



XXV. Contributions to the molecular theory of induced magnetism

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XXV. *Contributions to the Molecular Theory of Induced Magnetism.* By J. A. EWING, F.R.S., Professor of Engineering in University College, Dundee*.

AS the facts of induced magnetism become better known, increasing interest attaches to molecular theories and increasing difficulty attends the theories that are current. Weber's fundamental conception that the molecules of iron or nickel or cobalt are always magnets, and that the process of magnetizing consists in turning them from many directions towards one direction, has been strongly confirmed by the now well-established fact that there is a true saturation value, a finite limit to the intensity of magnetism, which may be reached or very closely approached by using a strong magnetic force †. Without going further back, to enquire (with Ampère) how the molecules come to be magnets, we may take this conception as the natural starting-point of a theory. But when we go on to examine the conditions of constraint on the part of the rotatable molecules which have been suggested to make the theory square with what is known about permeability, about residual magnetism and other effects of magnetic hysteresis, about the effects of stress, of temperature, of mechanical vibration, and so forth, we find a mass of arbitrary assumptions which still leave the subject

* Communicated by the Author, having been read before the Royal Society, June 19, 1890.

† Ewing and Low, *Phil. Trans.*, 1889, A, p. 221; see also H. E. J. G. du Bois, *Phil. Mag.* April 1890.

bristling with difficulties. Many of the phenomena suggest, for instance, the idea that there is a quasi-frictional resistance which opposes the turning of the molecular magnets; this notion lends itself well to account for the most obvious effects of magnetic hysteresis and the reduction of hysteresis by vibration. On the other hand, it conflicts with the fact that even the feeblest magnetic force induces some magnetism. My object in this paper is to refer to another (and not at all arbitrary) condition of constraint which not only suffices to explain all the phenomena of hysteresis without any notion of friction, but seems to have in it abundant capability to account for every complexity of magnetic quality.

In describing Weber's theory, Maxwell points out that, if each molecular magnet were perfectly free to turn, the slightest magnetic force would suffice to bring the molecules into complete parallelism, and thus to produce magnetic saturation. He continues:—"This, however, is not the case. The molecules do not turn with their axes parallel to the force, and this is either because each molecule is acted on by a force tending to preserve it in its original direction, or because an equivalent effect is produced by the mutual action of the entire system of molecules. Weber adopts the former of these suppositions as the simplest."*

Weber supposes a directing force to act in the original direction of the molecule's axis which continues to act as a restoring force in that direction after the molecule is disturbed. This assumed constraint is quite arbitrary; moreover, if it were the only constraint, there would be no residual magnetism when the deflecting force was withdrawn. Accordingly, Maxwell modifies Weber's theory by introducing the further assumption that when the angle of deflexion exceeds a certain limit the molecule begins to take permanent set. The development of this, however, does not agree well with the facts.

The alternative which is offered in the sentence I have quoted from Maxwell was not followed up by him, and seems to have been very generally overlooked, notwithstanding its obvious freedom from arbitrary assumption. Several writers, notably Wiedemann† and Hughes‡, have recognized the inter-molecular magnetic forces by suggesting that the molecules, when unacted on by any magnetizing force from outside, may form closed rings, or chains, "so as to satisfy their

* Maxwell, *Electricity and Magnetism*, vol. ii. § 443.

† Wiedemann, *Galvanismus*, 2nd ed. vol. ii. (1), p. 373.

‡ Hughes, *Roy. Soc. Proc.* May 10, 1883.

mutual attraction by the shortest path."* But Wiedemann expressly postulates a frictional resistance to rotation, which will prevent this arrangement from being more than approximately attained, and which may be more or less overcome by vibration †.

I lately commented on the fact that soft iron and other magnetic metals (notably nickel under particular conditions of strain ‡) show a remarkably close approach to instability at certain stages in the magnetizing or demagnetizing process §. When the magnetic force reaches a particular value, the rate of change of magnetism with respect to change of force may become enormous. Referring to this in a paper which has just been published ||, Mr. A. E. Kennelly has reverted to the idea of chains of magnetic molecules held together by the inter-molecular magnetic forces, and contends that when such a chain is ruptured by applying a sufficiently strong external magnetic force it will fall to pieces throughout, and the molecular magnets which compose the chain will take their alignment suddenly. He accordingly sketches what he calls a "chain-theory" of magnetization and an adaptation of the theory of Hughes, in which, however, he postulates an elastic resistance to the rotation of the molecules in addition to the constraint afforded by their mutual magnetic forces. Mr. Kennelly's remarks are highly interesting and suggestive; but I do not think (for reasons which will appear immediately) that the notion of closed magnetic chains can be maintained as a general account of the molecular structure of unmagnetized iron.

