ART XIX.—*On the Rotation of the Equipotential Lines of an Electric Current by Magnetic Action*; by E. H. HALL, Instructor in Physics at Harvard College.

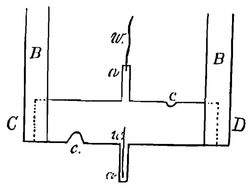
IN this article the results will be given of experiments made during the month of August, 1883, and at intervals since, in the Physical Laboratory of Harvard College. The substances which have been chiefly examined are copper, zinc, certain of their alloys, and iron and steel. Some mention will be made also of gold, cobalt, nickel, bismuth and antimony. In most cases when possible the metal was used in the form of a thin strip about 1·1 cm. wide and about 3 cm. long between the two pieces of brass B, B (fig. 1), which soldered to the ends of the strip served as electrodes for the entrance and escape of the main current. To the arms *a*, *a*, about 2 mm. wide and perhaps 7 mm. long, were soldered the wires *w*, *w*, which led to a Thomson galvanometer. The notches *c*, *c*, show how adjustment was secured. The strip thus prepared was fastened to a plate of glass by means of a cement of beeswax and rosin, all the parts shown in the figure being imbedded in and covered by this cement, which was so hard and stiff as to be quite brittle at the ordinary temperature of the air.

The plate of glass bearing the strip of metal so imbedded was, when about to be tested, placed with B, B, vertical in the narrow part of a tank whose horizontal section is shown in fig. 2. This tank T T containing the plate of glass with the metal

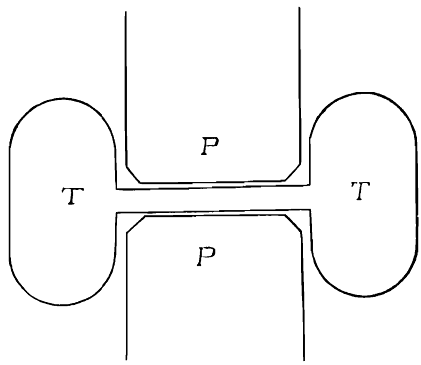
* Bull. Amer. Mus. Nat. Hist., vol. i, p. 140.

strip was placed between the poles P, P, of the electromagnet. The tank was filled with water which was sometimes at rest and sometimes flowing. By this means the temperature of the strip of metal was under tolerable control and the inconven ience from thermoelectric effects at *a* and *a* considerably lessened. The diameter of the plane circular ends of the pole pieces P, P, is about 3·7 cm.

1.



2.



The general method of most of the experiments to be mentioned did not differ much from that described in this Journal for September, 1880. The intensity of the magnetic field was estimated as before, by the impulse given to a galvanometer needle when a small coil in connection with the galvanometer was suddenly removed from the field. This impulse was compared with that given to the same needle by the current obtained by turning an earth inductor of known dimensions.

The direct current through the strip under examination was measured by means of a tangent galvanometer. The transverse current was measured by means of a Thomson galvanometer, the reduction factor of this instrument usually being determined by passing through it a current of known strength a few minutes before and a few minutes after each set of observations on the transverse current.

The rotational powers will, then, be given in ostensibly absolute measure, but an uncertainty of several per cent attaches to the values given owing to uncertainty in regard to the following quantities: 1st, the thickness of the strips examined; 2d, the dimensions of the small test coil used for getting strength of magnetic field; 3d, the horizontal intensity of the earth's magnetism; 4th, the reduction factors of the tangent galvanometer used; 5th, the magnitude of the direct effect exerted by the electromagnet upon the Thomson galvanometer at a distance of about 50 feet.

One of the most tr ublesome operations in these experiments is that of determining the thickness of the metal strips examined. Owing to the inevitable slight roughness of the surface, direct measurement with calipers is likely to give too great a thickness. On the other hand the density of many specimens is subject to considerable uncertainty and, therefore, the indirect method by means of weight and density, which is the method used, cannot be applied with full confidence. Moreover the latter method gives, at best, only the average thickness of the strip, whereas I have heretofore assumed, and in this article still assume, that the effective thickness of the strip is the thickness of that part which lies between the two arms *a*, *a*. My practice of late has been, therefore, to determine the average thickness by the weight and density method, making use of the best data available, and to estimate the thickness between the arms by adding to, or subtracting from the average thickness, according as the calipers indicated the thickness at that place to be greater or less than the average. In case of several of the strips to be mentioned hereafter this correction was somewhat carelessly made and there may be an inaccuracy of four or five per cent in the estimated "effective thickness." With other strips much care was taken in this respect and it is believed that the uncertainty in regard to the density of the metal is the greatest source of error in determining the thickness in these cases. Particulars will be given as the strips are in turn described.

