XI.—*On Superposed Magnetisms in Iron and Nickel.* By Professor C. G. KNOTT, D.Sc. (Plate XXIX.)

(Read 2nd July 1883.)

The experiments which form the subject of this paper are designed, in the first place, to test the relation pointed out by MAXWELL* between JOULE'S discovery of the lengthening of iron in the direction of magnetisation,† and WIEDEMANN'S later researches into the twisting of iron under the influence of longitudinal and circular magnetisations,‡ and, in the second place, to investigate the corresponding properties of nickel.

According to JOULE'S discovery, an iron bar or wire lengthens in the direction of magnetisation, and contracts in directions at right angles thereto. The extension is greater for a stronger magnetising force, and, if the metal is subjected to traction in the direction of lengthening, is smaller for a greater traction. In the experiments to be described a wire was fixed at its upper end, and stretched vertically by means of an appended mass. It passed centrally through a glass tube of nearly the same length, round which a helix of wire was wound. The length of the helix was 34·3 centimetres, and the total number of coils 196. A current passed through the helix magnetised the wire longitudinally. At the lower end of the wire was fixed a short copper wire, which dipped into a pool of mercury. By this means a current could be passed along the wire so as to magnetise it circularly. The twist produced under the joint influence of the longitudinal and circular magnetisations was measured by the deflection of a spot of light focussed upon a millimetre scale after reflection from a mirror attached to the lower end of the wire. Both the magnetising currents were measured on a Helmholtz tangent galvanometer.

The method of experimenting was as follows:—One of the currents was kept steady, while the other was varied through a considerable range. When both currents were flowing the free end of the wire came to rest in a definite position, which was registered by the reading on the scale. One of the currents was then reversed, and a second reading obtained. The difference between these readings was approximately four times the angle of twist. By successive

* See MAXWELL'S *Electricity and Magnetism* (2nd edition, vol. ii. § 448). The first edition comes to a wrong conclusion, in consequence of a misprint in WIEDEMANN'S *Galvanismus* (1st edition, Bd. ii. § 491). See also CHRYSTAL'S article on "Magnetism" in the *Encyclopædia Britannica* (vol. xv. pp. 269, 271).

† STURGEON'S *Annals of Electricity*, vol. viii. p. 219; and *Phil. Mag.*, 1847.

‡ WIEDEMANN'S *Galvanismus*, 1st edition, Bd. ii. § 491.

reversings and re-reversings of the current, a series of readings was obtained whose differences gave a good mean. From the numbers so deduced the true twist expressed in radians was easily calculated.

The first experiments were made with an iron wire, ·00435 square centimetres in cross section. The most important are those in which the current along the wire (the linear current) was kept constant, while the helical current was made to vary from under half an ampère to nearly six ampères. Five different series were taken with different values of the steady current. In the following tables the upper row gives the successive values of the helical currents in ampères, and the lower the corresponding twists in radians $\times 10^5$.

GROUP A.

Experiment I. Linear Current = ·575 Amp.

Helical Current,	0·377	0·741	1·289	2·045	2·573	5·019
Twist, . .	234	489	629	672	663	625

Experiment II. Linear Current = ·723.

Helical Current,	0·368	0·758	1·289	1·676	2·025	2·436	2·902	3·375	5·019
Twist, . .	307	597	816	877	907	900	881	832	703

Experiment III. Linear Current = 1·891.

Helical Current,	0·393	0·741	1·254	1·566	1·987	2·488	2·925	3·527	4·068	5·781
Twist, . .	372	762	1179	1335	1389	1389	1387	1345	1279	1077

Experiment IV. Linear Current = 3·157.

Helical Current,	0·460	0·700	1·254	1·991	2·488	3·157	4·592
Twist, . .	342	775	1251	1567	1680	1710	1652

Experiment V. Linear Current = 4·068.

Helical Current,	0·410	0·700	1·254	1·891	2·385	3·039	4·214
Twist, . .	390	810	1303	1678	1802	1886	1884

Three series were taken with steady helical current and varying linear current. They are as follows :—

GROUP B.

Experiment I. Helical Current = ·611 Amp.

Linear Current,	0·410	0·716	1·272	1·943	2·395	3·051	3·899
Twist, . .	126	357	742	1030	1125	1197	1225

Experiment II. Helical Current = 1·987 Amp.

Linear Current,	0·418	0·750	1·276	1·948	2·364	2·970	3·803
Twist, . .	127	312	767	1190	1358	1576	1754

Experiment III. Helical Current = 3·229.