I have experimented on the subject by making a model molecular structure consisting of a large number of short steel bar-magnets, strongly magnetized, each pivoted like a compass-needle upon a sharp vertical centre and balanced to swing horizontally. We cannot readily imitate in a model the two degrees of rotational freedom possessed by the axes of actual molecular magnets, but a group of magnets swinging in one plane gives a sufficiently good general idea of the nature of the equilibrium which is brought about by inter-molecular forces, and the manner in which that equilibrium is disturbed

* Hughes, *loc. cit.*

† Wiedemann, *Phil. Mag.* July 1886, p. 52; *Elektricität*, vol. iii. §§ 784-785.

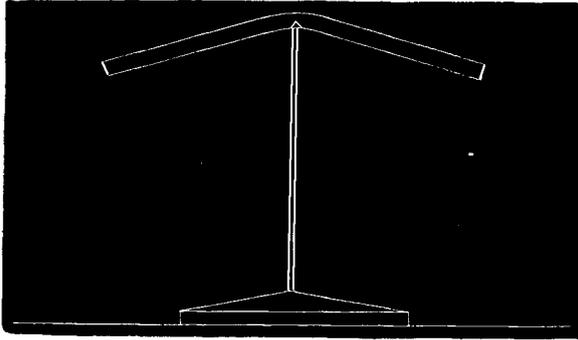
‡ See a paper by H. Nagaoka, *Journal of the Science College of the University of Tokio*, vol. ii. (1888) p. 304.

§ *Journal of the Institution of Electrical Engineers*, No. 84 (1890) pp. 38-40.

|| *The Electrician*, June 7 and 13, 1890.

when an external force is applied. The model is very easily made. Each magnet is a piece of steel wire about one tenth of an inch in diameter and two inches long (fig. 1), bent in

Fig. 1.



the middle to bring the centre of gravity below the point of support. The hole, or rather recess, for the pivot is made by a centre punch: the pivot itself is a sewing-needle fixed upright in a small base-plate which is punched out of a sheet of lead. The bars swing with but little friction, and their pole-strength is sufficient to make the mutual forces quite mask the earth's directive force when they are set moderately near one another. The group is arranged on a board on which lines are drawn to facilitate regularity in grouping when that is wanted, and the board slips into a large frame or open-sided flat box wound round the top, bottom, and two sides, with a coil through which an adjustable current may be passed to expose the group to a nearly homogeneous external magnetic force. The coil is wound in a single very open layer, through which a sufficiently good view of the group inside is obtained*. A liquid rheostat with a sliding terminal is used to secure continuity in varying the magnetic force. It is scarcely necessary to add that the magnetic force which is applied to the group is too weak to have any material effect on the magnetism of individual bars. It alters their alignment only, just as a magnetic force alters the alignment of Weber's molecular magnets.

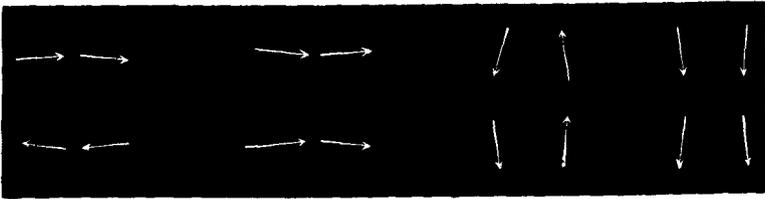
When a number of these magnets are grouped either in a regular pattern or at random, and are left after disturbance

* In showing the experiments, the board with the magnets on it may, of course, be placed in clear view above the coil; the coil is then made larger, or a stronger current is used.

