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VIII. *Hysteresis attending the Change of Length by Magnetization in Nickel and Iron.* By H. NAGAOKA, *Rigakushi* *.

[Plates I. & II.]

SINCE Joule's discovery † that the length of iron is changed by magnetization, the subject has been studied by Mayer ‡, Barrett §, Bidwell ||, and Berget ¶. Bidwell carried the investigation into very strong magnetizing fields, and discovered several new facts concerning the changes of length in ferromagnetic substances. So far, however, nothing has been definitely established regarding the manner in which these substances change length during cyclic changes of magnetization. The object of the present investigation is to ascertain if there is any hysteresis in the changes of length during magnetic cycles, and at the same time to determine its amount.

Several fruitless attempts were made before I obtained any definite result. The first method I had recourse to was that of interference-fringes. A small brass plate was brazed to the end of an iron wire, and a plane glass plate placed upon it. Separated by a thin air-film was a plano-convex lens of about 40 centim. focal length, with 23 fine dots on its plane face. The lens rested on a tripod. These different pieces of apparatus were detached from Fizeau's dilatometer. The change of length was determined by observing the displacement of the fringes produced by sodium-light. From the position of the dots it was possible to determine a change amounting almost to a hundredth part of a sodium wavelength D. But as each observation of the fringes required a few minutes, it was difficult to keep the temperature constant; and, moreover, owing to the uniformity of distribution of the fringes, it was not always easy to count the number displaced. Consequently it was necessary to devise a more delicate method, and, if possible, some means of compensating for temperature-effects.

* Communicated by Prof. C. G. Knott, D.Sc., F.R.S.E.

† Reprint of Papers, vol. i. p. 235.

‡ Phil. Mag. [4] xlv. p. 177.

§ 'Nature', 1882.

|| Proc. Roy. Soc. 1886; Phil. Trans. 1888; Proc. Roy. Soc. 1890.

¶ Compt. Rend. tom. cxv. p. 722.

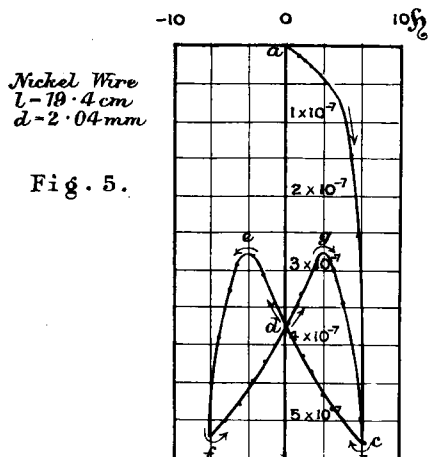


Fig. 5.

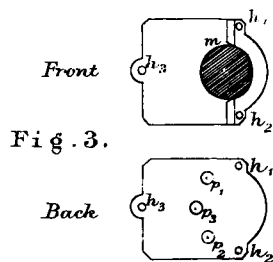


Fig. 3.

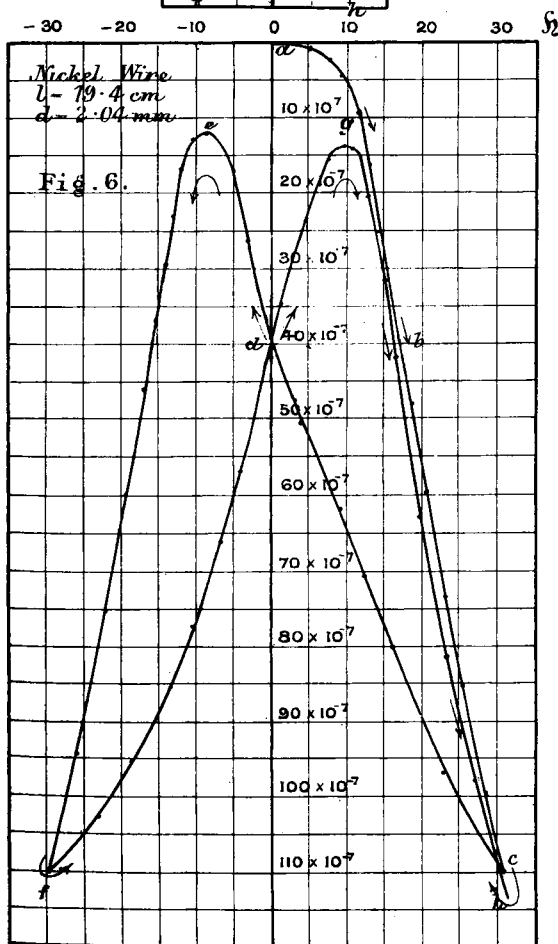


Fig. 6.

