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XXVII. *On the Electrical Resistance of Bismuth to Alternating Currents in a Strong Magnetic Field.* By GEORGE C. SIMPSON, B.Sc., Scholar of the Victoria University*.

ONE of the many anomalous properties of bismuth is the change which the resistance of a filament undergoes when placed perpendicular to the lines of force in a strong magnetic field; not only does its resistance very much increase, but, as discovered by Lenard, its resistance to alternating currents under these conditions is apparently different from its resistance to direct currents. Many experimenters have studied this difference, and although nearly all are agreed as to the way in which it varies with the strength of the field—the frequency remaining constant—each experimenter seems to have arrived at a different conclusion as to the way it varies with the frequency—the field remaining constant.

Lenard † (who measured the resistance of the bismuth by means of a Wheatstone-bridge, using an induction-coil to supply the alternating current, and a telephone in place of the galvanometer) concluded that the resistance of bismuth in a strong field is the same for alternating as for direct currents until frequencies of the order of magnitude of 10,000 per sec. are used.

On the other hand M. Sadovsky ‡, working at St. Petersburg, showed that with the bismuth in a strong field, an alternating current having a frequency of three or four alternations per second produced a change in the resistance of the bismuth.

In M. Sadovsky's apparatus an alternating current from a dynamo was supplied to a Wheatstone-bridge containing the bismuth. On the shaft of the dynamo three segments of brass, each extending over 60° of the circumference, were fixed. By pressing a spring into contact with the first segment, the galvanometer-arm was closed for $\frac{1}{3}$ of an alternation; on pressing another spring, the galvanometer arm was closed for the next $\frac{1}{3}$; and a third spring closed it for the next $\frac{1}{3}$ of an alternation. In this way the galvanometer was connected to the bridge, 1st, when the current was rising in the bismuth; 2nd, when it was at the crest of a wave (current maximum); 3rd, when it was decreasing. M. Sadovsky did not aim at quantitative results, but he obtained

* Communicated by Prof. A. Schuster, F.R.S.

† Wied. Ann. xxxix. p. 619 (1890).

‡ *Journal de la Société Physico-Chimique Russe*, vol. xxvi. no. 2 (1894).

the following qualitative ones :—If R_r , R_m , R_d , and R_c are the resistances of the bismuth to a rising, maximum, decreasing, and constant current respectively, then

$$R_r > R_m > R_c > R_d.$$

More recently R. Wachsmuth and C. Bamberger* found the resistance in strong fields to be quite independent of the frequency.

As these results are so mutually contradictory, Dr. Schuster suggested that I should undertake a research on the subject; my aim being to find how the resistance of bismuth to alternating currents depends on the frequency of the current if the field is kept constant and large.

In all my experiments a Hartmann and Braun bismuth spiral (having a resistance of 17.88 ohms at 21° C. in zero field) was placed perpendicular to the field produced by a large electromagnet, the field-strength being about 17,000 lines per sq. cm., so that the resistance of the bismuth in the field was double its value outside. The alternating current used was generally obtained from a small dynamo which gave a current curve approximately sinusoidal in shape.

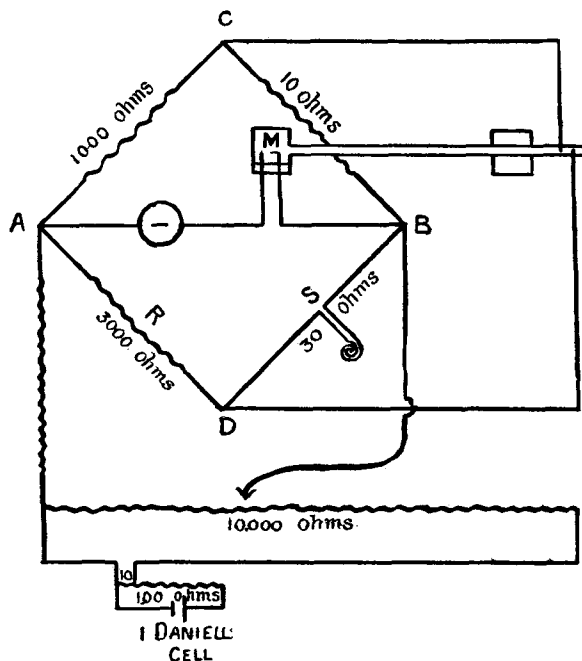
The method of experimenting was based on the following considerations :—As any small change in the resistance of a wire carrying a current may be considered as the result of an E.M.F. set up in the wire, whatever the changes in the bismuth may be due to they can be regarded as arising from an electromotive force set up in the bismuth itself. If on examination this E.M.F. (called in this paper the “bismuth E.M.F.”) should prove to be opposite in phase to and of the same wave-form as the—say simple harmonic—current causing it, it may safely be inferred that the change in the bismuth is really a change in the resistance pure and simple. But if the “bismuth E.M.F.,” while still possessing the proper wave-form, should be displaced 90° ahead or 90° behind, it would be necessary to conclude that in the one case there exists something of the nature of capacity, in the other something of the nature of self-induction in the bismuth. There is the further possibility of the “bismuth E.M.F.” having a different wave-form from that of the current.

