THE ARC IN A MAGNETIC FIELD.

By C. D. Child.

THE following is an account of certain phenomena observed when the electric arc is placed in a magnetic field. A preliminary description of these were given before the American Physical Society in March, 1904, and an abstract of the work appeared in the Physical Review.[1]

The First Experiment.— The connections of the first experiment are shown in Fig. 1. *A* and *B* are two carbons 12 mm. in diameter. *c* and *d* are carbon pencils 3.1 mm. in diameter placed near to the side of the arc. These are connected through a millivoltmeter having a resistance of 177 ohms. This voltmeter was quite dead beat and the period was about 1 sec. An electromagnet is placed near the arc and produces a field normal to the plane of the figure.

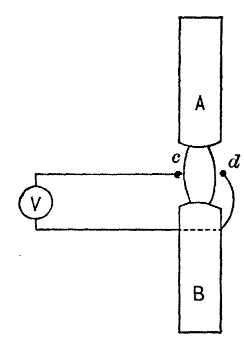

Fig. 1.

It was found quite impossible to place *c* and *d*, so that the potential difference between them continued to be zero, or even to place them so that it was constant. The pointer of the voltmeter would at times remain quite for several seconds and then change suddenly, sometimes changing only a slight amount and at other times reversing. It is impossible, at least, in air to keep the potential difference constant, because *c* and *d* are consumed rapidly and before the arc reaches a quiescent condition they are burnt away from it. But even though the reading of the voltmeter was not constant, it was evident that whenever there was a sudden change in the magnetic field, there was a corresponding change in the reading of the voltmeter. If the direction of the field was such that the arc was

[1] Phys. Rev., 18, 370.

displaced to the right, d would become positive, as compared with its former condition, and c negative; if to the left, c would be positive, and d negative. If in the first example d was already positive, it would become more so, and if negative, it would become less negative.

Electrometer Substituted for Voltmeter.— It was soon found that a voltmeter was not an ideal instrument for the purpose. As has been stated its resistance was only 177 ohms and the apparent resistance between the two pencils in the arc, even when they were very hot, appeared to vary from a few ohms to several hundred. On the other hand the period of such electrometers as were at hand was so great that the condition of the arc changed much during a reading. As has been stated, the rapid burning of the electrodes and especially the exploring pencils made it desirable to take readings as rapidly as possible. Moreover a voltmeter is a much more convenient instrument to use than an electrometer. As a result the experiments were nearly all performed first with a voltmeter and more careful measurements were afterwards taken with an electrometer. The electrometer used had a period of 16 seconds and was very nearly dead beat.

Thus the experiment already described was repeated using an electrometer instead of a voltmeter, and the same results were observed as before.

Modifications of this Experiment. — As will be seen later there is doubt about the real significance of this phenomenon, and consequently many variations of the experiment were tried. One of these may be described as follows: It has been shown that d in Fig. 1 has a higher potential when the arc is deflected by a magnet to the right and a lower one when it is deflected to the left. If A is the positive carbon, then the potential difference between A and d should decrease when the arc is shifted to the right, and increase when shifted to the left. Such changes were, indeed, found to occur.

On the contrary when the voltmeter was connected between B and d, the readings increased on deflecting the arc to the right, and decreased on deflecting it to the left. The opposite results followed when the exploring pencil was placed at c instead of at d.

A slight modification of this experiment was made by connecting a shunt between A and B and connecting d to some point of this shunt. The observation again indicated that the potential of d is increased when the arc is deflected to the right, and diminished when it is deflected to the left.

The electric force through the arc was also measured both with and without the magnetic field, and no difference could be detected in the two cases.

Rapid Reversing. — Since the potential difference between c and d was not for any length of time constant, an arrangement was used by which the ordinary fluctuations of this potential were eliminated and those produced by the magnetic field were retained. To do this the connections between c and d and the voltmeter were rapidly reversed. The voltmeter would thus normally show no deflection. But at the same time that these connections were reversed those running to the electromagnet were also reversed. The effect due to the magnetic field was thus shown as before.

The reversals were made by a wheel, as shown in Fig. 2. This was made of fiber, and was 10 cm. in diameter. It is a combination of a commutator and a collecting ring. 1 and 2 are connected to the carbon pencils, 3 and 4 to the voltmeter. With each revolution of the wheel two reversals would occur.