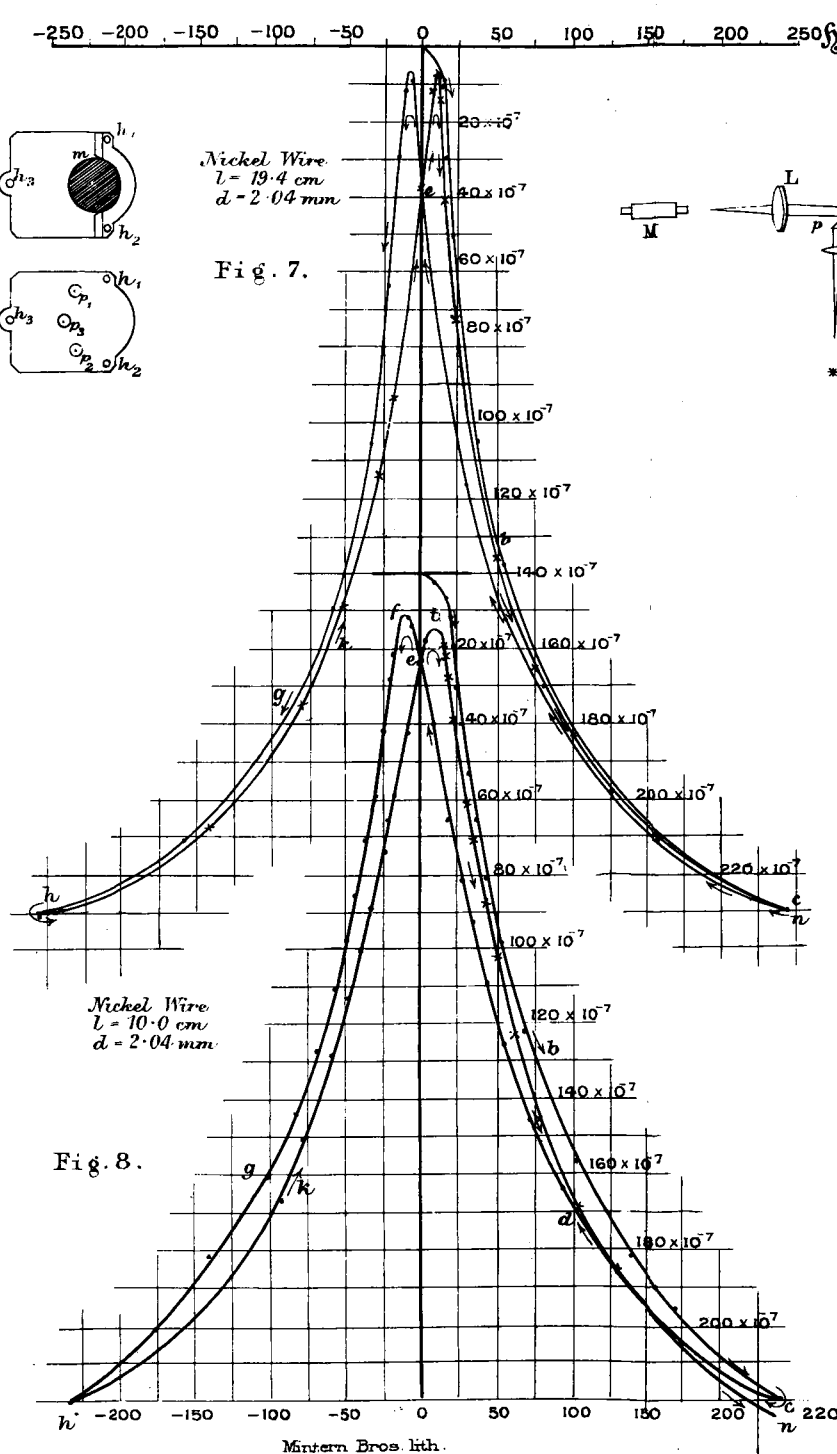


Fig. 8.

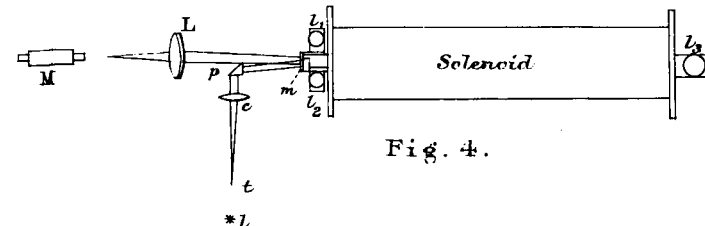


Fig. 4.