Two methods of experimenting were used. A direct method of obtaining the wave-form of the “bismuth E.M.F.” and of the current producing it will be first described.

* *Physikalische Zeitschrift*, I. ii. p. 127 (1899).

A Wheatstone-bridge (fig. 1) containing the bismuth, S, was balanced for steady currents, and then an alternating current supplied instead. The "bismuth E.M.F." which this alternating current set up caused an alternating difference

Fig. 1.



of potential across the galvanometer-arm AB in phase with, and of the same wave-form as, itself. An adjustable contact-maker, M, on the dynamo-shaft closed the galvanometer-arm for an instant at any required phase of an alternation; the result being a deflexion of the galvanometer which varied in magnitude and sign with the phase of the "make." The "make" having been set at a known phase, a potentiometer, connected to the ends of the galvanometer-arm, AB, was then adjusted until there was no deflexion of the galvanometer, in which case the potentiometer-reading gave the value of the "bismuth E.M.F." at the instant of the make.

Curve I. (fig. 2) shows the form of the "bismuth E.M.F." obtained in this way.

In order to compare this "bismuth E.M.F." with the curve of the current producing it, the bismuth spiral was

replaced by a non-inductive resistance S and the bridge balanced, after which the resistance R was increased by 2 per cent.; the difference of potential across the galvanometer-arm caused by this increase being balanced as before by means of the potentiometer.

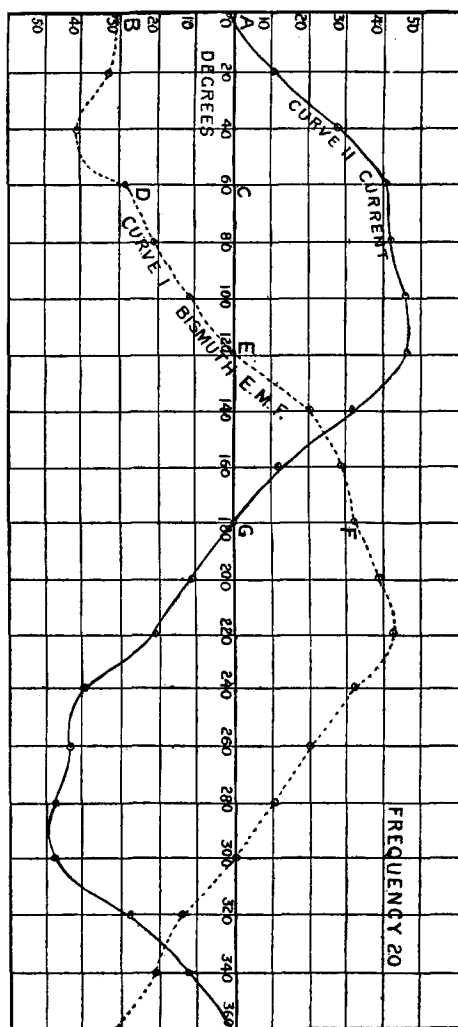


Fig. 2.

Curve II. (fig. 2) is the current curve corresponding to the "bismuth E.M.F." shown in curve I. On comparing these

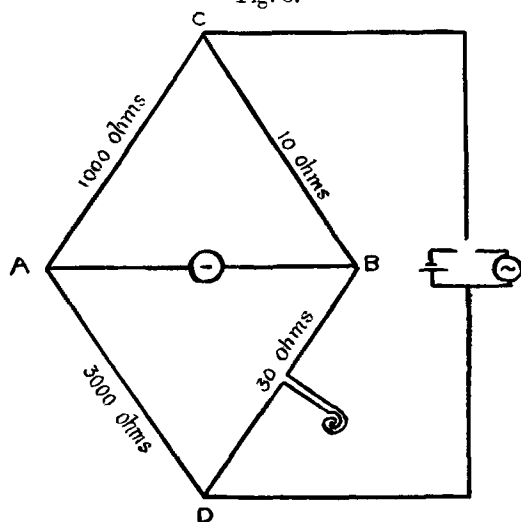
curves, it will be seen that within the limits of experimental error they are of the same wave-form, but that the E.M.F. curve lags about 120° behind the current curve.