Linear Current,	0·505	0·893	1·320	1·703	2·724
Twist, . .	152	387	718	877	1367

In both these series the wire was under a tension of 1950 grammes' weight. The representative curves are shown on Plate XXIX., iron groups A. and B. The current strengths of the varied current are laid down horizontally, and the corresponding twists vertically. The two series differ markedly, the A group showing a maximum twist for an intermediate current strength, the B group giving no such indication. That such a difference between the two cases should exist is not to be wondered at, since the magnetisation due to a linear current follows a different law from that due to a helical current. Indeed, it is impossible to magnetically saturate an iron wire by means of a linear current. Further than this, experiments of the B type need no discussion.

The maximum point in the curves of group A is a constant characteristic of all similar cases, as will be seen by reference to the curves of groups C and D. These represent further experiments with iron wires, in which is studied more particularly the effect of tension upon the amount of twist. In the following tables there are three distinct series under each experiment corresponding to three different tensions. The last column contains the tensions expressed in grammes' weight.

GROUP C.—Cross Section of Iron Wire = ·00276 sq. cc.

Experiment I. Linear Current = ·533 Amp.

Helical Current,	0·952	1·657	2·489	3·039	3·723	5·198	Tension.
Twist,	561	632	632	607	523	413	1360
	1013	1148	1161	1097	1013	875	712
	1123	1284	1258	1265	1097	923	388

Experiment II. Linear Current = 1·476 Amp.

Helical Current,	0·533	0·952	1·657	2 489	3·039	3·723	5·198	Tension.
Twist,	484	1213	1471	1484	1406	1299	1097	1360
	458	1077	1452	1594	1529	1426	1187	712
	439	1045	1503	1658	1684	1561	1323	388

Experiment III. Linear Current = 2·412 Amp.

Helical Current,	0·533	0·952	1·657	2·489	3·039	3·723	5·198	Tension.
Twist, ·0	0484	0877	1332	1445	1510	1555	1394	1360
	0490	1187	1742	1974	1974	2019	1800	712
	0394	0923	1394	1723	1820	1800	1645	388

GROUP D.—Cross Section of Iron Wire = ·000714 sq. cc.

Experiment I. Linear Current = 0·65 Amp.

Helical Current,	0·508	0·995	1·593	2·262	2·615	3·157	4·068	Tension.
Twist,	103	290	368	348	336	329	265	388
	142	400	613	619	613	574	484	258
	129	484	697	761	787	761	723	129

Experiment II. Linear Current = 0·973 Amp.

Helical Current,	0·508	0·995	1·593	2·262	2·615	3·157	4·068	Tension.
Twist,	...	...	794	839	865	807	774	388
	...	...	923	1090	1077	1013	884	258
	252	613	916	1045	1123	1084	1045	129

The direction of twist was as found by WIEDEMANN. If the current is passed down the wire from the fixed to the free end, and the wire is magnetised with north pole downwards, the free end, as looked at from above, twists in the direction of the hands of a watch. As pointed out by MAXWELL and CHRYSTAL, this agrees with JOULE'S discovery mentioned above. For the circular magnetisation due to the down current is right handed with reference to the current. Hence the resultant magnetisation lies in a direction intermediate to the circular and longitudinal magnetisations at any point; and as the iron extends in the direction of magnetisation, and contracts at right angles thereto, there will be a lengthening of the wire in a direction oblique to the axis, such as to cause a twist in the direction specified. The amount of twist depends not only on the magnetising force in this oblique direction, but also upon the obliquity, so that a maximum twist for an intermediate value of the helical current is quite in accordance with JOULE'S result that the extension increases with the magnetisation. Suppose, for example, that the circular and longitudinal magnetisations at a point on the wire are α and β, and that these give a resultant magnetisation $\sqrt{\alpha^2+\beta^2}$ in a direction making an angle, whose tangent is α/β, with the vertical line through the point. Let the extension along this direction be represented by $\mu\ (\alpha^2+\beta^2)$, an assumption approximately true according to JOULE's researches. Then the amount of twist per unit length of the wire will be

$$\tau = \mu(\alpha^2 + \beta^2)\alpha/\beta = \mu(\alpha^3/\beta + \alpha\beta)\,.$$

If α is constant, τ has a maximum value when

$$\beta = \alpha.$$

If β is constant, there is no such maximum value of τ. A comparison of curves A and B (Plate XXIX.) bear this out fully.