to come to rest free from external magnetic force, they of course assume a form which has no resultant magnetic moment, provided the number be sufficiently great ; but it is apparent that they do not arrange themselves in closed chains. Any such configuration would in general be unstable. Many stable configurations admit of being formed, and if the magnets are again disturbed and left to settle, the chances are much against any one configuration immediately repeating itself. One general characteristic of these configurations is that they contain lines consisting of two, three, or more magnets, each member of a line being strongly controlled by its next neighbours in that line, but little influenced by neighbours which lie off the line on either side. Thus, if there are two magnets simply, they form (as might be anticipated) a highly stable pair, thus:—



With three magnets, two form a line along one side of the triangle joining the fixed centres, and the third lies parallel, or nearly so, facing oppositely. Four magnets will usually form two lines with directions which lie nearly along two sides of the quadrilateral ; but diagonally opposite magnets may pair, leaving the others unattached. Suppose them set at the corners of a rectangle with unequal sides, they may lie in any of these forms



if the inequality in distance be not too great. All these configurations are stable, and the condition of least energy, while making the first of them the most probable, does not prevent the occasional formation of the others. In a long line, the same condition leads in general to this formation:—



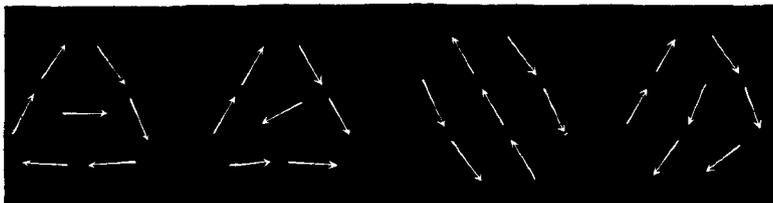
but it is by no means uncommon to find a line broken into two or more sections, thus:—



Seven magnets grouped so that the centres of six form a

regular hexagon, with one in the middle, have a great variety of possible stable configurations, of which these are examples:—

Fig. 2.



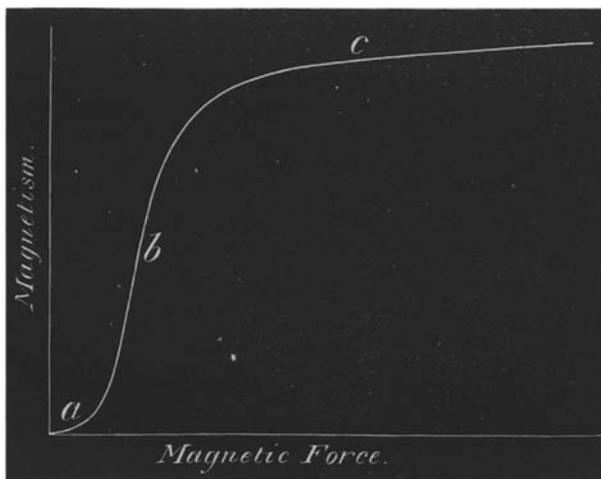
Experimental study of the forms which may be assumed by groups, and of the vibrations which may be transmitted through groups, is interesting, but to pursue it would be beside my present purpose. In all cases, the configuration assumed by a group is such that there is stability for small displacements, but different positions of the group may be stable in different degrees, and if members of the group be turned through a sufficiently great angle, they become unstable, and fall into a new position of stability, bringing about a partial reconstruction of the lines that characterize the group. Special interest attaches to square patterns, from the fact that iron and nickel (probably cobalt also) crystallize in the cubic system. In a square pattern of many members, we find, in general, lines running parallel with all sides of the square when the group settles without directive force after a disturbance.

Let the group, or collection of groups, be subjected to an external magnetic force, \mathfrak{H} , gradually increasing from zero. The first effect is to produce a *stable* deflexion of all members except those which lie exactly along or opposite to the direction of \mathfrak{H} . This results in giving a small resultant moment to the group (assuming that there was none to begin with), which increases at a uniform or very nearly uniform rate as \mathfrak{H} increases. This corresponds to the first stage in the magnetization of iron or other magnetic metal (*a*, fig. 3). The initial susceptibility is a small finite quantity, and it is sensibly uniform for very small values of \mathfrak{H} .