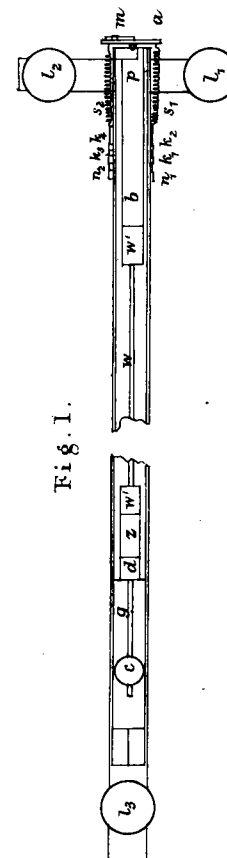


Fig. 1.

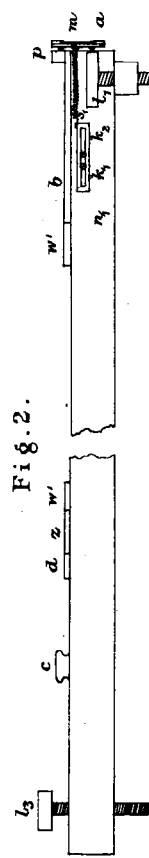
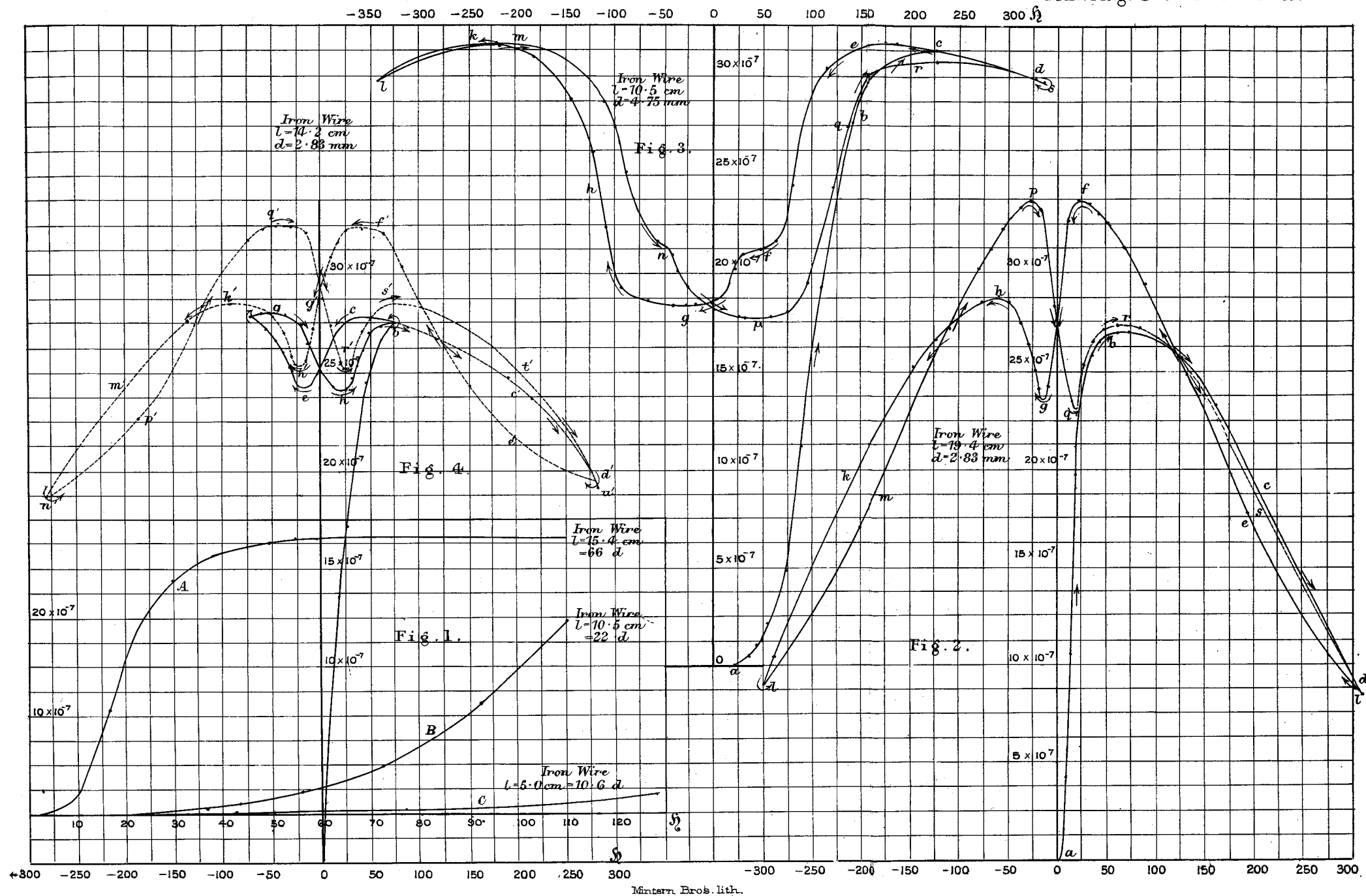