The 5th source of error was very troublesome in the experiments upon certain alloys. The galvanometer was unfortunately so placed that not only the magnitude but even the direction of this effect of the electromagnet might be varied when by any means the galvanometer needle was turned a few degrees from its ordinary position of rest.

Copper, Zinc and their Alloys.

More than three years ago (B. A. Report, 1881), I found that if the rotational power of copper is called —, that of zinc is +. At the same time a specimen of brass, exact composition unknown, had been found to lie between copper and zinc in this respect, but nearer the copper, having in fact a small — rotating power.

Through the kindness of Prof. Trowbridge and Mr. E. K. Stevens, I had at command in the summer of 1883 several alloys of copper and zinc in widely varying proportions. Specimens of these alloys had been analyzed chemically by Mr. Stevens, but as they had lain for some time in an exposed position after he had finished his work upon them, I feared the labels upon them might not be intact, and Mr. G. D. Moore of the Harvard class of 1884 has been kind enough to make new analyses for me, determining both the copper and the zinc in specimens furnished him in the form of thin strips such as were used in my own experiments. Mr. Moore found

Specimen.	Copper.	Zinc.
A	99·9 per cent.	----
B	81·08	18·51 per cent.
C	72·86	27·02
D	66·85	33·04
F	5·87	93·79
G	a trace	99·54

Specimen E which contained apparently about 50 per cent copper was so brittle that I did not succeed in getting it rolled into a thin sheet.

Most, if not all, of these specimens were annealed one or more times during the process of rolling. None of the strips examined, however, were annealed after the final rolling. All of the strips which were used were cut in such a way that the arms *a*, *a* extended in that direction in which the strips passed through the rolls.

As it is a somewhat troublesome matter to determine accurately the density of a thin strip of metal and as my immediate purpose did not demand great accuracy in this respect, it seemed allowable to estimate the density of the alloys from their composition. After certain rough experiments the density 8·9 was assumed for the copper, and 7·2 for the zinc. Assuming, what we know to be not strictly true, that the density of an alloy decreases regularly as its amount of zinc per unit mass increases, we find

Alloy.	Density.
B	8·6
C	8·4
D	8·3
F	7·3

The description of particular strips will now be given.

A. (No. 1.)

Length of main strip when weighed	4·20 cm.
Width of main strip when weighed	1·07 cm.
Area including that of the arms	4·98 cm. sq.
Weight	·202 grm.
Density	8·9
Average thickness from above	·00456 cm.

By calipers the thickness appeared to be at one end ·0046; other end ·0044; between arms ·0048; average ·0046. Take then for true thickness between arms ·00476.

The measurement with calipers in this case was not made with great care, and the correction here applied is open to some suspicion.

With this strip the space between the brass strips B, B (fig. 1) was about 3·2 mm.

B. (No. 1.)

Length of main strip when weighed	4·58 cm.
Width of main strip when weighed	1·08 cm.
Area, including that of the arms	5·32 cm. sq.
Weight	·184 grm.
Density	8·58
Average thickness from these data	·00403 cm.

From the indications of the calipers I concluded that the thickness between the arms was about 1½ per cent greater than the average thickness.

Hence thickness between the arms, ·00409 cm. This value, like that given for A, may be wrong to the extent of several per cent. Distance between strips B, B, about 3·2 cm.

C. (No. 1.)

Length of main strip when weighed	3·75 cm.
Width of main strip when weighed	1·08 cm.
Area of whole strip when weighed	4·39 cm. sq.
Weight	·1085 grm.
Density	8·44
Average thickness from these data	·00292 cm.

By calipers thickness at one end, ·0034; at other end, ·0032; between arms, ·0034; average, ·00333 cm. Take then for true thickness between arms ·00299 cm. Distance between strips B, B, about 3·2 cm.

D. (No. 1.)

Length of main strip when weighed	3·86 cm.
Width of main strip when weighed	1·07 cm.
Area of whole strip	4·45 cm. sq.
Weight	·1081 grm.
Density	8·33
Average thickness from these data	·00291 cm.

By calipers thickness at one end, ·0030; at other end, ·0030; between arms, ·0032; average, ·00307 cm. Take for true thickness between arms ·00304 cm. Distance between strips B, B, about 3·2 cm.

F. (No. 1.)

Length of main strip when weighed	3·70 cm.
Width of main strip when weighed	1·06 cm.
Area of whole strip when weighed	4·28 cm. sq.
Weight	·2915 grm.
Density	7·3
Average thickness from the data	·00934 cm.