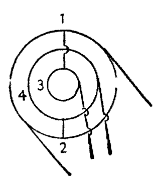

Fig. 2.

A similar arrangement was used for reversing the magnetic field the reversal of one circuit taking place at the same time as that of the other.

With this arrangement a reading of the voltmeter was attained which was at least always in the same direction, and the reading was reversed when the direction of the current through the arc was reversed, or the connections to the reversing wheel for the electro-magnet. The readings indicated as before that the current passed from d through the voltmeter to c, when the arc was deflected to the right.

The arc was then removed and c and d were connected by copper wires. No effect, whatever was then observed. This shows that the effect was not due to any E.M.F. induced by the alternations of the magnetic field.

Arc Deflected Mechanically. — But though the accuracy of the first observations was thus proven, there was still the possibility that the magnetic field was not the direct cause of the observed effect, that rather the mechanical motion of the arc was the direct cause. To test this the arc was blown to one side by a blast of air. This usually produced a smaller reading of the voltmeter whatever that reading might be, when that instrument was used. This was due to the fact that when the arc is blown to one side, the resistance between the pencils is increased.

When an electrometer was used, it was found that with the arc blown sufficiently to one side, so that one of the pencils became much cooler than the other, the cool one always became charged positively. Further investigation showed that the space about the arc had a higher potential than the arc itself and that when the arc was blown away from one of the pencils, that pencil became charged positively, merely because it was assuming the potential of the surrounding space.

The difference between the phenomenon in this case and that when the arc was deflected by a magnet was especially noticeable when the arc was entirely displaced from one of the pencils. Such a pencil was charged negatively when the arc was deflected by a magnet, and positively when deflected by a blast of air.

Moreover as long as both carbons were kept very hot no regular effect could be detected by blowing the arc, while deflecting it by a magnet always produced an effect.

The difference in these results was also strikingly shown when the potential difference between one of the pencils and one of the electrodes was examined. It has already been stated that in certain cases such potential differences increased, while in others they decreased, when the arc was deflected by a magnet. When it was blown to one side the potential difference in every case increased, provided the exploring carbon was kept in that part of the arc where the conductivity was good.

Further Test of Effect Produced by Mechanical Motion. — In order to test further the suggestion that the effect here studied was produced by the mechanical motion of the arc and not by the magnetic field, a fan was arranged which blew the arc first in one direction and then in the other. This arrangement is shown in Fig. 3. *W* is a wheel taking the place of the reversing wheel previously described. P is a pin fastened to the wheel and moving in the slit RH. H is a hinge. At R two fans F and F' are fastened at R and the arc is placed between them.

The reversals of the motion of the fan occurred at the same time as those of the connections to the voltmeter, so that this arrangement produces the same effect as far as mechanical motion is concerned as the magnetic field. But no deflection of the voltmeter was observed even when the velocity of the fan was increased until the arc was blown out.

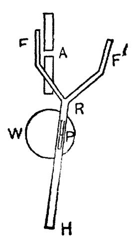

Fig. 3.

Varying the Rapidity of the Reversals. — The first thing varied was the period of the reversals. This tests again the possibility that the effect is due to the unequal heating of the two carbon pencils. Though the temperature of the carbon of the arc follows very closely the fluctuations of the arc, there was the possibility that the reversals could be produced so rapidly that the effect would decrease. It was found, however, that increasing the rapidity of the reversals did not diminish the effect. Thus when the number of reversals was increased from 4 per second to 25 per second, the reading of the voltmeter diminished from .35 volts to .30 volts. Several observations were made, but this is the average, and further investigation showed that this decrease in the reading is not due to any change in the conditions of the arc, but to the self-induction of the electro-magnet and the voltmeter and to changing contact resistance.

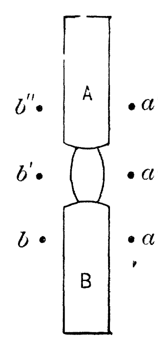

Fig. 4.