Hence, in the case of constant circular magnetisation and varying longitudinal magnetisation, the twist will first increase and then diminish as the latter is increased to its saturation point. For a stronger circular magnetisation the maximum point is pushed further on, until, when the circular magnetisation has reached the saturation point, there will be no subsequent fall off in the twist, *i.e.*, no true maximum point. These remarks apply strictly to a thin iron cylinder. In the case of a wire the effects are complicated. Still the curves on Plate I. bear out in a remarkable way these conclusions. Thus in fig. A the maximum point obviously occurs further to the right in the higher curve. In the following table a direct comparison between the linear current strength and the helical current strength, which corresponds to the maximum twist, is established:—

Linear Current, ...	0·575	0·723	1·891	3·157	4·068
Helical Current for Maximum Twist, .	2	2·2	2·4	3·1	3·5+

The highest curve has no distinctly marked maximum, a result in close agreement with the foregoing deductions. The other series of curves bear out the same conclusion.

JOULE also found that the extension for a given magnetisation was smaller when the wire was subjected to a greater tension. Hence, in general, we should expect the twist in a wire due to superposed circular and longitudinal magnetisations to be less for the greater tension, since the longitudinal extension will be diminished. This conclusion is quite borne out by curves C and D. With only one exception (namely, C III.) an increase in tension is accompanied by a decrease in twist. This result is not in accordance with WIEDEMANN's, who found the twist to be nearly independent of the tension. Possibly, however, he worked with a thickness of wire which for the special combination of current strengths and tensions was not sufficiently sensitive to the change of tension. A glance at the curves C and D shows how much greater is the sensitiveness to tension change for certain combinations than for others.

JOULE further discovered that when the tension exceeded a certain value, there was contraction instead of extension in the direction of magnetisation. This ought to give in these experiments a reversed twist under tensions higher than this critical value. Of this, however, there was no indication, although the thicker iron wire broke under a tension of 2600 grammes' weight, and was, therefore, subjected in experiments A to a comparatively high tension.

It remains now to consider nickel. The experiments were conducted in precisely the same manner as in the case of iron. The following are the tabulated results for a nickel wire of cross section, ·0056 sq. cc., length 36 cc., and tension 1950 grammes' weight; first, for a steady linear current and varied helical current, and second, for a steady helical current and varied linear current. As before, the currents are in ampères, and the twists in radians $\times 10^5$.

GROUP A. (Linear Current Steady.)

Experiment I. Linear Current = 0·674 Amp.

Helical Current,	0·368	0·700	1·210	1·891	2·303	2·616	3·016	3·997
Twist, . .	109	200	429	765	952	1077	1206	1458

Experiment II. Linear Current = 0·995 Amp.

Helical Current,	0·307	0·410	0·741	1·276	1·680	2·084	2·594	5·384
Twist, . .	55	103	281	570	871	1052	1303	1897

Experiment III. Linear Current = 2·510 Amp.

Helical Current,	0·368	0·700	1·210	1·891	2·303	2·616	3·016	3·997
Twist, . .	152	263	596	1119	1415	1923	2145	2552

Experiment IV. Linear Current = 3·039 Amp.

Helical Current,	0·205	0·393	0·741	1·313	1·726	2·084	2·594	3·591	5·384
Twist, . .	90	74	436	948	1310	1553	1894	2345	2819

Experiment V. Linear Current = 4·441 Amp.

Helical Current,	0·205	0·451	0·783	1·298	1·750	2·084	2·594	3·565	5·479
Twist, . .	123	219	584	1145	1535	1797	2126	2626	3152

Experiment VI. Linear Current = 5·578 Amp.

Helical Current,	0·368	0·576	0·952	1·521	1·938	2·784	4·519
Twist, . .	171	345	855	1442	1736	2268	2987

GROUP B. (Helical Current Steady.)

Experiment I. Helical Current = 0·658 Amp.

Linear Current,	0·368	0·578	1·097	1·815	2·368	2·724	3·277	3·815	4·796
Twist, . .	39	74	132	234	383	505	702	897	1019

Experiment II. Helical Current = 1·891 Amp.

Linear Current,	0·327	0·582	1·141	1·891	2·891	3·463	3·927	5·019
Twist, . .	57	89	180	420	954	1371	1700	1991

Experiment III. Helical Current = 2·702 Amp.

Linear Current,	0·327	0·582	1·141	1·891	2·891	3·463	3·927	5·019
Twist, . .	29	89	216	457	1126	1545	1948	2322

Experiment IV. Helical Current = 2·405 Amp.

Linear Current,	0·893	1·520	2·323	2·812	4·334	4·680
Twist, . .	368	819	1355	1561	1865	1890

Experiment V. Helical Current = 3·338 Amp.