By calipers thickness at one end, ·0098; at other end, ·0100; between arms, ·0100; average, ·00993 cm. Take for true thickness between arms ·00941 cm. Distance between strips B, B, about 3·2 cm.

G. (No. 1.)

Length of main strip when weighed	4·17 cm.
Width of main strip when weighed	1·09 cm.
Area of whole strip when weighed	5·03 cm. sq.
Weight	·1206 grm.
Density	7·2
Average thickness from these data	·00333 cm.

From a somewhat careful use of the calipers it appeared that the thickness between the arms was about 4½ per cent greater than the average thickness.

Take then for thickness between arms ·00348 cm. Distance between strips B, B, about 3·2 cm.

The main object in the experiments upon these metals and their alloys was to determine whether the alloys would range themselves according to any simple law so that the magnitude of the rotational power in any alloy might be inferred from its known proportions of copper and zinc. Some attempt was made, moreover, to determine the effect of change of temperature in different specimens.

It will be seen that the intensity of the magnetic field was kept nearly the same throughout the experiments of August upon copper, zinc, and their alloys. The strength of the direct current was, moreover, of about the same magnitude in all cases except the experiments of Aug. 11th on copper. On that day the current used was less than one half as strong as that used later. The same strip of copper was tested again Aug. 29th with a current of the usual strength and the agreement between the results obtained under so widely different conditions is quite close.

In the following table and throughout this article the C. G. S. system is used wherever no statement is made to the contrary. The following symbols used with the tables need explanation:

C means current along line C D (fig. 1).

M means intensity of magnetic field perpendicular to plane of paper in fig. 1.

R. P. means *rotatory power*, which is numerically defined by the expression $D\frac{E}{C\times M}$, in which D is the thickness of the metal strip, and E is the electromotive force resulting from C and M which maintains the *transverse* current.* The R. P. is considered *positive* when E is of such a character as to send a *positive* transverse current in that direction in which the conducting strip tends to move under the action of the main current and the magnetic force.

The temperatures referred to in the tables are those indicated by a thermometer placed in the water tank containing the plates when under examination (fig. 2).

Copper, Zinc, and their Alloys.

Strip.	Composition acc. to chem. anal.		Date.	Tem.	M	C	R. P. $\times 10^{15}$	R. P. near 24° C $\times 10^{15}$	Composition, etc.†	
	Percent Copper.	Percent Zinc.							P. c. Cop.	P. c. Zinc.
A	100 (99·9)		1883. Aug. 11	3°C.	5700	·0619	(−521)			
"	"		"	4·8°	5640	·0819	(−530)			
"	"		"	21·5°	5560	·0876	(−520)	(−520)		
"	"		Aug. 29	24·5°	6030	·1906	(−519)			
B	81·3 (81·08)	18·7 (18·51)	Aug. 18	25°	5750	·1800	(−404)	(−404)	91·3	8·7
C	73 (72·86)	27 (27·02)	Aug. 17	5·1°	5680	·1810	(−246)			
"	"	"	"	22·8°	5700	·1830	(−250)	(—250)	80	20
D	67 (66·85)	33 (33·04)	Aug. 13	6°	5830	·1680	(−178)			
"	"	"	"	25°	5930	·1680	(−166)	(−166)	73.6	26·4
F	6 (5·87)	94 (93·79)	Aug. 17	4°	5640	·1790	(+527)			
"	"	"	"	24°?	5690	·1780	(+496)	(+496)	24·3	75·7
G	0·0 (trace)	100 (99·54)	Aug. 15	4·4°	6150	·1860	(+838)			
"			"	25°	6130	·1850	(+830)	(+820)		
"			"	22·4°	6210	·1870	(+809)			

This table shows the results of experiments with the metal strips thus far described in detail. The last two columns give

* The R.P. of this article is the *reciprocal* of the quantity $\frac{M\times V}{E'}$ used in my article in the Amer. Jour. of Science, Sept. 1880.

† Composition of alloys which *à priori* might have been expected to have these values of R. P.

approximately the composition of plates which would have the observed rotatory powers if copper and zinc in uniting retained their individual powers unaltered. It will be perceived that in every case the proportion of copper demanded upon this basis is greater than the proportion in the actual plate.