Fig. 2.

I also tried an experiment with a system of levers ; but it did not work smoothly, so that the readings were capricious and could not be trusted.

These faults were, to a great extent, removed by the apparatus which I describe below. The horizontal and vertical projections of the apparatus are represented in fig. 1 and fig. 2 (Plate I.) respectively. The essential part consists of a stout brass bar $5\frac{1}{2}$ centim. long, 1 centim. broad, and 1.1 centim. high. It is provided with three levelling-screws (l_1, l_2, l_3). A carefully polished V-groove is cut along the bar. A small rectangular brass pillar (p) is erected at one corner of the bar. A small vertical V-groove is cut on it, and on this two points of the lever rest. The lever with a mirror attached is shown in fig. 3, both from the front and from behind. It is a small rectangular piece of brass with three steel points (p_1, p_2, p_3), of which two (p_1, p_2) rest on the V-groove in p . The other point (p_3) comes in contact with a small plane glass plate, which is fixed to the end of the movable brass rod. The point of contact is in the prolonged axis of the wire whose change of length is to be determined. The distance of the line $p_1 p_2$ from p_3 is 1.125 millim. Preliminary testing showed that the relative positions of these three fine steel points were not directly affected by the magnetizing forces. The plate has three holes (h_1, h_2, h_3). To the holes h_2, h_3 is attached a thin brass wire, which is pulled at its middle by means of a small spiral spring (s_2) of hard brass wire. Another spring (s_1), similarly made, is attached to the other hole. These springs can be adjusted by means of slide arrangements, n_1 and n_2 , attached to the sides of the bar. The circular mirror, m , attached to the lever was obtained from Hartmann and Braun.

The greatest difficulty in the measurement of change of length by magnetization arises from the temperature-changes produced by a current passing into the magnetizing coil. On this account most experimenters have passed the current only for a very short time, and observed the change before the temperature produced any effect. The consequence is that the changes are traced only by jumps. I found that the temperature-effect could be greatly compensated for by applying the principle of the gridiron-pendulum. This end was achieved by using zinc rods of different lengths such that, in any combination, the total expansion due to small changes of temperature in particular lengths of zinc and iron (or nickel) was equal to that in a particular length of brass.



Zinc rods 5 millim. thick were carefully turned on a lathe, and cut into proper lengths.

The extremities of the zinc rod (z in fig. 1) are concave, so that the convex ends of the brass rods (a, w') come into contact at the axial points of the rod. To the ends of the wire (w) are brazed two short brass rods (w', w'), about 1 centim. long and 5 millim. thick, with their ends made convex. [In brazing the wire care was taken that the axis of the wire coincided with the axes of the rods.]

A brass rod (b), 5 millim. thick, is placed in contact with w' . At the end of the rod a plane glass plate is attached, so that the steel point p_3 of the lever comes in contact with it. At the other extremity of the row of rods is a stop. It consists of a triangular prism of brass to which a brass rod (d), 5 millim. thick, is attached. The prism fits in the V-groove, and is fixed tightly by means of a clamping-screw, c . To adjust the length ($b c$) it is provided with a slit g . The screw (c) can be placed at any part of the slit, and the position of the movable system b, w', w, w', z , can be so adjusted that the plane of the lever is perpendicular to the axis of the system. The slight push exerted by the springs (s_1, s_2) on the movable system prevents the play of different parts among each other, and was sufficient to overcome friction during contraction.