These experiments having shown that an alternating current with a frequency of 20 passing through bismuth in a strong magnetic field produces an effect which may be represented by an alternating E.M.F. in the bismuth 120° behind the current, it remained to examine how the magnitude and phase of this "bismuth E.M.F." depend on the frequency of alternation.

For this purpose a different method of experimenting was adopted, the theory of which is as follows:—

Let an alternating E.M.F. be applied to a Wheatstone-bridge ADBC (fig. 3) containing the bismuth spiral in the

Fig. 3.



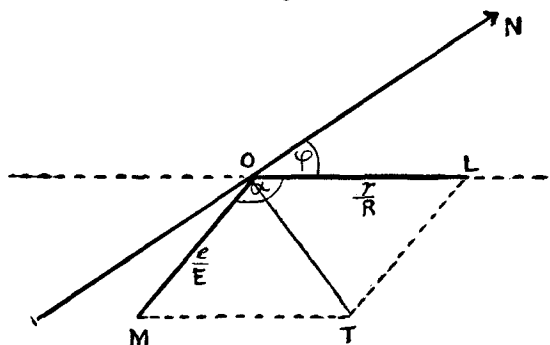
arm BD, and previously balanced for steady currents, so that the E.M.F. across BD is of the form $E \sin \theta$. Then the "bismuth E.M.F." produced in the spiral, lagging α° behind the current, will be of the form $e \sin (\theta - \alpha)$ —the largest value of e obtained in the experiments being only 3 per cent. of E , the current through the bismuth is practically in phase with the E.M.F. applied to B and D. There will now be a current through the galvanometer-arm AB, which being proportional to e may be written $K \frac{e}{E} \sin (\theta - \alpha)$. K depending on the resistances in the bridge.

This current is represented by OM in fig. 4.

If now a small resistance r be added to the resistance R in AC, a second current having the value $K \frac{r}{R} \sin \theta$ —represented in fig. 4 by OL—will pass through the galvanometer-arm. These two currents will have a resultant the magnitude and phase of which is given by OT.

This resultant current being alternating will produce no deflexion of the galvanometer; but let a two-part commutator, attached to the dynamo-shaft making one revolution per alternation, be introduced into the galvanometer-arm, and so arranged that the brushes can be set to commute at any desired phase, ϕ , of the current supplied to the bridge— ϕ is represented by the angle LON in fig. 4. In general

Fig. 4.



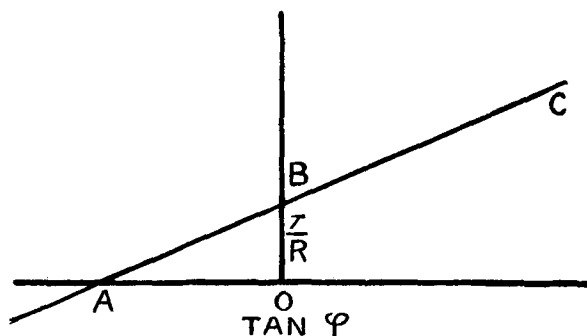
the galvanometer will now show a deflexion, but there will be one position of the brushes which will completely commute out the galvanometer current, and reduce the deflexion to zero. This will clearly happen when commutation takes place a quarter of a period ahead of or behind the galvanometer current, that is when the line ON in the diagram is perpendicular to OT. When this is the case it is at once seen from the diagram by projecting MT on OL that

$$\frac{r}{R} = \frac{e}{E} (\cos \alpha + \sin \alpha \tan \phi).$$

It having been found by experiment that for a given frequency e is proportional to E , this equation shows that if the frequency—and therefore $\frac{e}{E}$ and α —be fixed, $\frac{r}{R}$ is a linear function of $\tan \phi$; so that if a series of corresponding values

of $\frac{r}{R}$ and ϕ , for which the galvanometer deflexion is reduced to zero, be obtained experimentally, and $\frac{r}{R}$ be plotted against $\tan \phi$, a straight line such as ABC (fig. 5) will be obtained ;