Distance Between Exploring Pencils Varied. — The distance between the exploring carbons was then varied. It was found, however, that the results obtained when the pencils were more than 7 or 8 mm. apart depended very largely on the height of the exploring carbons. Thus at ab the potential difference was small, at $a'b'$, it was much larger, while at $a''b''$, it was reversed. It was probably small at ab because there they were only barely touched by the arc. At $a'b'$ they were more directly in the arc. At $a''b''$ the effect appeared to be due to the mechanical motion of the arc, and not to any magnetic cause. If the arc is blown to the right b'' will be in the hot gases arising from the arc more than a''. It will consequently have more nearly the potential of the arc, and as we have seen the arc is negative as compared with the surrounding space.

Current through Arc Varied. — The current through the arc was varied from 5 to 25 amperes, but no definite change in the potential difference between the exploring pencils was discovered. According to the measurements taken the change was at least less than one part in twenty.

Length of Arc Varied. — The effect was found to increase when the length of arc was increased. The following observations were taken, using an electrometer, the alternating apparatus, a current of 12 amperes, and a distance between the pencils of 9 mm.

TABLE I.

Length of Arc.	Potential Differences Between Pencils.
3	1.7
6	2.5
9	3

Strength of Field Varied. — Next the strength of the field at the arc was varied. To determine the strength of the magnetic field a long solenoid 3.5 sq. cm. in cross section was wound with 13.8 turns per cm. One hundred turns of wire were wound about this and the throw of a ballistic galvanometer was observed when a given current was sent through the primary turns. This was compared with the throw produced by 100 turns at a given distance from the electromagnet which had been used with the arc. The effects observed in this way with the electromagnet at different distances from the arc are given in Table II.

TABLE II.

Distance from Solenoid.	Magnetic Field.	Potential Difference Between Pencils.
6	13.4	4
9	7.5	3
12	5	2.2
15	3	.8

The distances between the arc and the end of the magnet are given in column 1, the strength of the field in electromagnetic units in column 2, and the potential difference between the exploring carbons in volts in column 3. The current through the arc was 12 amperes and the length of the arc was 5 mm. These readings were taken with the electrometer and alternating apparatus.

Phenomenon Dependent on Quality of Carbons Used. — While making these observations it was found that the amount of the effect depended very largely on the kind of carbon used. Those first used were solid, but in changing the apparatus cored carbons were unintentionally substituted, and for some time none of the experiments which had been performed could be repeated. In time it was found that it was the change in carbons which caused the difference. It was found that, in general, solid carbons gave a greater effect than cored. It happened that the first ones used gave a greater effect than any others investigated. I do not know their make, as they had been in the laboratory a number of years.

Different Substances in the Arc. — Further investigations showed that the effect was diminished very much when certain salts were placed in the arc. Indeed with some it vanished entirely. In testing this a hole was drilled for 2 or 3 cm. into the carbon and this was filled with the salt to be investigated. Only a very small effect was found with NaCl, and none whatever with KNO_3. Moreover, no effect was found with the arc between iron or copper terminals.

An attempt was made to use graphite terminals, but it was found difficult to maintain any arc with the terminals far enough apart to insert the exploring carbons, even when using a voltage of 200 volts, and when the exploring carbons were inserted a very small magnetic field was sufficient to extinguish the arc. As a result no measurements were made with graphite terminals.

Phenomena in a Vacuum.— It was also found that the effect disappeared in a vacuum. The observations were made in a tube which has been described in a previous article[1] the exploring pencils were 1.6 mm. in diameter. They were led into the tube by the method which had been previously used in examining the electric force in the arc. A series of readings thus taken are given in Table III., the distance between the exploring carbons was 5 mm. and they both became white hot while in the arc. The arc was 7 mm. long. The current was 10 amperes. The end of the electro-

[1] PHYS. REV., 19, 117.

magnet was 7 cm. from the arc, making the field at the arc 10 electomagnetic units. Column 1 gives the pressure of gas in millimeters of mercury. Column 2 gives the difference in potential between the exploring carbons in volts.

TABLE III.

Pressure of Gas.	Potential Difference Between Pencils.
750	3.3
550	2.5
400	1.9
300	2
200	1.2
100	.7
50	.4
20	.2

At 6 mm. pressure no effect could be detected either with an electrometer or with a voltmeter. A galvanometer having a constant of 3.6×10^{-5} ampere per scale division was also used and it was even then impossible to detect any effect. The galvanometer had a resistance of 445 ohms and a period of 13.5 sec.