Perhaps the following short explanation of figs. 1 and 2 will make the various parts of the apparatus clear:— l_1, l_2, l_3 , levelling-screws; a , lever with three steel points (dots in the figure); p , pillar with vertical groove; s_1, s_2 , brass springs attached to the lever for adjustment; n_1, n_2 , slide arrangement for adjusting the strength of the springs; k_1, k_2, k_3, k_4 , clamping-screws for n_1, n_2 respectively; b , brass rod with plane glass; w', w' , brass rods attached to the extremities of the wire w ; w , wire whose change of length is to be measured; z , compensating zinc rod; d , brass rod attached to the stop; g , slit in the stop; c , clamping-screw.

The rod was placed inside a solenoid 30 centim. long, which lay in a horizontal position magnetic east and west. It had a resistance of 0.63 ohm, and gave a field of 37.97 C.G.S. units for a current of one ampere. The internal diameter of the solenoid was 3.0 centim., and no part of the measuring apparatus came in contact with it. Care was taken to place the apparatus along the axis of the solenoid, and so to place the wire that its middle point coincided with that of the solenoid. These precautions were always necessary, especially when the wire was thick.

The optical method for observing the change of angle requires little explanation. When the Gauss-Poggendorff method is used at a great distance, it requires very strong illumination of the scale and a good observing-telescope; or when the reflected spot of light is read on the scale, electric- or lime-light must be used. This inconvenience can be removed in the following manner (see fig. 4).

A fine glass thread t is placed vertically in the focus of a small achromatic lens c , and illuminated by a lamp. The ray, after passing the lens, is reflected by a right-angled prism p , and thrown on the mirror m . After reflexion in the plane mirror, the ray traverses an achromatic lens L (whose focal length was about 70 centim. in my experiment). The image of the glass thread is then observed by means of a microscope, M , provided with a micrometer. I used a microscope detached from a geodetic comparator; the magnifying-power was about 40, but if great exactness be desired it can be increased about five times, provided sufficient illumination be given. In place of the glass thread at t I tried a fine slit, spider or silk thread, and diamond traces on glass; but it was found best to use a glass thread of such thickness that its image was a little greater than the movable double threads of the micrometer. In the present experiment, 1776 divisions of the micrometer were equal to $524''\cdot 1$, so that a single division was equal to $0''\cdot 295$. The displacement of one micrometer division, therefore, gave a change of length

$$= \frac{0\cdot 1125 \times 0\cdot 295 \times 4\cdot 848 \times 10^{-6}}{2} \text{ centim.}$$

$$= 0\cdot 805 \times 10^{-7} \text{ centim.} = 0\cdot 00137 \lambda_D,$$

where λ_D represents the wave-length of the sodium-line D.

In experiments with the nickel wire through wide ranges of magnetizing force, the contraction was so great that the image of the thread passed out of the field of the microscope. The lens and microscope were then replaced by a telescope, in the focus of which was placed a scale divided to tenths of a millimetre; a single division corresponded to $20\cdot 2 \times 10^{-6}$ centim. It is easy to see that the collimating-lens c can be replaced by the lens L . For this, it is necessary to place the prism between M and L , and the thread t at such a distance that the optical path through the prism to the lens is equal to its focal length. This method of measuring small

changes of angle can be advantageously used in various other researches*.

The magnetizing current was supplied by Bunsen cells, and its strength was measured by a Thomson Graded Galvanometer. The galvanometer was gauged by means of a deciampere balance. The current was always changed continuously by means of a liquid slide included in the circuit.

A rough plan of the arrangement of the different parts is given in fig. 4.

The hysteresis accompanying the change of length in nickel is not so complicated as in iron. I will first describe a few experiments made with the former metal. A nickel wire, 19.4 centim. long and 2.04 millim. thick, was carefully annealed by placing it due magnetic east and west in a porcelain tube, and heating it red-hot in a charcoal fire. The wire was then placed in the V-groove of the apparatus, and inserted in the solenoid. The strength of the current was gradually increased, and, at convenient intervals, the corresponding readings of the micrometer and galvanometer were noted, till the magnetic field was 10.2 C.G.S. units. The contraction of the wire was at first very slow, but when the field was about 8 the rate of change was greatly increased. As the field was diminished the wire tended to return to its former state, but not by its former course. There was lagging, so that the wire, for the same strength of field, was more contracted than when the field was on the increase. In fact, when the field was diminished to zero, the wire still remained contracted 38.2×10^{-8} of its original length. When the current was reversed, the wire continued in its tendency to recover its former length until the reversed field became equal to 5. There the recovery stopped, and the wire began once more to contract, and the contracted length in field -10.1 was nearly the same as that in field $+10.2$. On decrease of current, the same succession of changes took place. The changes are graphically represented in fig. 5 (Pl. I.), where the course is in the order of the letters of the alphabet. The curve *cdefgh* of a cycle from the highest field and back to it is nearly symmetrical with respect to the line of zero field, forming complete loops on both sides. The measurements are given in Table I. at the end of the paper.