Fig. 5.



and since

$$\cot \alpha = AO,$$

and

$$\frac{e}{E} = \frac{OB}{\cos \alpha},$$

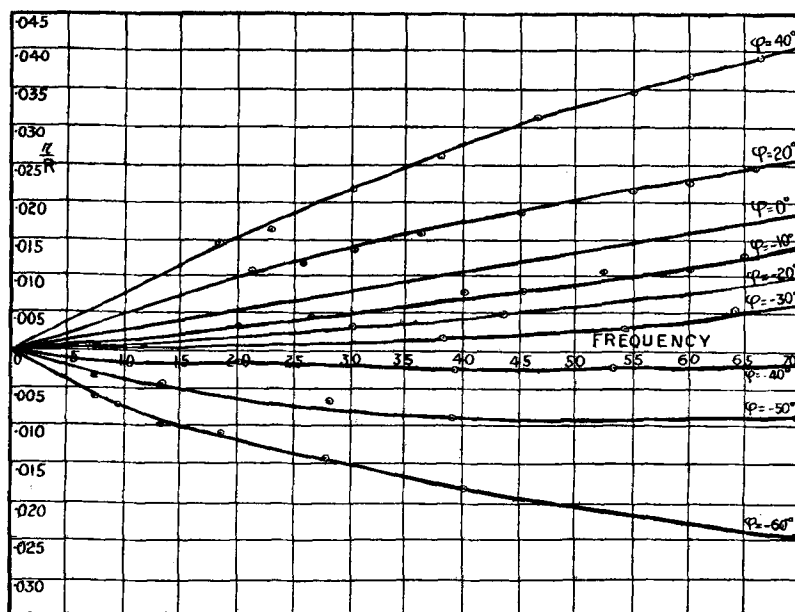
the values of α and $\frac{e}{E}$ can at once be deduced for that particular frequency, and for other frequencies in a similar manner.

In order to carry this theory into practice it was necessary to balance a Wheatstone-bridge containing the bismuth by means of a steady current; then to substitute an alternating current, put a commutator into the galvanometer-arm so as to commutate any current through the galvanometer, and to reduce the consequent deflexion of the galvanometer to zero by means of a change in the resistance of one of the ratio arms. When this was attempted practical difficulties were met with, chiefly due to the fact that the real resistance of the bismuth was continually undergoing a slight change owing to fluctuations in the temperature of the room and in the magnetic field. Although these changes were only small they were quite sufficient to mask the effect looked for if many seconds were required to readjust the bridge.

This difficulty was overcome by having a switch so arranged that when it was in one position a steady current from a cell was applied to the bridge, and the galvanometer connected straight across AB; while when it was in another position

the cell was replaced by a dynamo; a commutator, on the dynamo shaft, was introduced into the galvanometer-arm, and a shunt was connected to the ratio-arm. When this had been done it was quite easy to keep the bridge balanced for steady currents, the necessary change in the resistance of the ratio-arm being made by means of the shunt.

Fig. 6.