Suppose that, without going beyond this stage, we remove \mathfrak{H} ; the molecular magnets, not having been deflected beyond the limit of stability, simply return to their initial places, and there is no residual magnetism. This, again, agrees with the fact that no residual magnetism is produced by very feeble magnetizing forces. Up to this point there has been no magnetic hysteresis. But let the value of \mathfrak{H} be increased until any

part of the group becomes unstable, and hysteresis immediately comes into play. At the same time, there begins to be a marked augmentation of susceptibility—that is to say, a marked increase in the rate at which resultant moment is acquired. It is not difficult to arrange groups in which the state of instability is reached with one and the same value of \mathfrak{H} throughout the group. But, in general, we shall have different elementary magnets, or different lines of them, reaching instability with different values of \mathfrak{H} . The range of \mathfrak{H} , however, which suffices to bring about instability throughout the whole, or nearly the whole, of the members in most groups is not large; we, therefore, find in the action of the model a close analogy to the second stage (*b*, fig. 3) of the process of magnetization, in which the magnetism rises more or less suddenly, as well as to the first stage (*a*).

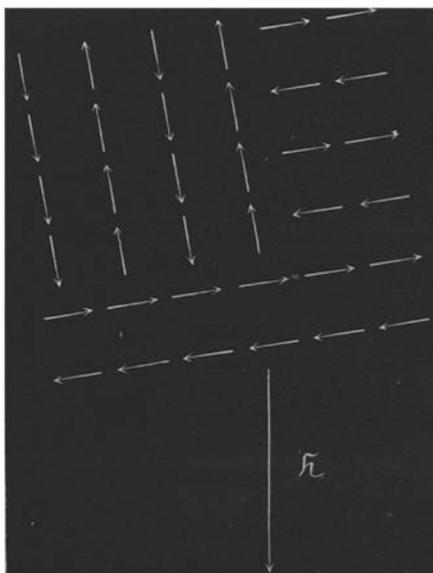
Fig. 3.



During the second stage (*b*), the magnetic elements fall for the most part into lines which agree more or less exactly with the direction of \mathfrak{H} . If, at the end of this stage, we remove \mathfrak{H} , we find that a very large proportion of the moment which the group has acquired remains; in other words, there is a great deal of residual magnetism. To take an instance, suppose we have a group lying initially as in fig. 4, and apply a magnetic force, \mathfrak{H} , in the direction sketched, the first stage (*a*) deflects all the molecular magnets slightly, without making any of them become unstable; the second

stage (*b*) brings the molecules into the general direction shown in fig. 5, or rather that is the direction they assume

Fig. 4.

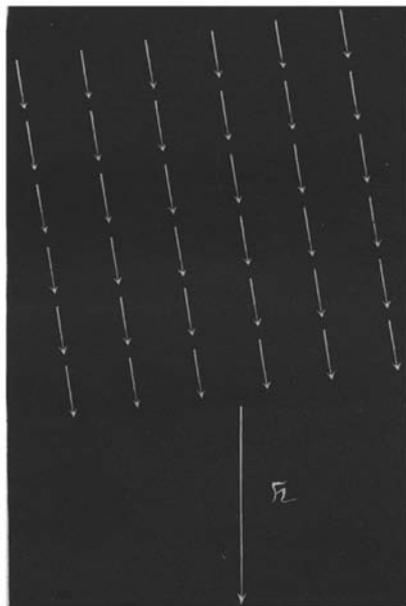


when \mathfrak{H} is removed, and the residual magnetism contributed by the group is then the sum of their moments resolved along \mathfrak{H} . When \mathfrak{H} is acting, the components along \mathfrak{H} are slightly greater, for the molecules are then (stably) deflected through a small angle towards the line of \mathfrak{H} .

Let \mathfrak{H} be further increased—we now have the third stage (*c*) (fig. 3), which consists in the closer approach to saturation that is caused by the molecules being more nearly pulled into exact line with \mathfrak{H} (fig. 6). Whether there will be instability during the deflexion of them from the lines of fig. 5 will depend on the closeness of the poles, and on the inclination of the lines of fig. 5 to the direction of \mathfrak{H} (see below). In some groups saturation will be complete with a finite value of \mathfrak{H} ; in others, it will only be closely approximated to. In magnetizing any actual specimen of iron, we have, of course, to deal with a multitude of groups the lines to which lie at very various inclinations to \mathfrak{H} . If we remove the force \mathfrak{H} at a point in stage *c*, we find very little, if any, more residual magnetism than was found at the end of stage *b*. The

ratio of residual to induced magnetism is a maximum about the end of stage *b*, and diminishes as stage *c* proceeds. This, again, agrees completely with the observed facts.