On reannealing and experimenting between fields ± 30 ,

* I found lately that it is more advantageous to replace the prism *p* and the mirror *m* by a small rectangular prism attached at *m*. The positions of telescopes and collimators must be suitably changed.

we get a similar curve of hysteresis (fig. 6, Pl. I). The only difference between the two is that the field which gives the minimum contraction is higher in the second case.

With still greater range of the magnetizing field very similar results are obtained, as shown by the curves (figs. 6 and 7, Pl. I.). An examination of these curves will illustrate the character of the hysteresis better than a mere verbal description.

The contraction of the magnetized nickel wire does not show any maximum so far as the experiment goes, but the curves have two points of inflexion, one in weak and the other in tolerably large fields. The measured changes of length are nearly the same as those given by Bidwell*. (See Table II. at the end of the paper.)

Before entering into the description of the hysteresis observed in iron, I will describe a few experiments on the changes observed in iron wires of different lengths. The curves A, B, C (fig. 1, Pl. II.) represent the elongations observed in iron wires whose lengths were 66, 22, and 10·6 times the diameter respectively. In the longest, the elongation reaches a maximum in field 70 nearly, and shows an inflexion-point before reaching the maximum. In curves B and C the inflexion-point has not been reached. On continuing the curve B (given in fig. 3, Pl. II.), the maximum is found in field 230, which is very large compared to the former. This relation of the elongation to the length of the magnet is very analogous to the well-known relation of magnetization to length.

The changes wrought by a cycle of magnetization on the length of iron wire is so complex as to require a detailed description. An experiment made on a wire 19·4 centim. long and 2·83 millim. thick will illustrate the nature of the hysteresis. (For measurements, see Table III.) The curve given in fig. 2 (Pl. II.) shows that the elongation in weak fields increases gradually, but that, beyond a certain strength of field, it increases rapidly until it reaches the "wendepunkt." The rate of change then gradually lessens, and the elongation reaches a maximum in field 70. Beyond this point, in increasing fields, the elongation diminishes steadily. The curve thus traced up to field 305 is *a b c d*. With decreasing current the wire again elongates, but shows lagging, so that the length of the wire for the same strength of field is shorter on the return journey until field 120 is reached. Here the branches of the curve cross. In lower fields accordingly the

* Proc. Roy. Soc. 1890.

elongation is greater in the descending than in the ascending curve, until field 25 is reached. At this point the wire begins to shorten very abruptly. In zero field the wire is, nevertheless, longer than at the first maximum. When the field is reversed, the length continues to decrease, but only slightly, until field -15 is reached. Here the minimum occurs, and the wire begins again to lengthen. The rate of increase is comparatively slow, and reaches a maximum in field -70 . Beyond this the wire shortens quite rapidly, and nearly in the same way as in ascending positive fields. With decreasing magnetizing current, the wire again shows hysteresis and the part lm goes below kl . The two branches cross in field -110 , and the wire goes on elongating till it reaches a maximum at p in field -25 . The course of changes from l till the field reaches its former maximum value is nearly similar to the curve $defghkkl$, as will be seen from inspection of the curve $lmpqrst$ (the return curve beyond q is given in dotted lines to avoid confusion). Although the curve of hysteresis during a magnetic cycle is very complex,* it is symmetrical with respect to the line of no magnetizing force. It is evident that the maximum and minimum points in the curve are due to the lagging of the maximum elongation.

The measured elongations of the wire are nearly the same as those given by Bidwell. The field at which the wire recovers its original length will probably be about 400. On extrapolating from the curves given by Bidwell*, I find that when the wire has no longitudinal stress it will show no elongation at about the same strength of the magnetizing force.

The course of the curve is somewhat changed when the limiting field is only a little greater than that of maximum elongation. This case is elucidated in fig. 3 (Pl. II.), from an experiment made on a wire 10.5 centim. long and 4.75 millim. thick. On account of the shortness of the wire compared to its thickness, the first maximum is only reached in field 230 approximately, and, moreover, the slope of the curve in higher fields is very gradual. After describing the curve $abcd$, the curve $defghklmnpqrst$ is traced during a cycle. The peculiarity observed in this case is that in place of having the maxima as in fig. 2, there are curious "humps" in the curve at f and n . Had the magnetizing current been sufficiently strong to cause a large decrease of elongation, the

* *Loc. cit.*

maxima would probably have been produced at or near these places. (For measurements see Table IV.)