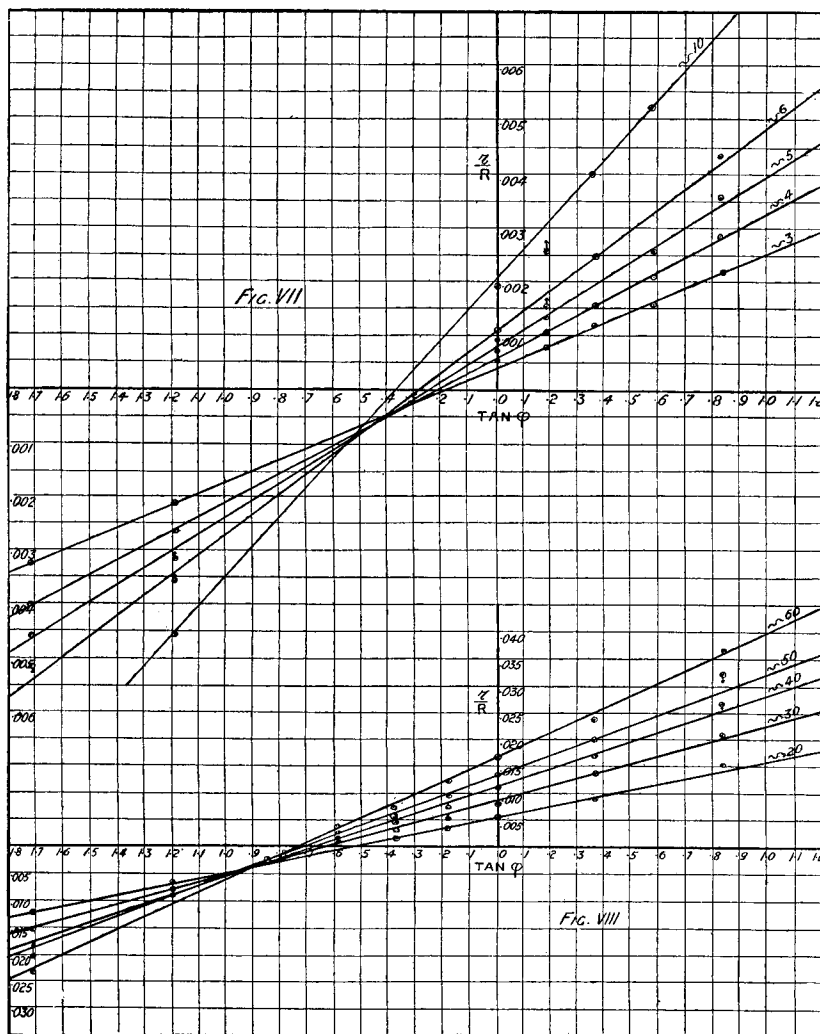
Two series of experiments were made: the first dealing with frequencies between 10 and 70 per sec., in which the alternating current was obtained from the dynamo mentioned above; and the other dealing with frequencies between 3 and 10 per sec., the alternating current in this case being obtained from a liquid commutator which gave a current having an accurate sine wave form.

In performing an experiment it was found best to set the brushes of the commutator in the galvanometer circuit to commute at a known angle ϕ , and then to find the ratio $\frac{r}{R}$ for different frequencies.

The results from such a series of experiments are shown in fig. 6; from these curves another series was drawn, figs. 7 & 8, in which the values of $\frac{r}{R}$ for a given frequency are

plotted against $\tan \phi$. These latter are straight lines as explained above, and give at once the values of α and $\frac{e}{E}$ for

Figs. 7 & 8.



each frequency. It is also interesting, having obtained the values of α and $\frac{e}{E}$, to split the "bismuth E.M.F." up into

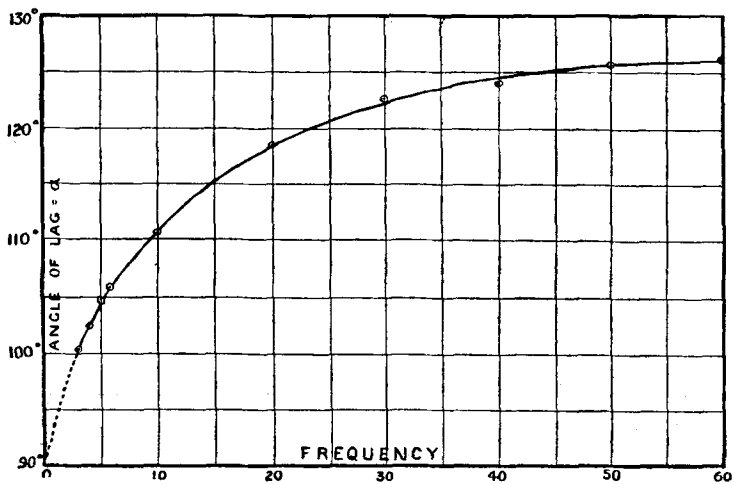
two components, one 90° and the other 180° behind the current, for the former component may be considered as due to something in the nature of self-induction, and the latter to a real rise in the resistance of the bismuth.

Table I. shows the values of α , $\frac{e}{E}$, $\frac{e}{E} \cos \alpha$ (the resistance component), and $\frac{e}{E} \sin \alpha$ (the self-induction component) for different frequencies.

TABLE I. (See figs. 9 & 10.)