It seemed useless to try a more sensitive galvanometer. For without any magnetic field the potential differences betwen the two pencils in the arc fluctuated from zero to .2 volt and one cannot well eliminate an effect of this size so completely as to study one which was less than .001 volt.

Possible Explanations.— During the experiments it was noticed that a magnetic field has less effect in deflecting the arc to one side when it is in a vacuum than when in air. Thus the field used with the vacuum was 15 units and it scarcely affected the appearance of the arc, while it extinguished it entirely when using the same length of arc and same current in air. It was thought at first that this might possibly be the cause of the disappearance of the effect in a vacuum. But the effect also decreases when NaCl was placed in the arc, and in that case the arc is blown fully as much to one side as with ordinary conditions.

In a recent article by Weintraube[1] it is stated that when a magnetic field is produced about a mercury arc in a vacuum the bright spot at the cathode moved in one direction, while the vapor of the

[1] Phil. Mag. (6), 7, 95.

arc moved in the opposite. Special notice was, therefore, taken of the arc in air and it was found that generally the bright spot did not move at all, when the magnetic field was produced, but that when it did, it moved in the same direction as that of the vapor of the arc.

It is evident that an explanation for these phenomena must explain the many cases where the effect disappears. We find that wherever it disappears the drop in potential at the anode is much smaller than it is with carbons where it is large. Thus with a solid carbon the drop in potential between the anode and an exploring pencil placed as near to it as possible was 41 volts. With a cored carbon with which the effect was scarcely noticeable the drop was 30 volts. With the iron with which experiments were performed it was 16 and with copper 21 volts. In a previous article[1] it has been shown that with the carbons there used the drop was 50 volts with a pressure of 730 mm. of mercury, 43.5 at one of 200 mm., and 26.8 at 10 mm. Thus is all cases where the effect disappears the drop in potential at the anode is much diminished.

There is another set of facts with which the phenomena may be connected. It was shown in a previous article that with ordinary carbons the positive discharge from an arc to a surrounding cylinder was greater than the negative.[2] This indicated that the positive ions had the greater velocity. When salts were placed in the arc, or when other electrodes than carbon were used, the negative discharge was approximately as great, or even greater than the positive. In a more recent article[3] it was shown that in a vacuum the negative discharge again became the greater. So that in all cases which have thus far been studied when the drop in potential at the anode is small, the discharge from an arc to a cylinder becomes relatively larger and the effect due a magnetic field disappears.

In view of the complications existing in the arc it may be unwise to offer any explanation of the phenomena here described, and yet an attempt to do so may lead at least to further investigation, and I would, therefore, suggest the following:

[1] Phys. Rev., 19, 120.
[2] Phys. Rev., 12, 137.
[3] Phys. Rev., 19, 125.

The usual equation for the Hall effect is $Z = \frac{1}{2} XH(u - v)$ where Z equals the electric force due to the Hall effect; X, the impressed electric force; H, the magnetic field; and u and v, the velocities of the positive and negative ions respectively for unit electric force. The directions of the quantities are those indicated in Fig. 5. If we should apply these equations to the arc we would conclude that the positive ions have velocities enormously greater than the negative.

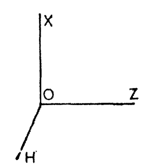

Fig. 5.

However, in deriving this equation the assumption is made that the ions have no component of motion perpendicular to the X direction, whereas in the arc there is such motion. It is the motion of the ions to one side which causes the arc to be deflected. This equation, therefore, can not be said to hold in this case. However, from physical considerations we shall be led to the same general conclusion as when treating the matter mathematically, that is, we are led to believe that the positive ions have the greater velocity.

In the arc both positive and negative ions are deflected, but those having the greater velocity will be deflected most. This can be shown as follows:

Let $e =$ the charge on an ion.

Let $m =$ the mass of the ion.

Let $H =$ the magnetic force in the direction of the Y axis.

Let $X =$ the electric force in the direction of the X axis.

Let x and z be the distances from the origin along the X and Z axes to the point where the ion is at a given instant.

If the X, Y, and Z axes are at right angles to each other and if the ion starts from a condition of rest at the origin

$$y = \frac{X}{\omega H}(\omega t - \sin \omega t)$$

and

$$x = \frac{X}{\omega H}(1 - \cos \omega t)$$

where

$$\omega = \frac{He}{m}.[1]$$

[1] Thomson's Conduction of Electricity through Gases, 88.