Fig. 5.

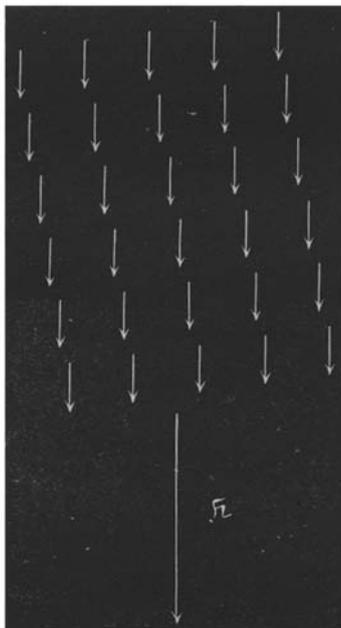


There is *some* hysteresis during the removal (whether complete or partial) and reapplication of magnetic force, because (provided we have enough groups to deal with) there will be some lines of elements which pass to and fro through a condition of instability during the removal and reapplication of the force. For certain inclinations of the line, the movements are not reversible.

Suppose, next, that having applied and removed a strong force \mathfrak{H} , leaving strong residual polarity, we begin slowly to reverse \mathfrak{H} . At first, the effects are slight; presently, however, instability begins, and, as the force is increased within a narrow range, we find the molecules all upset. This is followed by a stage of nearly elastic deflexion as saturation is approached. Thus, the well-known general characteristics of cyclic processes are all reproduced in the model (see fig. 8 below).

Again, a small repeated cyclic change of \mathfrak{H} superposed upon a constant value of \mathfrak{H} produces small changes of aggregate polarity, which are reversible if the change of \mathfrak{H} is very

Fig. 6.



small. This, as Lord Rayleigh has shown*, is what happens in a magnetic metal, and the susceptibility with respect to small cyclic changes is small in the model, just as it is in the actual solid.

The chief facts of permeability and retentiveness, and hysteresis generally, are therefore at once explicable by supposing that Weber's molecular magnets are constrained by no other forces than those due to their own mutual magnetic attractions and repulsions. No arbitrary constraining forces are required. In the model the centres of rotation are fixed; in regard to the actual solid we may make an equivalent supposition, namely, that the distances between the molecular centres do not change (except in so far as they may be changed by strain).

Hysteresis, then, is not the result of any quasi-frictional

* Phil. Mag. March 1887.

resistance to molecular rotations; it occurs whenever a molecule turns from one stable position of rest to another through an unstable condition. When it is forced to return, it again passes through a condition of instability. This process, considered mechanically, is not reversible; the forces are different for the same displacement, going and coming, and there is dissipation of energy. In the model the energy thus expended sets the little bars swinging, and their swings take some time to subside. In the actual solid the energy which the molecular magnet loses as it swings through unstable positions generates eddy currents in surrounding matter. Let the magnets of the model be furnished with air-vanes to damp their swings, and the correspondence is complete.

A regular group of elementary magnets, especially when furnished with air-vanes, gives a good illustration of what has been called magnetic viscosity. When the imposed force \mathcal{H} reaches a critical value one of the outer members of the group becomes unstable, and swings slowly round; its next neighbours, finding their stability weakened, follow suit, and the disturbance spreads through the group in a way eminently suggestive of those phenomena of time-lag in magnetization which I have described in a former paper*.

The model shows equally well other magnetic phenomena which presumably depend on the inertia of the molecules, such as the fact that a given force causes more magnetic induction when suddenly applied than when gradually applied, and leaves less residual magnetism when suddenly removed than when gradually removed.

The well-known effects of mechanical vibration in augmenting magnetic susceptibility and reducing retentiveness are readily explicable when we consider that vibration will cause periodic changes in the distances between molecular centres. This has not only a direct influence in making the molecular magnets respond more easily to changes of magnetic force by reducing their stability during the intervals when they recede from each other, but tends indirectly towards the same result by setting them swinging.