At the time these experiments were made I supposed plate B to contain about 92 per cent of copper, which would have furnished an exception to this rule. Thinking some serious error might have been made in estimating the thickness of this plate, or that of the copper plate or the zinc, I prepared with very great care plates No. 2 of A, B and G. These new plates were similar to those already described, but were in length between B and B about 2·2 cm. As the vacation was now over and my opportunities for experimental work were limited, I contented myself with making, in the main, comparative experiments with these plates. I did not redetermine the horizontal intensity of the earth's magnetism and I made no attempt to determine the direct effect of the electromagnet upon the Thomson galvanometer with which the transverse current was observed. I knew that this direct effect was small and I endeavored to arrange matters in such a way that it would affect all the new results with A, B and G in the same direction and to nearly the same extent. The intensity of the magnetic field in the experiments with these plates was about the same as in the previous experiments with the alloys. This intensity was determined as usual on October 20th, when the effect of change of temperature upon the plate B No. 2 was tested, but on October 13th, when A No. 2 and B No. 2 were compared, and on October 27th, when A No. 2 and G No. 2 were compared, this determination was not considered necessary. On October 13th A No. 2 was tested first, then B No. 2, then A No. 2 again. This arrangement tended to make the result of the comparison independent of any progressive diminution in the strength of the current operating the electromagnet, and it saved much time. On October 27th the same method was followed.

I shall not attempt to give the result of these experiments in absolute measure, but shall write the results obtained on an arbitrary scale.

Specimen.		Per cent of Copper.	Per cent of Zinc.	Temp.	R. P.
A.	No. 2.	99·9	----	----	100(−)
B.	"	81·08	18·51	21°	76·1(−)
"	"	"	"	4°	78·7(−)
G.	"	----	99·54	----	158·8(+)

A No. 2 and B No. 2 were compared at about 25° C., A No. 2 and G No. 2 at about 19° C.

The values of R. P. given in the first table are in the following proportion:

		R. C.
A	No. 1.	100 (−)
B	"	77.6 (−)
C	"	157·5 (+)

This agreement was regarded as highly satisfactory, all things considered, and the apparent exception which, as stated above, had been noted in the case of B appeared to be confirmed. The result of the chemical analysis, however, showed that this alloy, which according to the label found upon it contained nearly 92 per cent of copper, really had the composition given in the tables above. Alloy B, then, does conform to the rule that the alloys of copper and zinc have rotating powers nearer to that of copper than the composition of the alloys would have led one to expect.

Influence of Temperature.

It will be seen that in the case of copper, zinc and all the alloys except C, a fall of temperature appears to cause a slight increase in the numerical value of of the rotating power. It is possible that upon further trial the apparent exception furnished by C would disappear. It does not, on the other hand, seem probable that the agreement in a particular direction of five cases out of six is entirely accidental. In the case of D the apparent change caused by fall of temperature is very considerable, but the observations made with this alloy were particularly unsatisfactory, the needle of the Thomson galvanometer being quite unsteady, while the total effect to be measured was small.

The experiments upon iron and steel were in the main repetitions of those already published, but made with more care.

Soft Iron.

The dimensions of the strip of soft iron used in the experiments were roughly as follows:

Length between terminals B, B, (fig. 1), ------	2·9 cm.
Width, ------------------------------------	1·06 cm.
Thickness, ----------------------------------	·0041 cm.

Like the strip used in 1882* it was obtained through the kindness of Prof. Langley of the Allegheny Observatory, and the two strips had probably nearly the same composition and character.

* This Journal, March, 1883.

Although the test made in 1882 was not satisfactory, it seemed to me to indicate that the R. P. of soft iron was slightly greater at high than at low magnetic intensities, and I hazarded the opinion that future experiments would prove this to be the case. This opinion has scarcely been justified by the result. The table given below does indeed appear to indicate a very slight increase in the R. P. as M rises from 801 to 3264 and again as M rises from 3264 to 5835, but the increase in the numbers as observed is too slight to deserve any confidence.

Date.	Temp.	M.	C.	R.P.	Estimated R.P. at 28°.
Aug. 22, '83.	6·2°	791·4	·1771	$+7147\times10^{-15}$	
"	28·2	797·6	·1742	+8302	
"	28·3	804·6	·1794	+8304	
	28·25	801·1		8303	$+8290\times10^{-15}$
Aug. 23.	28·1	3259	·1728	8306	
"	28·4	3274	·1702	8289	
"	27·65	3260	·1696	8306	
	28·05	3264		8300	$+8297\times10^{-15}$
Aug. 24.	28·7	5797	·1839	8391	
"	28·1	5833	·1842	8310	
"	28·0	5875	·1853	8245	
	28·27	5835		8315	$+8300\times10^{-15}$
Aug. 27.	27·25	8626	·1894	8139	
"	28·35	8690	·1898	8261	
"	27·95	8636	·1911	8200	
	27·85	8651		8200	$+8208\times10^{-15}$

Fall of R. P. for 1° fall of temperature equals approximately $\frac{2}{3}$ per cent.