Linear Current,	0·867	1·494	1·797	2·298	2·702	3·277	4·519
Twist, . .	439	929	1226	1639	1909	2168	2374

The representative curves are shown on Plate XXIX., nickel groups A and B. The chief points of difference between the behaviour of iron and nickel are these: first, the direction of twist in the nickel is the reverse of that in the iron; and second, there is no maximum in the nickel A group of curves. The free end of the nickel wire twists in the direction opposite to the hands of a watch, as looked at from above, when the wire is traversed by a down current, and is magnetised with north pole downwards. This agrees with BARRETT'S discovery,* that nickel contracts when magnetised. The possibility of a maximum, again, depends upon how the amount of contraction varies with the magnetisation, and also, since the abscissæ represent currents and not magnetisations, upon the relation which holds between these last.

The B curves are very similar in form to the B curves of the iron. It will be noticed that curve IV. of this series lies for the most part higher than curve III., although the steady helical current is smaller in the former; also that I., II., and III. seem to fall together, as belonging to the same set, while IV. and V. form a system by themselves. The reason of this would seem to be that between the dates, June 2nd and 4th, namely, on which these sets were taken, the nickel wire underwent some physical change. Probably this was of the nature of a change in temper, since on the latter date the nickel wire was for an instant traversed by a current of sufficient strength to make it glow red hot. Taking this consideration into account, and neglecting curve A, III., which is obviously a bad experiment, we conclude that the twist due to the superposition of circular and longitudinal magnetisations in nickel wire increases with

* See *Nature*, vol. xxvi. 1882.

either magnetisation, so that the amount of contraction of nickel when magnetised increases with the magnetising force.

The effect of varying tension was tried with two sizes of nickel wire—an intermediate size of ·002 sq. cc. cross section, and a thin wire of ·0002 sq. cc. cross section. The following are the tabulated results, the tensions being expressed in grammes' weight.

GROUP C.—Intermediate Wire.

Experiment I. Linear Current = ·533 Amp.

Helical Current,	0·517	0·995	1·703	2·594	3·216	4·140	5·779	Tension.
Twist, . .	...	131	265	374	432	465	639	712
	...	161	303	152	490	574	619	388
	39	168	219	555	626	826	871	258
	39	200	465	729	839	923	1000	64

Experiment II. Linear Current = 1·612 Amp.

Helical Current,	0·517	0·995	1·703	2·594	3·216	4·140	5·779	Tension.
Twist, . .	245	432	903	1400	1594	1852	2174	1360
	168	538	955	1439	1529	1768	2032	712
	136	555	1097	1490	1761	2052	2284	388
	142	384	1116	1652	1813	2149	2374	258
	71	465	1148	1768	2084	2297	2561	64

Experiment III. Linear Current = 2·489 Amp.

Helical Current,	0·517	0·995	1·703	2·594	3·216	4·140	5·779	Tension.
Twist, .	181	394	871	1645	1725	2064	2568	2656
	155	697	1233	1832	2071	2348	2813	1360
	265	839	1561	1981	2207	2594	2942	712
	265	852	1619	1603	2110	2639	3084	388
	265	845	1697	2258	2490	2774	3103	258
	232	936	1897	2568	2877	3148	3407	64

GROUP D.—Thin Wire.

Experiment I. Linear Current = ·442 Amp.

Helical Current,	0·575	1·003	1·703	2·615	3·216	4·067	5·577	Tension.
Twist, . .	96	147	258	439	490	684	813	258
	200	394	813	1400	1774	2181	2961	194
	361	707	1510	2278	2755	3529	4497	129
	226	432	1000	1594	1903	1968	2170	97
	142	245	561	1045	1322	1613	1819	64

