	15,100
7	9·47	7	22·5	14,500
6	8·63	6	21·3	14,100
5	7·60	4·8	19·2	13,400
4	6·53	3·3	16·5	12,400
3	5·18	2·2	13	11,000
2	3·67	1	8	8,630
1	1·83	0·2	2·8	5,070

The ends of the coil which were soldered together were then unsoldered without disturbing the soldered connexion between the torsion-wire and one end. The other end was bent so as to dip into a small mercury-cup in the axial line, so that a known current, measured by a second electro-dynamometer, could be sent through the coil. During this change no part of the apparatus was moved at all; it was, however, necessary to redetermine the zero position, which was now rather more difficult, for the resistance of the torsion-wire was so great in comparison with that of the coil alone, that the throw at any angle was only about one tenth of what it was before. As before, the current from 10 to 1 cells was sent successively through the coils of the electromagnet and an electro-dynamo-

meter. The current from a Daniell cell was sent through the suspended coil and measured. In the fourth column of the following Table will be found the deflection of the coil due to currents tabulated in columns 2 and 3. In the fifth column is the deflection due to the residual magnetism; and in the sixth column the strength of field in absolute units, calculated from the formula

$$H = \frac{3.73 \times \text{deflection in degrees}}{\text{deflecting current in absolute units} \times \cos \delta}$$

TABLE IV.

Number of cells.	Magnetizing current, in amperes.	Deflecting current, in amperes.	Deflection = δ .	Deflection due to residual magnetism.	Calculated field, in absolute units.
10	11.92	.514	65	4	11,200
9	11.05	.530*	64	4	10,260
8	10.52	.502	63	4	10,320
7	9.48	.496	62.5	4	10,150
6	8.63	.480	61.5	4	10,050
5	7.60	.480	60.3	4	9,470
4	6.45	.480	59	4	8,930
3	5.14	.480	57	4	8,120
2	3.67	.480	51.5	4	6,470
1	1.98	.480	40.5	4.5	4,140

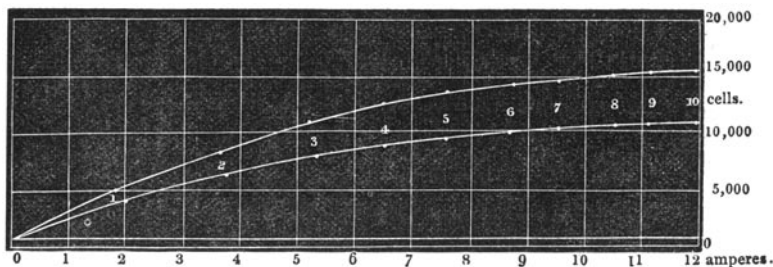
* Obviously over-estimated, hence small results.

The residual magnetism was always the same till one cell only had been employed to excite the electromagnet, when the deflection was clearly greater. This I repeated several times with one and with more than one cell: a deflection of $4\frac{1}{2}^\circ$ was always obtained from one cell, and of 4° from more than one cell. To obtain a still higher residual magnetic effect, I drew the terminal along a fine wire and gradually diminished the field; by this means I obtained a residual field giving a deflection of $5^\circ.4$. The magnetic fields corresponding to the deflections 4, $4\frac{1}{2}$, and 5.4 are 312, 352, and 422 absolute units.

Fig. 3 shows the field-intensity measured by the two methods. They do not agree, nor are they quite proportional, nevertheless they are of the same order of magnitude. The discrepancy is greater than would be expected from errors of an experimental kind, even though the apparatus was hastily

improvised. Nevertheless the agreement, such as it is, shows that it will be worth while to carry out a series of experiments

Fig. 3.



with the accuracy and care that are needed in physical investigations. This I intend to do as soon as I am able. It will then perhaps be possible to tell whether this method of determining conductivity or field-intensity is to be relied upon: it certainly in convenience and simplicity compares very favourably with any of the usual methods.

XXX. *Proceedings of Learned Societies.*

GEOLOGICAL SOCIETY.

[Continued from p. 159.]

April 2, 1884.—Prof. T. G. Bonney, D.Sc., F.R.S., President,
in the Chair.

THE following communications were read:—

1. "The Rocks of Guernsey." By the Rev. E. Hill, M.A., F.G.S. With an Appendix on the Microscopic Structure of some of the Rocks, by Prof. T. G. Bonney, D.Sc., F.R.S., Pres.G.S.

The southern part of the island is a high plateau consisting entirely of gneiss. This is very coarse, and the bedding is seldom well marked. The bedding, when visible, coincides with the foliation, and the author hopes that hereafter an order of succession may be established. At Rocquaine Castle occur a few slaty beds intercalated in the gneiss, the origin of which is somewhat difficult to understand. The northern part, low ground with hummocks, consists principally of a group of crystalline or subcrystalline rocks, in constitution diorites or syenites. They are described by Ansted as sedimentary rocks metamorphosed into syenites; but they show no bedding either in the many quarries, or, in general, in the shore outcrops, nor do their varieties occur in any manner indicating an order

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