On the other hand the decrease in the observed value of the R. P. as M rises from 5835 to 8651, though slight, seems to me strong evidence of an actual falling off in the value of the R.P. of iron at high magnetic intensities.

In any case it appears, and this was one of the important questions to be answered by the experiments, that the R. P. of iron under magnetic forces of varying intensity is more nearly constant than the R. P. of nickel, for according to previous experiments* the R. P. of nickel in a magnetic field of intensity 8700 is many per cent, perhaps 20, less than in a magnetic field of intensity 2000.

The one trial made at low temperature confirmed the inference drawn from a similar trial made the year before,† that a fall of 1° C. diminishes the R. P. in soft iron about $\frac{2}{3}$ per cent. It is with these experiments as a basis that I have ventured to

* Phil. Mag., Sept., 1881. † This Journal, March, 1883, p. 218.

make the slight changes necessary to deduce from the observed results the values of the R. P. at 28°.

A test was made with this strip of soft iron for a permanent change in the direction of the equipotential lines. A similar experiment with tempered steel the year before had been successful and the description of the method I will quote from a previous article (this Journal, March, 1883). "This plate, with the usual electrical connections, and with a current flowing through it, was placed in the usual position between the poles of the electromagnet, the magnet current was turned on, then off, and the plate removed from between the poles in order to avoid the action of the very considerable residual magnetism of the electromagnet. A reading of the Thomson galvanometer in the transverse circuit was now made, then the plate was replaced between the poles and the current turned on again but in the opposite direction. The magnet current being again interrupted, the plate was again removed from the field and another reading of the Thomson galvanometer was made." Making this experiment with the soft iron and with a battery of 50 cells, the result was a negative one. If any permanent effect was produced, it was probably a small part of one per cent of the temporary effect produced while the plate was subjected to the magnet's action.

Steel.

The steel used in this series of experiments was obtained from Montgomery & Co., New York, and was designated by the letters "F. C. R." which stand for "French Cold Rolled." This steel as it came from the dealers was pliable and soft enough to be quite readily cut with a pocket knife. The first strip to be described was tested in this "natural" condition.

No. 1 (*untempered.*)

Length of main strip when weighed	4·13 cm.
Width of main strip when weighed	1·10 cm.
Area of whole strip when weighed	4·88 sq. cm.
Weight	4·21 grm.
Density	7·9
Average thickness from these data	·01092 cm.
Estimated thickness between arms	·01116 cm.
Distance from B to B, about	3·1 cm.

No. 2 (*tempered.*)

The dimensions of this strip were not so carefully taken. It was so brittle that I felt obliged to use caution in applying the calipers to it. It appeared to be of about the same thickness as No. 7 and I assumed it to have exactly the same thickness. The distance from B to B was about 2·6 cm.

Results obtained with these two strips are shown in the following table:

	Date.	Temp.	M.	C.	R.P.
No. 1.	Nov. 24.	18·7°	1647	·0970	$+12000\times10^{-15}$
"	"	2·5	1629	·1007	$+11230\times$ "
		16·2			770

Decrease for 1° fall of temperature, approximately ·4 per cent.

No. 2.	Dec. 1.	18·°	1602	·0870	$+32720\times10^{-15}$
"	"	1·9	1587	·0908	$+30800\times$ "
		16·1			1920

Decrease for 1° fall of temperature, approximately ·4 per cent.

The magnitude of the rotational coefficient in the soft steel is about 1½ times, and that in tempered steel about 4 times as great as that in the soft iron. This agrees very well with the conclusion drawn from the hasty experiments of the year before, when a piece of steel from a clock-spring was used. When a sensitive galvanometer is used, an ordinary permanent horse-shoe magnet of half inch bar produces an easily discernible effect in the strip of tempered steel.

It should be stated that two or three months before the trials which furnished this table were made, both these steel strips had been subjected, in the usual position, to a magnetizing force of about 8500 intensity. It does not seem probable that the results just recorded were seriously affected by this previous experience of the steel.

This first magnetization was for the purpose of detecting, if possible, a *permanent* effect, such as had been observed a year before in a piece of tempered clock-spring, but had been vainly looked for in soft iron.