If t_1 is the time necessary for the ion to move over its mean free path and x_1 and y_1 the corresponding values of x and y,

$$\frac{y_1}{x_1} = \frac{\omega t_1}{3} - \frac{(\omega t_1)^3}{90} + \cdots$$

But the average velocity during this time, if there had been no magnetic force would have been $Xet_1/2m$. This will be the same as the average velocity for any number of mean free paths and if we let v_a equal the average velocity when the electric force is one

$$v_a = \frac{et_1}{2m}.$$

Then

$$\omega t_1 = \frac{Het_1}{m} = 2Hv_a$$

and

$$\frac{y_1}{x_1} = \frac{2Hv_a}{3} - \frac{(2Hv_a)^3}{90} + \cdots$$

If now $v_a = 1000$ cm. per sec. for one volt per sec. and $H = 10$ E.M. units the ratio between the first and second term equals $\frac{2}{3}\, 10^{-9}$, so that for such cases as are here considering $y_1/x_1 = \frac{2}{3}Hv_a$.

There will be $1/x_1$ of the collisions per cm. so that the total deflection in going 1 cm. in the x-direction $= y_1/x_1 = \frac{2}{3}Hv_a$ which is greater, the greater the average velocity of the ion.

This case is evidently quite different from that of cathode rays. There practically all of the deflection takes place while the ion is moving with uniform velocity, while here it is supposed to occur where the velocity is uniformly accelerated.

If then the negative ions are deflected most, the part of the arc to the right, namely, in the Z direction, will have an excess of negative ions, and the potential at the right will be lower than that at the left. If on the other hand the positive ions have the greater velocity, then the potential at the right will be positive as compared with that on the left. This latter is what was found to be the case. The potential on the side toward which the arc was deflected was greater than that from which it was deflected. We are, therefore, led to believe that in the arc the positive ions move more rapidly.

That this should be so in a place as hot as the electric arc is not what one would have expected. Yet reasons for believing that this is possible have been given elsewhere.[1] When the anode is very hot we may expect ebullition of the anode with subsequent condensation on the negative ions, causing them to move more slowly. This slow movement would react on the drop in potential at the anode, making it greater.

On the other hand where there are negative ions formed with greater ease, as with NaCl, there would be less ebullition and less condensation on the negative ions. This would account for the smaller drop at the anode, for a greater negative discharge to a surrounding cylinder, and for the disappearance of the magnetic effect if, as would appear, this effect is due to the greater velocity of the positive ions.

It has also been found that there is less condensation on the negative ions when in a vacuum and that there is a corresponding increase in their velocity.[2] This again would explain the smaller drop in potential at the anode, the greater discharge from the arc, and the disappearance of the effect which we have been studying.

But on the other hand it would not explain why the effect does not appear in a vacuum in the opposite direction. Therefore, we can not as yet consider this as a complete explanation.

Summary. — If two carbon pencils are placed on the opposite sides of an arc, the potential difference between them is changed when the arc is deflected toward one of them by means of a magnetic field. This change may be as high as four volts. The effect can not be produced by blowing the arc to one side, nor by moving the carbon pencils to one side of the arc. Rapidly reversing the field and with each reversal reversing the connection to the voltmeter does not diminish the effect.

The effect decreases as the strength of the field is diminished. Changes in the current through the arc do not appreciably influence it. It is, however, increased by lengthening the arc.

The effect is smaller with cored than with solid carbons. It decreases and in some cases entirely disappears when salts are

[1] Phys. Rev., 15, 346.
[2] Phys. Rev., 15, 349.

placed in the arc, and it could not be detected with an arc between metals. An attempt was made to observe it with graphite terminals, but it was impossible to maintain an arc between such terminals when in a magnetic field.

The effect decreases as the pressure on the surrounding gas is diminished and with a pressure of approximately 1 cm. of mercury it disappears.

The common equation for the Hall effect does not apply in this case, since there is here a motion of the ions transverse to the direction of the impressed E.M.F. It is possible, however, to explain almost all of the observations by assuming that the positive ions move more rapidly than the negative ones.

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December, 1904.