Fig. 4 (Pl. II.) represents double magnetic cycles made on a wire 14·2 centim. long and 2·83 millim. thick. When the maximum elongation was reached in field 75 (which is slightly greater than in fig. 2, because the wire is shorter), the magnetizing force was decreased and a cycle performed. The cyclic curve is *b c d e f g h*. The curve evidently shows hysteresis, and is symmetrical with respect to the vertical axis. When this cycle was completed, the field was further increased till a sufficient decrease of elongation set in, and a second cycle with greater range was gone through. The curve (shown in dots) is *d' e' f' g' h' k' m' n' p' q' r' s' t' u'*, and is in every respect similar to that given in fig. 2

The experiments above described prove that elongation in iron and contraction in nickel by magnetization both show decided hysteresis. The curve of hysteresis is symmetrical with respect to the line of zero magnetizing force, so that the elongation or contraction during cyclic changes is an even function of the magnetizing force. When the wire is magnetized, it cannot be brought to its original length by simple reversal of field. While this paper was passing through the press, Mr. Lochner published the results of his investigation on the change of length in soft iron by magnetism, in the December number of this Magazine. The curve given in fig. 3 of his paper distinctly shows hysteresis.

Some of the elongations measured in nickel and iron wires are given in the following Tables.

TABLE I.—Nickel wire : *l*=19·4 centim., *d*=2·04 millim.

H.	$-\frac{\delta l}{l} \times 10^3.$	H.	$-\frac{\delta l}{l} \times 10^3.$	H.	$-\frac{\delta l}{l} \times 10^3.$
0	0	3·6	43·6	— 3·8	44·3
2·0	1·2	2·2	41·5	— 2·4	42·0
2·8	1·7	0	38·2	0	36·8
3·6	2·5	— 1·8	34·1	1·6	32·7
4·7	3·3	— 2·6	30·3	3·3	29·9
6·6	4·2	— 4·5	27·8	4·1	27·4
8·5	14·8	— 6·7	28·7	4·6	27·8
9·2	25·4	— 7·8	32·4	5·4	28·6
10·2*	53·0	— 8·9	39·0	6·3	29·6
7·3	49·8	— 10·1*	51·9	7·9	34·1
5·8	48·7	— 7·9	50·2	10·0	50·3
4·7	46·4	— 5·7	48·2	10·2	53·7

* Give maximum magnetizing field.

TABLE II.—Nickel wire : $l=10\cdot0$ centim., $d=2\cdot04$ millim.

H.	$-\frac{\delta l}{l} \times 10^7.$	H.	$-\frac{\delta l}{l} \times 10^7.$	H.	$-\frac{\delta l}{l} \times 10^7.$
0	0	35.2	92.8	— 46.5	113
11.2	2.0	25.6	80.8	— 37.5	101
14.6	6.1	19.5	64.7	— 30.2	89
17.8	18.2	9.0	40.4	— 22.7	74.8
22.9	30.3	0.0	24.2	— 18.0	64.6
25.6	40.4	— 7.8	14.1	— 15.1	58.6
30.3	52.5	— 11.9	12.1	— 8.8	42.4
36.7	64.6	— 16.1	20.2	0.0	24.2
44.2	80.8	— 20.1	26.2	4.9	18.2
54.4	98.9	— 24.3	42.4	12.4	18.2
68.9	123	— 29.4	58.5	15.9	22.2
82.3	139	— 37.3	70.7	18.8	26.2
102.4	158	— 42.5	84.8	21.8	38.3
118.6	168	— 49.4	98.9	25.9	46.5
139.4	182	— 57.9	111	28.8	60.5
158.2	190	— 67.8	127	35.2	70.6
171.4	196	— 80.7	144	42.2	86.8
230.6	218	— 101.4	162	49.7	103
235.8*	220	— 141.5	182	59.0	121
173.9	206	— 170.3	200	67.6	129
147.8	196	— 231.6*	220	80.2	146
117.9	182	— 160.4	204	104.8	168
89.6	164	— 125.2	188	126.3	186
71.8	146	— 90.9	166	149.9	196
56.1	125	— 77.0	150	175.0	206
45.7	109	— 58.7	127	234.7*	224
37.7	107				

* Give maximum magnetizing field.

TABLE III.—Iron wire : $l=19\cdot44$ centim., $d=2\cdot83$ millim.