The effects of temperature which are common to the three magnetic metals may be stated thus:—Let any moderate magnetizing force be applied, not strong enough to produce anything like an approach to magnetic saturation, and let the temperature be raised. Then the permeability *increases* until the temperature reaches a certain (high) critical value, at which, almost suddenly, there is an almost complete disappearance of magnetic equality. As regards the first effect,

* Roy. Soc. Proc., June 1889.

it is clear that an increase of permeability is to be expected from the theory ; expansion with rise of temperature involves a separation of the molecular centres, and therefore a reduction of stability. As regards the almost sudden loss of susceptibility which occurs at a high temperature, it may do no harm to hazard a rather wild conjecture. We may suppose the molecular magnets to be swinging more or less, the violence of the swings increasing as the temperature rises, until finally it develops into *rotation*. Should this happen, all trace of polarity would of course disappear. The conjecture that the molecular magnets oscillate more and more as the temperature rises, is at least supported by the fact (carefully investigated by Hopkinson * in iron and nickel ; data for cobalt also have lately been supplied by du Bois †) that under *strong* magnetic forces rise of temperature reduces magnetism ; for with strong forces the molecular magnets are already ranged so that their mean direction is nearly parallel to \mathfrak{H} : hence the earlier effect of heat (to diminish stability and facilitate alignment) does not tell, and the increased swinging simply results in reducing the mean value for each molecule of its moment resolved parallel to the magnetizing force.

Before referring to effects of stress we may consider shortly the stability of a pair or line of magnets, treating each as a pair of poles subject to the law of inverse squares. Take first a single pair of equal magnets with centres at C and C' (fig. 7). The poles P P' would lie in the line CC', but for the imposed force \mathfrak{H} , which produces a deflexion CC'P' or C'CP = θ .

Let α be the angle which \mathfrak{H} makes with the line of centres, m the pole-strength, and r the half length of the magnetic axis of each magnet. The deflecting moment is

$$2\mathfrak{H}mr \sin(\alpha - \theta),$$

and the restoring moment is

$$\frac{m^2 \overline{CN}}{\overline{PP'}^2},$$

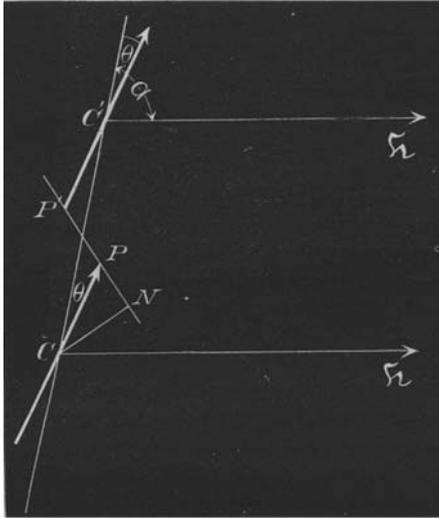
CN being drawn normal to PP'. The restoring moment at first increases with θ , but passes a maximum at a value of θ which depends on the relation of r to the distance between the centres. The condition of equilibrium is

$$2\mathfrak{H}mr \sin(\alpha - \theta) = \frac{m^2 \overline{CN}}{\overline{PP'}^2};$$

* Phil. Trans. 1889, A, p. 443 ; Roy. Soc. Proc., June 1888.

† Phil. Mag. April 1890.

Fig. 7.



and as \mathfrak{H} and θ are increased the equilibrium becomes neutral, that is to say, the condition of instability is reached, when

$$\frac{d}{d\theta} \{2\mathfrak{H}mr \sin (\alpha-\theta)\} = \frac{d}{d\theta} \frac{m^2\overline{CN}}{\overline{PP}^2}.$$

These two equations serve to determine the value of \mathfrak{H} and of θ at which instability occurs. If we have to deal with a long line of magnets instead of a single pair, we have to write $2m^2$ instead of m^2 in the restoring moment.

A considerable amount of stable deflexion is possible when the distance between the poles is not small compared with r . When the direction of \mathfrak{H} is not much inclined to CC' (that is, when α has a value approaching 0) there is no instability. In rows with various inclinations to \mathfrak{H} , the first to become unstable as \mathfrak{H} is increased will be that for which $\alpha-\theta$ is equal to $\frac{1}{2}\pi$.