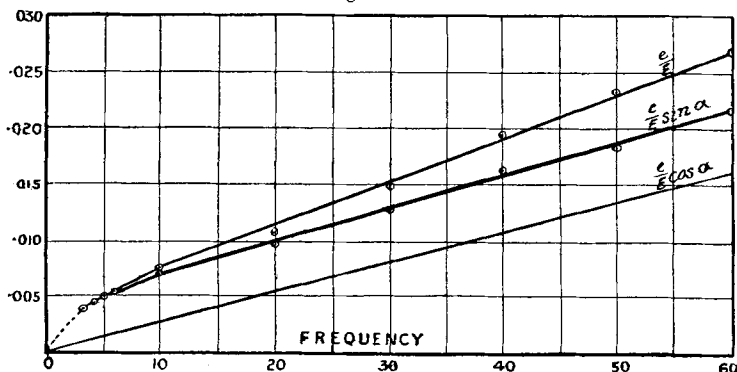
Frequency.	Angle of lag of "Bismuth E.M.F." behind the current producing it.	$\frac{e}{E}$	$\frac{e}{E} \cos \alpha$.	$\frac{e}{E} \sin \alpha$.
3	100 13'	·0040	·0007	·0039
4	102 25	·0047	·0010	·0046
5	104 35	·0052	·0013	·0050
6	106 20	·0054	·0015	·0052
10	110 20	·0075	·0026	·0070
20	118 20	·0112	·0053	·0098
30	122 40	·0148	·0080	·0125
40	123 50	·0194	·0108	·0161
50	125 45	·0230	·0135	·0188
60	126 30	·0269	·0160	·0215

Fig. 9.



The results of these experiments, although they do not indicate what really takes place in the bismuth, show that, whatever it is, it may be represented by an alternating E.M.F.

Fig. 10.



set up in the bismuth, the magnitude and phase of which for frequencies between 10 and 60 per sec. is very nearly given by the equations

$$\frac{e}{E} \sin \alpha = 0.0035 + 0.0003 n,$$

and
$$\frac{e}{E} \cos \alpha = 0.00266 n,$$

so that
$$\tan \alpha = 1.13 + \frac{13.2}{n},$$

and
$$\frac{e}{E} = 0.0035 + 0.00039 n.$$

On studying Curve I. (fig. 2) it can at once be seen that these conclusions explain the results obtained by M. Sadovsky. For, on closing the galvanometer-arm of a bridge, which has been balanced for steady currents during the 60° of rising current, a current represented by the area ADBC would pass through the galvanometer; this would appear to be due to a rise in the resistance of the bismuth. On closing the galvanometer-arm for the next 60° a current, represented by the area CDE, would pass through the galvanometer; this current would be less in value, but of the same sign as the previous one: hence, again, the resistance of the bismuth would appear to have been raised. This, then, accounts for the apparent fact that

$$R_r > R_m > R_e.$$

But when the galvanometer-arm is closed during the next 60° , the current through the galvanometer is in the opposite direction, for it is represented by the area EFG; thus R_d would appear less than R_c .

These experiments were made in the New Physical Laboratory of the Owens College, Manchester: where, in order to complete the research, I hope to be able to investigate the relations between the magnitude and phase of the "bismuth E.M.F." and the field-strength; also to investigate the whole effect at the temperature of liquid air.

XXVIII. Note on the Spark-discharge.

By SIEGFR. GUGGENHEIMER, *Ph.D.**

THE interest in the phenomena accompanying the spark-discharge in gases has been revived recently by a discussion between Mr. Swyngedauw† and Prof. Warburg‡. The complete discordance between the opinions of these authors led me to undertake the experiments described below with the view eventually to decide the question at issue. I may at once say that the result of my experiments and theoretical considerations is to confirm the views of Prof. Warburg.

1. The fact that the spark-potential is independent of the nature of the radiation employed to shorten the time of retardation (Warburg's *Verzögerung*) made it seem probable that this potential depends upon the momentary state, *i. e.* upon the degree of ionization of the gas. Therefore it was to be expected that the "Verzögerung" would also be destroyed, or at least shortened, if, instead of using direct radiation, we introduce a sufficient number of ions in the space containing the sparking system. The experiments confirmed this expectation.

2. In the sides of a brass tube 20 cm. long and 3 cm. interior diameter were fitted two ebonite plugs facing one another. Through each of these plugs passed a brass wire terminated inside the tube by a brass ball of 7 mm. diameter.

* Communicated by Prof. J. J. Thomson, F.R.S.

† R. Swyngedauw, *Journ. de Phys.* ix. p. 488 (1900); Bichat & Swyngedauw, *Rapports of the Paris Congress*, iii. p. 164 (1900).

‡ E. Warburg, *Verhandlungen der Deutsch. Phys. Gesell.* ii. p. 212 (1900).