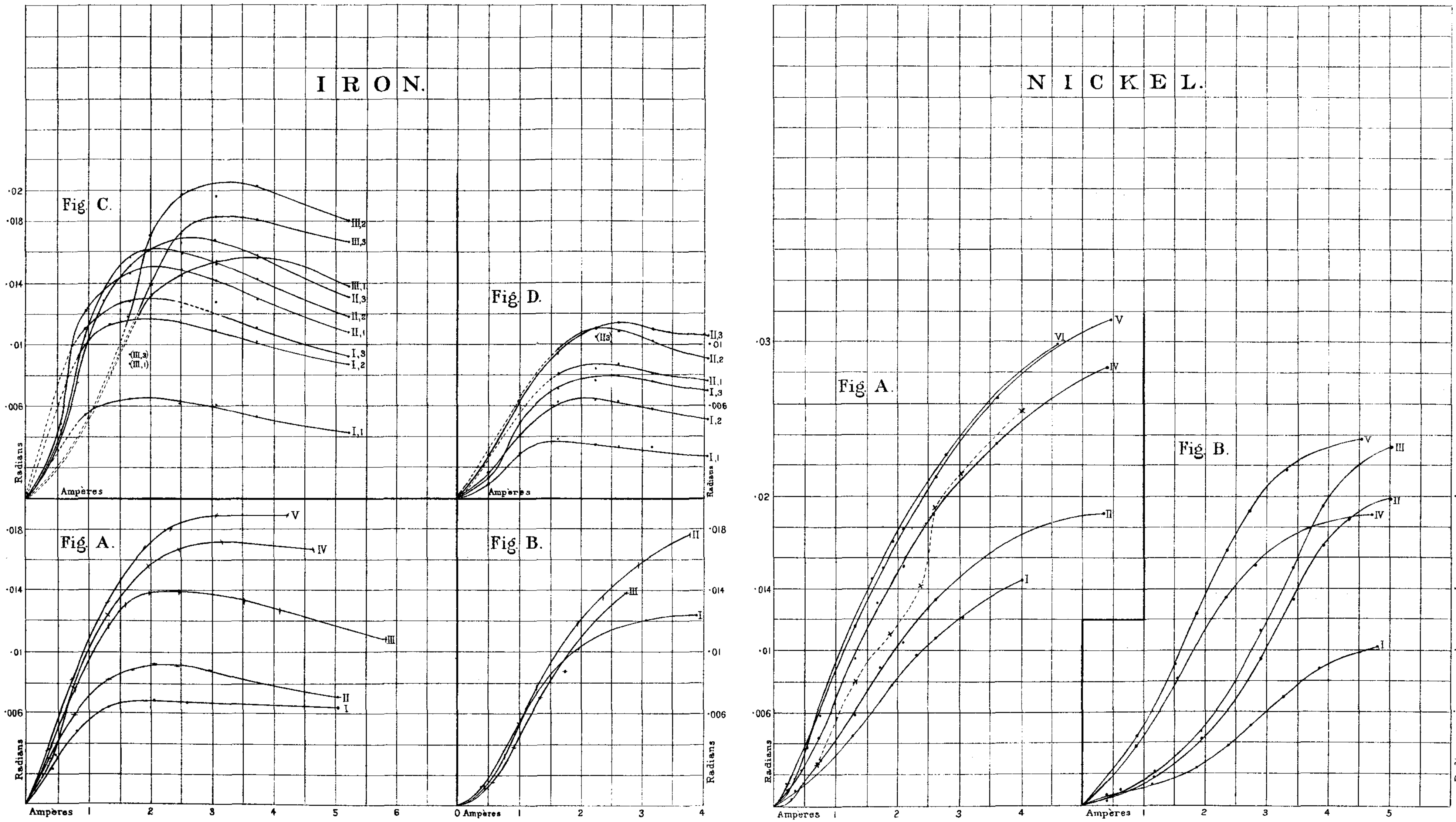
Experiment II. Linear Current = ·825 Amp.

Helical Current,	0·558	1·003	1·703	2·594	3·240	3·927	5·290	Tension.
Twist, . .	...	290	465	794	971	1335	1542	258
	187	368	464	1065	1258	1652	2103	194
	226	452	826	1161	1400	1897	2155	129
	452	987	1742	2619	3013	3471	3968	97
	458	1006	2052	2981	3155	3600	4090	64

Here also, as a glance at these numbers will show, increased tension is in general accompanied by diminished twist. Experiment D, I. is, however, quite exceptional, as the twist reaches a very pronounced maximum for an intermediate tension. With the same wire, and with the linear current nearly doubled in strength, this peculiarity quite disappears. It is impossible at present even to suggest an explanation.

The experiments described above were all made in the Physical Laboratory of Edinburgh University during the months of March, May, and June of this year. The object primarily aimed at was to establish the explanation given by MAXWELL and CHRYSTAL of WIEDEMANN'S torsion effect in iron under the influence of superposed magnetisms, and then to extend the same to the case of nickel. This, I think, has been effected. At the same time other facts have been brought to light, especially as to effect of tension, which will probably repay more careful study.

My thanks are due to Professor TAIT for providing me with the specimens of pure nickel wire, and to Professor CHRYSTAL for his ever ready and valuable advice.



SUPERPOSED MAGNETISMS IN IRON & NICKEL.

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