If α , the half distance between the poles in the undeflected position, be small compared with r , there is but little deflexion before instability occurs, and in that case, provided α be not small, nor nearly equal to π , the occurrence of instability is defined by the condition

$$\frac{d}{d\theta} \frac{\overline{CN}}{\overline{PP}^2} = 0,$$

which is satisfied when $\tan \phi = \frac{1}{\sqrt{2}}$; ϕ being the inclination of PP' to the line of centres. Hence, with the same proviso (α not nearly equal to 0 or to π , and α small compared with π), the value of \mathfrak{H} which causes the instability is

$$\mathfrak{H} = \frac{m}{12\sqrt{3} \cdot a^2 \sin \alpha}$$

for a single pair of magnets, and twice this quantity for the middle members of a long row. This is of course least for magnets which lie normal to \mathfrak{H} .

In the special case when $\alpha = \pi$, instability occurs when

$$\mathfrak{H} = \frac{m}{8a^2}$$

with the single pair, or $m/4a^2$ with the row.

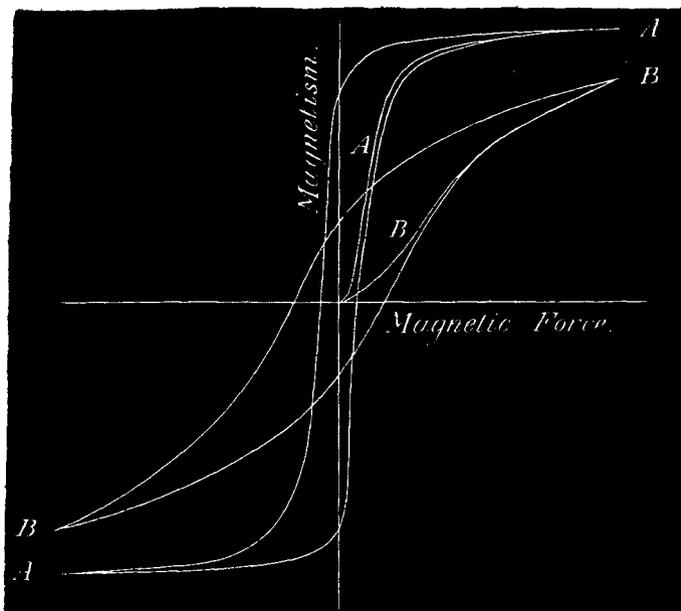
Applied to the case of a group of rows, uniform in distance between the centres, but various as regards their direction with respect to \mathfrak{H} , these considerations show that after \mathfrak{H} has reached a value sufficient to make the most susceptible members unstable, no very great increase is required to bring about instability in by far the greater number of the other rows. One general effect of increasing the distance between all the centres is to reduce the range of variation of \mathfrak{H} within which most of the different rows become unstable as the force is progressively increased.

In annealed metal, where we may expect considerable general homogeneity, as regards distance between the centres of the molecular magnets, we find that practically the whole of the abrupt stage in the process of magnetization is included within narrow limits of magnetizing force. We accordingly obtain curves like A A (fig. 8).

When the metal is strained sufficiently to receive permanent set the curves take more rounded outlines (such as B B), showing less susceptibility throughout, less residual magnetism, and more coercive force. The most natural explanation of this, on the basis of the molecular theory, appears to be that set produces on the whole a shortening of the distances between molecular centres, hence greater stability and more coercive force; but this is associated with heterogeneity, that is variety in the distances, hence the rounded outlines of the curves. We know that set tends to develop, or at least to emphasize, heterogeneity; for instance, a bar of iron or steel pulled in the testing-machine stretches irregularly after the elastic limit is passed.

The effects of stress and consequent elastic strain on magnetic quality are so complex and so various in iron, nickel,

Fig. 8.



and cobalt, that it would be premature to attempt any full discussion of them from the point of view of the theory now sketched. Only a few general features need be referred to at present. Some of these can be traced experimentally in the model by setting the supports of the magnets upon a sheet of thin india-rubber, which may be stretched or distorted to imitate the conditions of longitudinal or torsional strain.