No. 2 showed a permanent effect equal to about 1½ per cent of the temporary effect, a result agreeing very well with that obtained with the tempered clock-spring. No. 1 showed a permanent effect relatively, and even absolutely, larger than that in No. 2. It was about 5 per cent of the temporary effect. In both cases the tests made were hasty, and the results obtained are only approximately correct. I believe it has been observed that residual magnetization is, under certain conditions, greater in soft than in hard steel.

Gold.

The only experiment of importance made with gold was a test for permanent effect. The strip used was the one experimented with the year before, a description of which has already been published (this Journal, March, 1883). The permanent effect, if any was produced, must have been a very small part of one per cent of the temporary effect.

COBALT.

In the Philosophical Magazine for September, 1881, I said, "No thin strips of the metal [cobalt] being at hand, a slice was sawn from a small block of moderately pure cast cobalt and worked into the form of a cross. To the extremity of each arm of this cross was soldered a thin strip of copper . . . . for the purpose of making the electrical connections. The cross of cobalt with the copper strips attached was now fastened with hard cement [beeswax and rosin] to a strip of glass," etc. It was the same piece of cobalt, reduced now with file and emery paper to a thickness of about ·0062 cm., that served during this new series of experiments. The central portion of the cross was about 2 mm. square, and the arms, about 3 mm. long and 2 mm. wide, projected from it at right angles.

The main object of the recent test was to determine the effect produced in cobalt by change of temperature. It is assumed that the intensity of the magnetic field remained constant during these experiments. It is possible, however, that it diminished one or two per cent during the series. The error introduced in this way is of slight consequence for the present purpose. Again, the direct effect of the electromagnet in disturbing the needle of the Thomson galvanometer was neglected, together with certain other particulars which may have introduced a constant error of several per cent into the values obtained for the rotatory power.

No. of Exp.	Date.	Temp.	M.	C.	R.P.
1.	Dec. 22, '83.	3°	3463	·1251	$+2092 \times 10^{-16}$
3.	"	1·3°	"	·1243	+2061
		2°			2076
2.	"	18°	"	·1238	+2441
4.	"	"	"	·1244	+2390
		18°			2415

Decrease of R. P. for fall of 1° C. is approximately $\frac{9}{10}$ per cent.

BISMUTH.

I can only confirm what Prof. Righi* has already published concerning the rotational effect in this metal. The rotational power appeared to be about 260 times as great numerically as that of tempered steel and of the opposite sign.

The slice of bismuth used was obtained, shaped and mounted in much the same manner as the slice of cobalt already described. The length and breadth of the bismuth cross were somewhat greater than the corresponding dimensions of the cobalt and the thickness was about 1 mm.

* Acc. dei Lincei Transunti, June, 1883.

It seems probable that a thin slice of bismuth, properly prepared and mounted, will come to be a valuable instrument for measuring the intensity of strong magnetic fields.

ANTIMONY.

The powerful effect observed in bismuth suggested an examination of antimony. A slice of this metal much like the slice of bismuth just mentioned was prepared. The cross suffered in shape a good deal in making the adjustment. The final average thickness in the central portion was estimated at 1·2 mm.

Date.	Temp.	M.	C.	R.P.
1884, July 26th,	21·8°	1696	·1150	$+114100\times 10^{-15}$
Aug. 8th,	21·1°	1638	·1104	$+117300\times$ . . .
Aug. 8th,	3°	1638	·1104	$+123900\times$ . . .

The two trials of August 8th were not entirely independent of each other, as only one test of the intensity of the magnetic field and of the sensitiveness of the Thomson galvanometer was made during the two trials of that date. The results as they stand indicate an increase of the rotational power with fall of temperature, but the experiments were too hasty to justify a conclusion upon the matter.

Several experiments have resulted from the criticisms or suggestions of other investigators.

MR. BIDWELL'S THEORY.

This has been so recently and so widely published that it is hardly necessary for me to state it in detail.

In *Science* (March 28th, 1884), I replied very briefly to Mr. Bidwell's first paper, stating that I found the transverse current in a strip of soft steel to be in the same direction when the strip was fastened to the supporting plate by a clamp across the middle of the strip only, as when it was fastened by means of clamps at its ends only.

Mr. Bidwell has in his second paper (Phil. Mag., April, 1884), described an experiment which he appears to consider conclusive against the previously accepted view of the "rotational effect." In brief he obtains what he calls a "reversal" of the transverse effect in gold, using a strip of that metal having two narrow longitudinal slits lying on the same straight line and nearly meeting in the center of the strip.

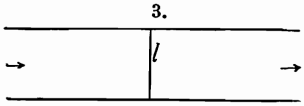
I shall not undertake here an extended discussion of this interesting experiment of Mr. Bidwell. My view of the matter is in substance as follows:

Let l in fig. 3 represent an equipotential line in a strip of metal through which an electric current is flowing, the metal being in a normal condition.