H.	$\frac{\delta l}{l} \times 10^7.$	H.	$\frac{\delta l}{l} \times 10^7.$	H.	$\frac{\delta l}{l} \times 10^7.$
0	0	22.1	33.3	— 55.5	32.2
9.1	4.2	13.2	32.7	— 48.2	33.0
13.7	10.5	0.0	27.8	— 37.7	33.2
19.2	19.8	— 8.6	24.4	— 29.0	33.4
25.1	23.2	— 20.8	24.2	— 16.8	33.2
35.5	25.8	— 24.4	25.1	— 2.7	28.1
43.6	26.6	— 29.3	26.5	0.0	27.8
59.6	26.8	— 38.4	27.4	7.5	25.9
78.4	27.0	— 47.5	28.1	20.0	22.9
127	25.6	— 76.4	28.1	24.6	24.1
206	18.7	— 121.2	26.8	29.2	25.3
305 *	8.8	— 144.5	25.2	37.9	26.5
193	17.6	— 289	10.4	46.7	27.2
133	24.9	— 299 *	9.0	60.0	27.2
87.4	29.3	— 201	17.1	87.7	27.1
68.4	31.3	— 155	22.5	124	25.6
54.6	32.6	— 106	27.1	164	23.0
38.1	33.1	— 80	30.1	201	18.5
32.6	33.3	— 68.6	31.2	310 *	8.5

* Give maximum magnetizing field.

TABLE IV.—Iron wire : $l=10.5$ centim., $d=4.75$ millim.

H.	$\frac{\delta l}{l} \times 10^7.$	H.	$\frac{\delta l}{l} \times 10^7.$	H.	$\frac{\delta l}{l} \times 10^7.$
0	0	30.0	20.8	— 89.1	25.1
21.2	0	23.6	20.2	— 57.0	21.6
37.1	0.4	0.0	18.3	— 42.4	20.8
43.9	1.0	— 19.2	18.3	— 35.6	20.2
55.9	2.0	— 26.8	18.3	— 24.8	19.3
72.3	4.8	— 37.6	18.3	0.0	18.0
92.5	11.2	— 52.2	18.4	24.6	17.7
110	19.2	— 69.4	18.4	32.8	17.5
144	27.6	— 93.0	19.3	58.3	17.7
208.5	31.0	— 109.2	22.3	74.1	18.0
333 *	29.8	— 122.6	26.1	98.3	19.6
188.6	31.7	— 145.6	28.9	118	24.4
115.2	30.3	— 181	30.9	140	27.4
83.5	23.9	— 343 *	29.9	159	30.0
60.6	21.5	— 215	31.4	228	30.6
49.8	21.2	— 110	28.7	341 *	29.2

* Give maximum magnetizing field.

TABLE V.—Iron wire : $l=14.2$ centim., $d=2.83$ millim.

First Cycle.					
H.	$\frac{\delta l}{l} \times 10^7.$	H.	$\frac{\delta l}{l} \times 10^7.$	H.	$\frac{\delta l}{l} \times 10^7.$
0	0	-34.1	25.4	13.0	24.2
17.7	13.5	-41.0	26.0	25.2	24.0
27.3	17.1	-47.5	26.5	31.4	24.6
32.7	20.5	-58.0	27.1	38.6	25.3
46.2	24.4	-74.8	27.7	43.9	26.0
60.2	26.5	-66.9	27.9	57.4	26.9
74.0	27.4	-51.8	27.9	62.8	27.2
56.2	27.7	-35.4	27.9	72.1	27.3
43.5	27.7	-23.9	27.9	Continued to second cycle.	
25.9	27.7	-20.5	27.3		
0.0	25.5	-15.6	26.3		
-27.3	24.3	0	25.2		
Second Cycle.					
72.1	27.3	0	29.0	-32.7	32.3
90.0	27.2	- 9.2	27.2	- 16.4	32.1
115	26.7	- 23.4	25.5	0	28.9
193	24.7	- 31.5	25.7	8.9	27.2
215	23.6	- 40.0	27.0	24.3	25.0
282	19.3	- 50.0	27.9	31.4	25.5
197	21.6	- 57.6	28.0	42.2	26.9
153	24.3	- 84.7	28.3	55.4	28.2
106	28.9	- 135	27.6	66.0	28.2
79.0	30.5	-280 *	18.7	84.5	28.1
63.2	31.9	- 184	22.7	89.0	28.0
40.8	32.2	-118	28.4	115	27.7
25.2	32.2	- 74	31.8	144	27.2
16.7	31.7	- 59	32.3	184	26.0
8.9	30.7	- 47	32.3	286	18.8

* Give maximum magnetizing field.