When pulling stress is applied, those rows of molecular magnets which lie more or less along the direction of the stress have their stability reduced by the lengthening of the lines of centres; similarly, rows which lie more or less normal to the stress have their stability increased. The resulting effect on the general susceptibility of the material will depend on which of these conflicting influences preponderates. Let pull be applied before magnetization begins, while the metal is still in a neutral state. The stretching of longitudinal lines and the contraction of transverse lines will not only alter the stability of those molecules which continue to lie in their original rows, but will tend to make the members of those

rows which are much lengthened swing round and form transverse lines in which they will be more stable than before. We may therefore reasonably expect that the permeability with regard to strong fields will be reduced by pull, as it actually is both in iron and in nickel, though with regard to weak fields the permeability may be increased, as it is in iron.

Again, the theory explains well why the effects of stress are by no means the same (1) when the stress is applied first and the magnetic force after, and (2) when the magnetic force is applied first and the stress after.

Let a moderate magnetizing force be applied and then begin to apply stress. The first effects are in general large, for the strain precipitates into instability those molecular magnets which were already on the verge of instability. This is beautifully apparent in iron (see *Phil. Trans.* 1885, part ii., plates 63 and 64); and the theory shows why the first effects are not reversible, why they do not disappear when the stress is removed, and why it is only in subsequent applications and removals of the stress that the magnetic changes become cyclic.

The same remark evidently applies to the first effects of stress on residual magnetism; also to the first effects of temperature-change either on induced or residual magnetism. Again, the theory shows that when a cyclic change of stress is repeated, there will be hysteresis in the corresponding changes of magnetism, whether induced or residual, unless either the cyclic range is very small or the magnetism approaches saturation. During each application of the stress some molecular magnets will swing through unstable positions; during the removal of stress they will swing back, but not at the same values of stress. And it will be characteristic of this hysteresis that the variation in magnetism will begin slowly when the change from applying to removing stress, or from removing to applying stress, begins. All this agrees with the facts.

Moreover, the theory shows that even in the absence of any resultant magnetization a cycle of stress makes the molecular configuration pass through a series of changes which will at first not be cyclic, but will become cyclic when the stress-cycle is repeated, and in which any intermediate value of the stress will be associated with different configurations during the going and coming parts of the process. In other words, we see that there will be hysteresis in the relation of molecular configuration to stress when a cycle of stress is repeated. Hence certain rather obscure effects which have been observed in magnetic experiments; for instance, where an iron wire is

loaded and partially unloaded down to a given load before being magnetized, its permeability is not the same as when the wire is completely unloaded and reloaded up to the same load. Experimental results of this kind led me in 1884 to write :—"If we apply and remove stress in a wire whose magnetic state is entirely neutral, we cause some kind of molecular displacement in the relation of which to the applied stress there is hysteresis."* The theory now offered shows how this happens. Hence also the remarkable hysteresis which the thermoelectric quality of iron exhibits with regard to cyclic changes of stress, discovered by Cohn, and more fully described in *Phil. Trans.* 1886, p. 361. The hysteresis of molecular configuration with respect to stress has been proved to be removable or reducible by vibration.

From this theoretical explanation of hysteresis in the effects of stress, it at once follows that a cyclic change of stress (provided it be not very small) involves some dissipation of energy in a magnetic metal, whether the piece be magnetized or not. We may expect this dissipation to be most considerable under conditions which make the magnetic hysteresis large. But it will occur even when there is no external trace of magnetism.

This of course implies that, in a cyclic process of loading and unloading, work must be spent. There is no perfect elasticity in a magnetic metal, however slowly the process of straining be performed. Under any load there is less strain during application than during removal. This is borne out by experiments on the extension of iron wires (*Brit. Assoc. Report*, 1889, p. 502).

The same action occurs to a marked degree in torsional strains. In a twisted specimen there will be a tendency on the part of the molecular magnets to range themselves along lines agreeing more or less with the direction of maximum contraction. Alternate twisting to opposite sides should therefore cause much molecular swinging through unstable positions, with consequent dissipation of energy, even in a piece which is not magnetized.

Without going at present into details, it may be added that the phenomena of molecular "accommodation" studied by Wiedemann and by H. Tomlinson accord with the theory, and that it seems to lend itself well to explain the very remarkable results which have been obtained by Nagaoka †

* *Phil. Trans.* 1885, part ii. p. 614.

† *Journal of the College of Science of the University of Tokio*, vol. ii. 1888.