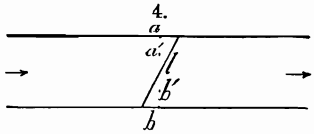
In fig. 4, l represents the corresponding equipotential line when the metal strip is acted upon by a powerful magnetic force in a direction perpendicular to the plane of the paper.

If now a and b be connected by means of a wire, a current will flow from a to b through the wire. If a' and b' be connected in the same way, a weaker current will flow from a' to b' through the wire.

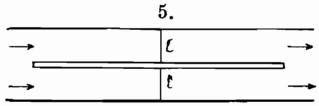
3.



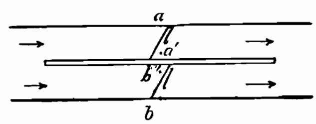
4.



5.



6.



7.

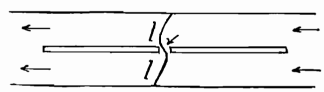


Fig. 5 represents a metal strip having along its middle a slit longer than the diameter of the magnetic poles between which the slit is placed, l and l being corresponding equipotential lines when the strip is in its normal unstressed condition.

Let a magnetic force act as before. Each of the lines l, l in fig. 5 is rotated about its center through the same angle as l in figs. 3 and 4. The result is shown in fig. 6.

If now a and b be connected by means of a wire a current will flow from a to b through the wire. If a' and b' be connected in same way a current will flow from b' to a' through the wire.

To get Mr. Bidwell's case, imagine a narrow bridge of metal to be left crossing the slit between a' and b'. Such a bridge would serve as a shunt to the wire which we have imagined connecting a' and b' but would not reverse the relative potentials of these two points. The lines l, l, as Sir Wm. Thomson pointed out at the Philadelphia meeting, would now take a form something like that shown in fig. 7.

As the bridge across the slit becomes wider such lines as l will become more nearly straight till finally the condition of things represented in fig. 4 will be practically reproduced. On the other hand if the slit in fig. 5, were short compared with the width of the poles of the magnet, a *reversal* such as Mr. Bidwell detected should not occur.

Mr. Tomlinson's Suggestion.

In the Philosophical Magazine for May, 1884, Mr. Tomlinson stated that certain relations which he had discovered indicated that the rotational effect in nickel should be greater at low than at high temperatures. He therefore called in question the conclusion to the contrary which I had drawn from certain hasty and very rough experiments made before the use of the water tank gave me the means of easily controlling the temperature of the metal under examination. I have, therefore, recently taken up the matter again. I used the same piece of nickel with which the former test was made (Phil. Mag., Sept., 1881, p. 163), but the strip was now so much damaged while being fastened upon glass that it was necessary to cut its width down a good deal in order to obtain the "arms" for the side connections. The following table shows the results obtained.

No. of exp.	Date.	Temp.	M.	C.	R.P.
1	July 28, '84.	22°	1717	·03074	14940×10^{-15}
2	"	4·9°	1703	·03135	13760 "
3	" 29,	20·5°	1652	·03140	14710 "
4	" 30,	2·2°	1636	·03123	12810 "
5	" "	21·2°	1629	·03121	15060 "
6	Aug. 1,	2·8°	1671	·03137	13180 "
7	" 4,	26·1°	1691	·03140	15110 "
8	" "	4·1°	1627	·03112	13220 "

Combining the 1st, 3d, 5th and 7th, we have

Temp.	R.P.
22·5°	14960×10^{-15}

From the 2d, 4th, 6th and 8th we have

3·5°	13240×10^{-15}

Decrease for 1° fall of temperature = approximately .6 per cent.

It will be noticed that the results obtained at low temperatures do not accord so well as those at high temperatures. This fact is in all probability due to the difficulty experienced in preventing slight fluctuations of temperature while the colder water was flowing through the tank. Irregularity in the flow of this water causes disturbing thermo-electric currents.

The quantity called R. P. in this paper corresponds to the $\frac{E'}{V}$ of my 1881 paper divided by the F of that paper. Calculating the R. P. of nickel from the 188 experiments I find it to be about 12700×10^{-15}, for a field of intensity 1660. In looking about for an explanation of this disagreement I found that the thickness of the strip had been called ·00104 cm. in 1881, and ·0012 cm. in the later experiments. The former estimate was obtained by weight, the latter by measurement with calipers. The difference accounts well enough for the different values obtained for the R. P. Which estimate of the thickness is the more reliable I will not undertake to decide.

Summary.

	$10^{15} \times$ R.P. at 20°C.
Copper	−520
Zinc	+820

Four alloys of copper and zinc were tested. If a series be made beginning with zinc and ending with copper, the four alloys being ranged between according to composition, the series thus formed will be the same as that obtained by ranging these metals and alloys according to the algebraic magnitude of their R. P's. In the alloys, however, the R. P's, are algebraically somewhat nearer that of copper than might be expected from the composition.

Iron	+7850

R. P. nearly constant through wide range of magnetic intensity but apparently decreasing slightly at high intensities.
No ascertained *permanent* effect.

Steel, *soft*	+12060

Permanent effect about 5 per cent of temporary effect.

Steel, *tempered,*	+33000

Permanent effect about $1\frac{1}{2}$ per cent of temporary effect.

Gold (no new test of magnitude of R. P.)	−660

No ascertained permanent effect.

Cobalt	+2460
Nickel	−14740
Bismuth	−8580000
Antimony	+114000

A fall of 1° C. in temperature causes

in the R.P. of	Iron,	a fall of	$\frac{2}{3}$	per cent approx.
	Steel, soft,	"	$\frac{1}{3}$	"
	Steel, temp'd,	"	$\frac{1}{3}$	"
	Cobalt,	"	1	"
	Nickel,	"	$\frac{2}{3}$	"
	Non-magnetic metals, apparently a small increase.			

Appendix.

At the Philadelphia meeting of the American Association I stated that I had compared the behavior of a strip of soft steel cemented to a plate of glass with that of a similar strip fastened to a plate by means of a clamp. In preparing the matter for publication, however, I found that the test had not been made so carefully as was desirable, and I have therefore just repeated the experiment with the assistance of Mr. W. A. Stone, of the Harvard class of 1886.

I shall call the cemented strip A. It has been already mentioned as No. 1 in the preceding article. The clamped strip I shall call B. Both strips were cut from the same sheet of soft steel. Each is about $1{\cdot}1^{\mathrm{cm}}$ wide and $3{\cdot}2^{\mathrm{cm}}$ long between the terminals of brass. A is about ${\cdot}011^{\mathrm{cm}}$ thick and possibly a few per cent thicker than B. A suffered rather more than B in the process of adjustment (fig. 1).

A was not only fastened to its plate with the cement of beeswax and resin, but was imbedded in the cement, the latter covering it with a layer probably a millimeter or more in thickness. The plate was not placed in water for this test. The bearing of the clamp which fastened B to its plate was of wood, possibly a millimeter wide, and extended nearly from arm to arm of the strip. To prevent any very great bending each end of the strip was loosely tied to the plate with a piece of twine. Otherwise the strip was free and was exposed to the air.

The measurements recorded below were made between five and six o'clock, January 17th. There was an interval of one minute between successive readings of the Thomson galvanometer. No measurement of the intensity of the magnetic field was made. It is assumed that this intensity during the one trial of A, which was made between the two trials of B, was equal to the mean intensity during these two trials.

The signs + and − refer to the direction of magnetization, R and L to direction from the zero point of the Thomson galvanometer scale. The zero position of the index in these experiments was a considerable distance to the right of the zero of the scale. The tangent galvanometer measured the direct current through the strip.

	Thomson Galv.		Tangent Galv.
			74·0°
	+	−	73·9
	53 R	0	73·7
Strip B.	52 "		73·7
	51 "	3 R	73·6
	52 −	1·5 = 50·5	73·8, tan. = 3·44

				74·9°
				74·8
	43 R		8·0 L	74·7
Strip A.	43 "		6·5 "	74·7
	43 "			74·6
	43	+	7·2 = 50·2	74·7, tan. = 3·66

				73·7°
				73·6
	54·5 R		7·0 R	73·5
Strip B.	53·0 "		7·5 "	73·4
	52·5 "			73·3
	53·3	−	7·2 = 46·1	73·5, tan. = 3·38

From 2d we have

$$\text{A.} \qquad 50{\cdot}2 \div 3{\cdot}66 = 13{\cdot}7$$

From 1st and 3d,

$$\text{B.} \qquad \frac{50{\cdot}5 + 46{\cdot}1}{2} \div \frac{3{\cdot}44 + 3{\cdot}38}{2} = 14{\cdot}2$$

Of course absolute agreement in so rough a test was not to be expected. The difference of about 3 per cent here observed might easily be accounted for. I think Mr. Bidwell will admit that his theory would have predicted a different result of the comparison.

Cambridge, January 19, 1885.